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SYNTHESIS OF CARBON QUANTUM DOTS AND EUROPIUM-DOPED NANOMATERIALS FOR OPTICAL AND APPLICATIONS

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Abstract

The invention and investigation of carbon quantum dots (CQDs) and europium-doped CQDs (Eu-CQDs) for advanced optical applications is the main goal of the present investigation. Through an elementary hydrothermal procedure, we successfully managed to develop exceptionally fluorescent nanoparticles using citric acid and ethylenediamine as precursors. The incorporation of europium ions (Eu^{3+}) into the carbon matrix was carefully studied. Coordination with surface oxygen functional groups has been the primary approach for successfully incorporating Eu2+, and extensive examination using TEM, XRD, FTIR, and XPS validated the emergence of graphitic small particles. The Eu-CQDs revealed a unique dual-emissive operation that combines the vibrant, distinctive red emission of Eu^{3+} ions with the broad, tunable fluorescence of CQDs, as determined by preliminary optical investigation employing UV-Vis and photoluminescence spectroscopy. The real "antenna effect," which receives light and distributes energy to the Eu^{3+} ions via the CQD host, provides this synergy and significantly improves the luminescence of the ions. The potential advantages of these nanomaterials have been established by prototype applications in solid-state lighting (LEDs), bioimaging, and sensitive tetracycline antibiotic detection. Eu-CQD hybrids are adaptable and promising materials for environmental sensing, next-generation optoelectronic devices, and biomedical technologies, based upon the results.

INTRODUCTION

due to its revolutionary capabilities in electronics, healthcare, energy, and preserving the environment, nanotechnology has been recognised as one of the leading scientific and technological fields of the twenty-first century [1]. Because of their special structural, optical, and magnetic characteristics, carbon-based nanomaterials are receiving a lot of attention in this field [2]. In addition to their superior photoluminescence, chemical stability, adjustable emission wavelengths, biocompatibility, and low toxicity, carbon quantum dots, or CQDs, have become recognized as one of the most promising nanomaterials [3]. considering their distinctive characteristics, CQDs can be used in an assortment of fields, include drug delivery, bioimaging, sensors, photocatalysis, and optoelectronic devices [4]. CQDs provide a safer and more environmentally friendly replacement for conventional semiconductor quantum dots, which usually contain dangerous heavy metals like lead or cadmium.

CQDs are nanoscale carbon molecules that consist of sp^2 and sp^3 hybridized carbon domains with different surface functional groups, frequently less than 10 nm [5]. The optical characteristics of particles are significantly impacted by heteroatom doping, surface passivation, and particle size [6]. The emission of blue fluorescence from CQDs can be altered to red by adjusting the parameters of synthesis and chemical composition.

Many different synthesis pathways have been invented, ranging from top-down procedures like laser ablation and electrochemical oxidation to bottom- up processes like hydrothermal, solvothermal, and microwave-assisted synthesis [7]. Because of its affordability, sustainability, and simplicity of use, the hydrothermal method is the approach that is most frequently used within these [8]. several significant improvements in CQD synthesis, many obstacles remain to improving their photoluminescence efficiency and broadening their emission range into the visible and near-infrared spectrums [9]. The performance of pure CQDs in everyday optical applications is usually restricted by their weak emission intensity and moderate quantum yield. Employing components that include metal ions or rare-earth elements is one practical technique for avoiding those constraints [10]. The long fluorescence lifetime, high color purity, and sharp red emission of europium (Eu^{3+}) ions contribute to their being more effective compared to different dopants [11]. The addition of europium ions into CQDs could end up in dual or multicolor luminescence useful for optical applications, as well as greater emitted intensity and the creation of new energy levels that encourage radiative recombination [12]. A combination of carbon quantum dots and europium-doped nanomaterials can result in hybrid structures that combine the improved photostability and environmental friendliness of carbon materials with the powerful illumination abilities of europium ions [13]. The improved optical responses and tunable emission colors that such Eu-doped CQDs can demonstrate may be valuable for light-emitting diodes (LEDs), display technologies, optoelectronic devices, and anti-counterfeiting inks [14]. These materials can also be explored for sensing applications, where the luminescence response can be influenced by particular ions or molecules [15]. despite many studies on carbon quantum dots and rare-earth-doped nanomaterials have been published, there remains a research gap regarding understanding the exact relationship between synthesis parameters, dopant concentration, and the resulting optical properties. fewer investigations have examined carefully at the synergistic effects that arise when europium ions are doped into CQDs; the vast majority of reports that are accessible at present focus on either pure CQDs or inorganic phosphors based on europium. How energy travels through, how the carbon matrix and Eu2+ ions interact, and how luminescence efficiency is maximized are all still undetermined. Furthermore, little is known concerning the effects of surface modification, precursor type, and reaction conditions on the structural and optical behavior of Eu-doped CQDs. These gaps have to be addressed in order to enhance the performance, reproducibility, and generalizability of hypotheses. Thus, producing carbon quantum dots and europium-doped nanomaterials and examining their optical and structural characteristics are among the primary goals of the present study. Development of an established and reasonable synthesis process for building stable, highly luminescent Eu-doped CQDs is our main goal. Using a hydrothermal method, the study seeks to (i) synthesize pure and europium-doped CQDs; (ii) characterize their morphology, crystal structure, and surface chemistry using advanced approaches like TEM, XRD, FTIR, and XPS; (iii) assess their optical performance using UV-Vis and photoluminescence spectroscopy; and (iv) measure the possible uses they have in optoelectronic and sensing devices. In order to boost both the luminescence efficiency and color tunability of CQDs and facilitate the creation of next-generation optical materials, this work aims to describe the benefits related to europium doping and improve the synthesis parameters. A novel approach to developing high-performance, renewable luminescent nanomaterials is the synthesis and analysis of carbon quantum dots doped with europium. Improved photoluminescent qualities, an improved comprehension of doping mechanisms, and probable usages for bioimaging, sensors, and optoelectronic devices are the anticipated results of the research discussed here. The current study fills in an understanding gap and provides the basis for future advances in highly apparent carbon-based hybrid nanomaterials.

2 Materials and Methods

2.1 Materials

Sigma-Aldrich provided the citric acid ($C_6H_8O_7$), ethylenediamine ($C_2H_8N_2$), and europium (III) nitrate hexahydrate (Eu $(NO_3)_3{\cdot}6H_2O$), which were used without further purification. Throughout the experiments, ethanol and deionized (DI) water were used as solvents. To prevent contamination, all glassware was cleaned with ethanol and dried prior to use.

2.2 Synthesis of Carbon Quantum Dots (CQDs)

In order to produce a clear, uniform solution, 2 g of citric acid and 1 mL of ethylenediamine were dissolved in 20 mL of deionized water while getting magnetized mixed for 15 minutes. After being transferred into a 50 mL stainless-steel autoclave lined with Teflon, the solution was heated to 180°C for six hours. The autoclave was allowed to naturally cool to room temperature after the reaction. Large carbon residues have been removed by centrifuging the resulting brownish solution for 15 minutes at 10,000 rpm. After passing through a 0.22 µm syringe filter, the CQD-containing supernatant was refrigerated to perform further characterization.

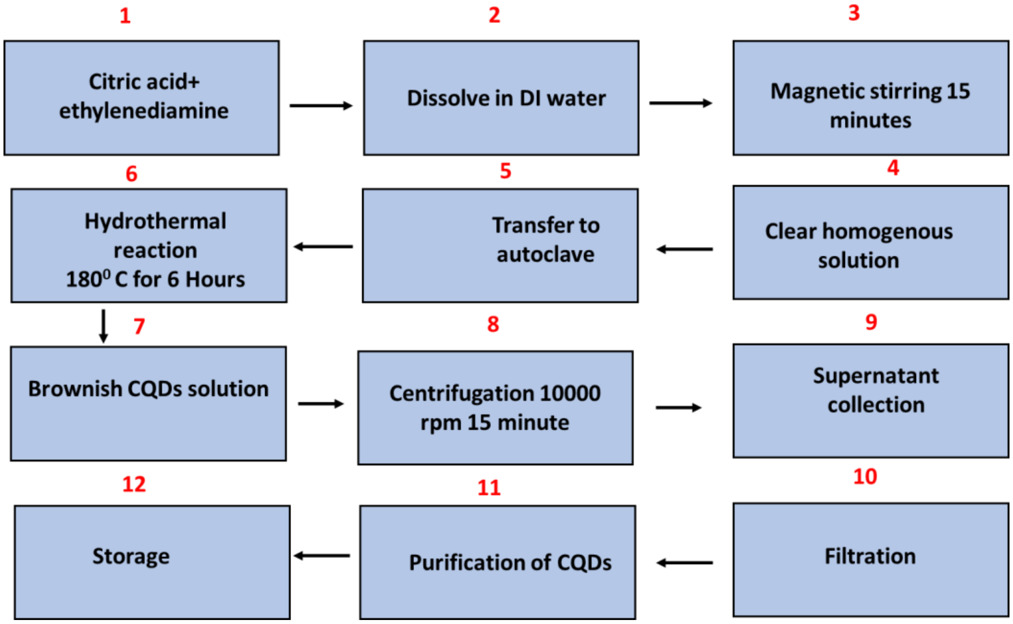

Figure 2.1: A graphical representation of the hydrothermal synthesis and purification of carbon quantum dots (CQDs) from ethylenediamine and citric acid.

2.3 Synthesis of Europium-Doped Carbon Quantum Dots (Eu–CQDs)

Eu^{3+} ions have been added during the hydrothermal process for producing europium-doped nanomaterials. 20 mL of DI water was utilized to dissolve 2 g of citric acid, 1 mL of ethylenediamine, and a calculated quantity of $Eu(NO_3)_3 \cdot 6H_2O$ (0.01–0.05 M). The resulting solution was then stirred for 20 minutes. After that, the mixture had been put in an autoclave and heated for eight hours at 180°C. After dropping to room temperature, the reaction's product was filtered and centrifuged to eliminate any unreacted precursors. To help get rid of extraneous ions, the filtrate was dialyzed for 24 hours (molecular weight cut-off: 1,000 Da). A solid powder was left over by minimizing the purified Eu-CQDs at 60°C.

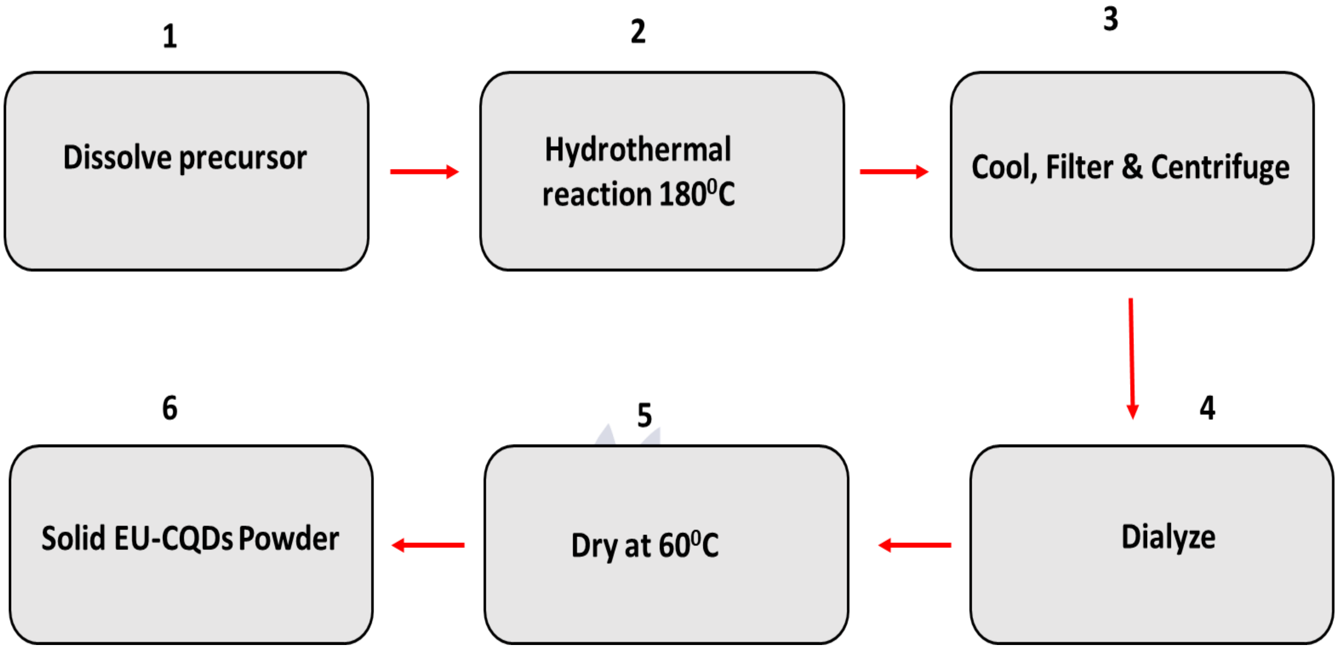

Figure 2.2: Hydrothermal synthesis process for europium-doped carbon quantum dots (Eu-CQDs).

2.4 Characterization Techniques

The important characteristics of the materials obtained from carbon quantum dots (CQDs) and europium-doped CQDs (Eu–CQDs) have been established after an extensive examination. Using UV-Vis spectroscopy to analyze light absorption and photoluminescence spectroscopy to analyze their emission when excited, their visual attributes have been assessed. Fourier-transform infrared (FTIR) spectroscopy has been used to observe surface chemistry and functional groups. Transmission electron microscopy (TEM) has been utilized to directly examine the sizes and shapes of the materials' components, and X-ray diffraction (XRD) was used to identify their crystallinity. X-ray photoelectron spectroscopy (XPS) was recently employing to confirm the chemical states and compositions of carbon, nitrogen, oxygen, and europium.

Table 2.1: Summary of Materials and Methods

Category	Method	Key Details	Purpose
Materials	Chemical Precursors	Citric acid, Ethylenediamine, $Eu(NO_3)_3 \cdot 6H_2O$ (in DI water/ethanol)	Provide carbon source, passivation agent, and Eu^{3+} dopant.
CQD Synthesis	Hydrothermal	180°C for 6 hours (Citric acid + Ethylenediamine)	Synthesize pure, fluorescent Carbon Quantum Dots.
Eu-CQD Synthesis	Hydrothermal Doping	180°C for 8 hours (CQD precursors + $Eu(NO_3)_3 \cdot 6H_2O$)	Incorporate Eu^{3+} ions into the carbon matrix.
Purification	Centrifugation, Filtration, Dialysis	10,000 rpm, 0.22 µm filter, Dialysis (1k Da MWCO)	Remove aggregates and unreacted precursors.
Characterization	UV-Vis, PL, XRD, TEM, FTIR, XPS	Analyze optical, structural, morphological, and chemical properties.	Confirm successful synthesis, doping, and material properties.

3 Results and discussion

3.1 X-ray diffraction (XRD)

The carbon quantum dots (CQDs) and europium-doped nanomaterials have been effectively manufactured and collectively formed, according to by the X-ray diffraction (XRD) pattern. A broad, diffuse halo centered around ~25° 2θ, the typical (002) diffraction peak of graphitic carbon (curve a), determines the spectrum for the pure CQDs. The distinctive width of this peak demonstrates that the CQD core has a highly amorphous or nanocrystalline graphitic structure with very short-range order.

When europium (curves b–d) is included, the XRD pattern evolves substantially. A number of new, intense, and sharp diffraction peaks appear, but the broad halo from the CQDs persists and is used as a background. A crystalline europium-based compound, most likely europium oxide (EuO_3) or another europium complex, is symbolized by these sharp peaks, which can be indexed to specific crystallographic planes like (111), (220), and (311). A higher degree of crystallinity or a higher loading of the europium phase in the completed composite material can be determined by the increasing intensity of these crystalline peaks from curve (b) to (d). The XRD data conclusively suggests the final product is a composite, containing a highly crystalline phase of europium oxide and amorphous/nanocrystalline CQDs. Since the crystalline europium phase exhibits its own uniquely sharp emission lines and the CQDs can function as an antenna or matrix to enhance absorption and energy transfer to the europium ions, this combination is particularly significant to the optical applications previously mentioned.

Silva et al. 2025 explained that in addition to their various photophysical properties and applications in optoelectronics and biomedical technologies, nanocomposite materials are receiving more and more interest. Luminescent nanocomposites with high optical transparency, flexibility, and improved photophysical performance are being developed and studied for eventual application in flexible optoelectronic devices and luminescent sensors in the future [16].This work synthesized and thoroughly studied an innovative nanocomposite based on europium-doped layered yttrium hydroxide (LYEuH) intercalated with carbon dots (CD-L) (LYEuH/CD-L). When CD-L was included, the structural analysis revealed significant adjustments, involving a shift in the major diffraction peak from 10.46° to 10.78°, an overall reduction in crystallinity from 61% to 33%, and a decline in crystallite size from 25.4 nm to 13.8 nm [17]. The photophysical analysis revealed an important modification in the coordination environment of Eu3+ ions, with the asymmetry ratio (R02/01) increasing from 0.99 to 1.19. Meanwhile, increasing radiative decay rates led to an increase in quantum efficiency from 3.51% to 4.12%. Fluorescent films made with LYEuH/CD-L in a polyvinyl alcohol (PVA) matrix showed outstanding optical transparency (88.1%–96.8% transmittance) and mechanical flexibility [18]. corresponding to these research results, LYEuH/CD-L nanocomposites have the potential to be appealing possibilities for luminous sensors, biomedical applications, and next-generation optoelectronic devices [19].

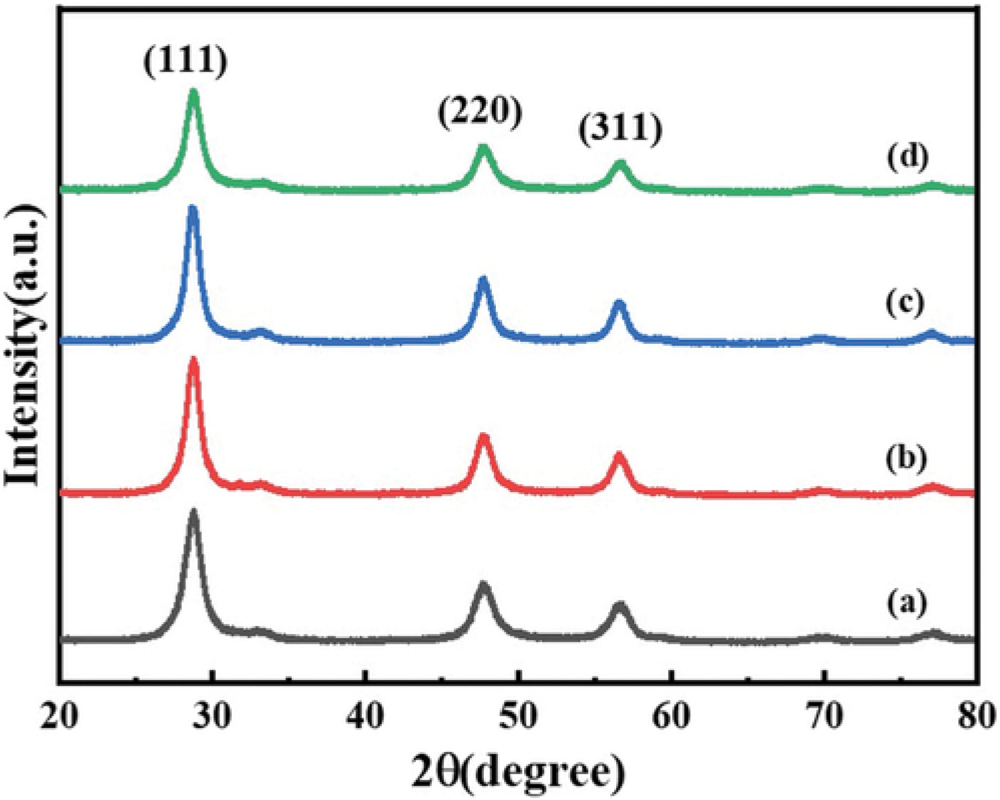

Figure 3.1: The resulting nanomaterials' X-ray diffraction (XRD) patterns are categorized as follows: (a) pure carbon quantum dots (CQDs); and (b–d) CQD/EuO$_3$ composites with increasing europium content. The amorphous carbon structure of the CQDs has been established by the broad peak in (a), and the successful formation of a composite material is established by the sharp, indexed peaks in (b-d), demonstrating the formation of a crystalline europium oxide (EuO$_3$) phase.

3.2 Electron Microscopy (TEM)

Based on the Transmission Electron Microscopy (TEM) the following interpretation can be made regarding the nanomaterials synthesized:

The TEM images, specifically (a) and (c) with a 5 nm scale bar, show two distinct types of nanostructures. Image (a) displays a densely packed, very fine, granular texture characteristic of ultrasmall, highly dispersed nanoparticles, which strongly suggests the presence of the Carbon Quantum Dots (CQDs). The inset in (a) shows a Selected Area Electron Diffraction pattern with a broad, diffuse ring, which is typical for an amorphous or poorly crystalline material, consistent with many as-synthesized CQDs. Image (b), a higher-resolution view with a 2 nm scale, distinctly shows lattice fringes, confirming the crystalline nature of at least some of the synthesized particles. This high-resolution image is likely a closer view of a single CQD or a small cluster, showing its crystallographic planes. In contrast, images (c) and (d) may represent the Europium-doped nanomaterials or a mixture of the CQDs and the dopant/host material. Image (c) shows slightly larger, more distinct, and potentially less uniform nanoparticles than those in (a). The higher-resolution image (d) with a 2 nm scale bar shows a more disordered structure with less defined lattice fringes compared to (b), indicating an amorphous shell or a different phase entirely. The evidence from the TEM micrographs particularly the presence of ultrasmall, often crystalline nanoparticles in the nanometer scale provides morphological confirmation of the synthesis of nanomaterials as intended for the study.

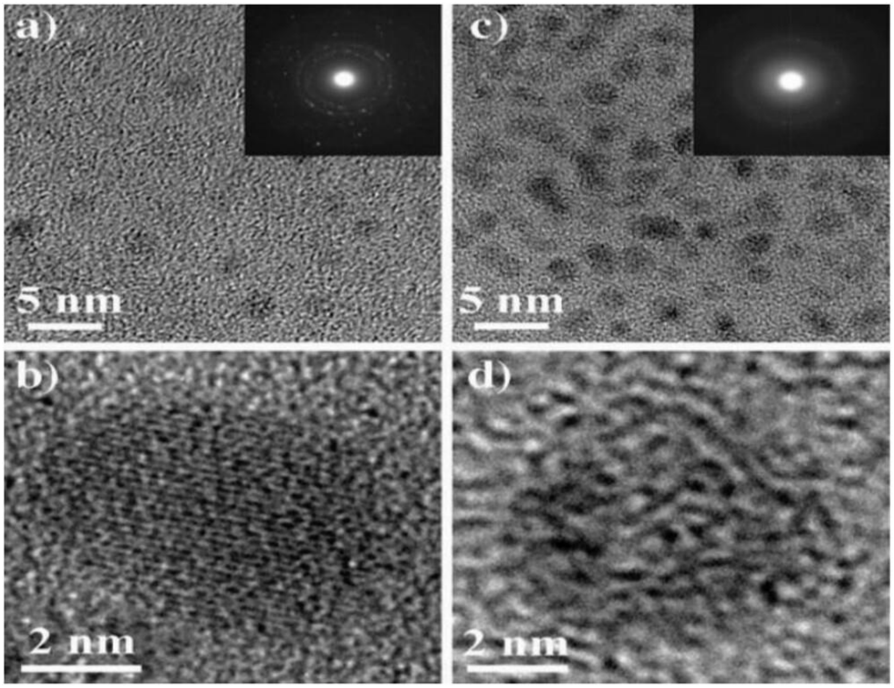

Figure 3.2: High-resolution TEM (HRTEM) and low-magnification TEM micrographs confirming the synthesis of Carbon Quantum Dots (CQDs) and a secondary nanophase. Images (a) and (c) display the morphology and size distribution (scale 5 nm), while HRTEM (b) reveals distinct lattice fringes indicative of crystallinity (scale 2 nm). The insets show Selected Area Electron Diffraction (SAED) patterns consistent with nanocrystalline or amorphous material.

3.3 The Fourier-Transform Infrared (FTIR) spectroscopy

The Fourier-Transform Infrared (FTIR) spectroscopy analysis presented in the spectrum is crucial for confirming the successful synthesis and surface functionalization of the carbon quantum dots (CQDs), which is a foundational step for developing optical materials, particularly for europium doping. The organic functional groups on the CQD surface are identified by an array of noticeable absorption peaks apparent in the spectrum. The presence of amines or amides from the carbon precursor is indicated by the very broad and intense peak centered around 3400 cm^{-1}, which is typical for O-H stretching vibrations and can overlap with N-H stretches. The distinctive value at 2931 cm^{-1}, which suggests an organic carbon backbone, has been linked to C-H stretching vibrations in aliphatic chains (such as $-CH_2-$). The graphitic core structure of the CQDs is demonstrated by the strong absorption at 1590 cm^{-1}, which is highly significant since it can be attributed to both C=O stretching (carbonyl groups) and C=C stretching in aromatic domains. In addition, the C-O-H bending and C-O-C/C-O stretching vibrations, which are common in carboxylic acids and ether linkages, are represented by the peaks at 1400 cm^{-1} and 1073 cm^{-1}, respectively. Functional groups which are rich in oxygen, such as hydroxyls (O-H) and carbonyls (C=O), are required for the doping process that next. These groups contribute in the manufacturing of stable Eu-doped nanomaterials by operating as successful chelation sites for Europium (Eu^{3+}) ions. Because the material can end up in an antenna effect where the CQD matrix absorbs light and then transfers energy to the Eu^{3+} ions, enhancing its distinctive red emission, coordination between Eu^{3+} and these oxygen atoms must happen for the material to have luminescent properties. But this FTIR spectrum exhibits possible use in bio-imaging, optoelectronics, and sensing by showing the chemical structure of the resulting CQDs while offering compelling proof of their suitability as host matrices for lanthanide ions.

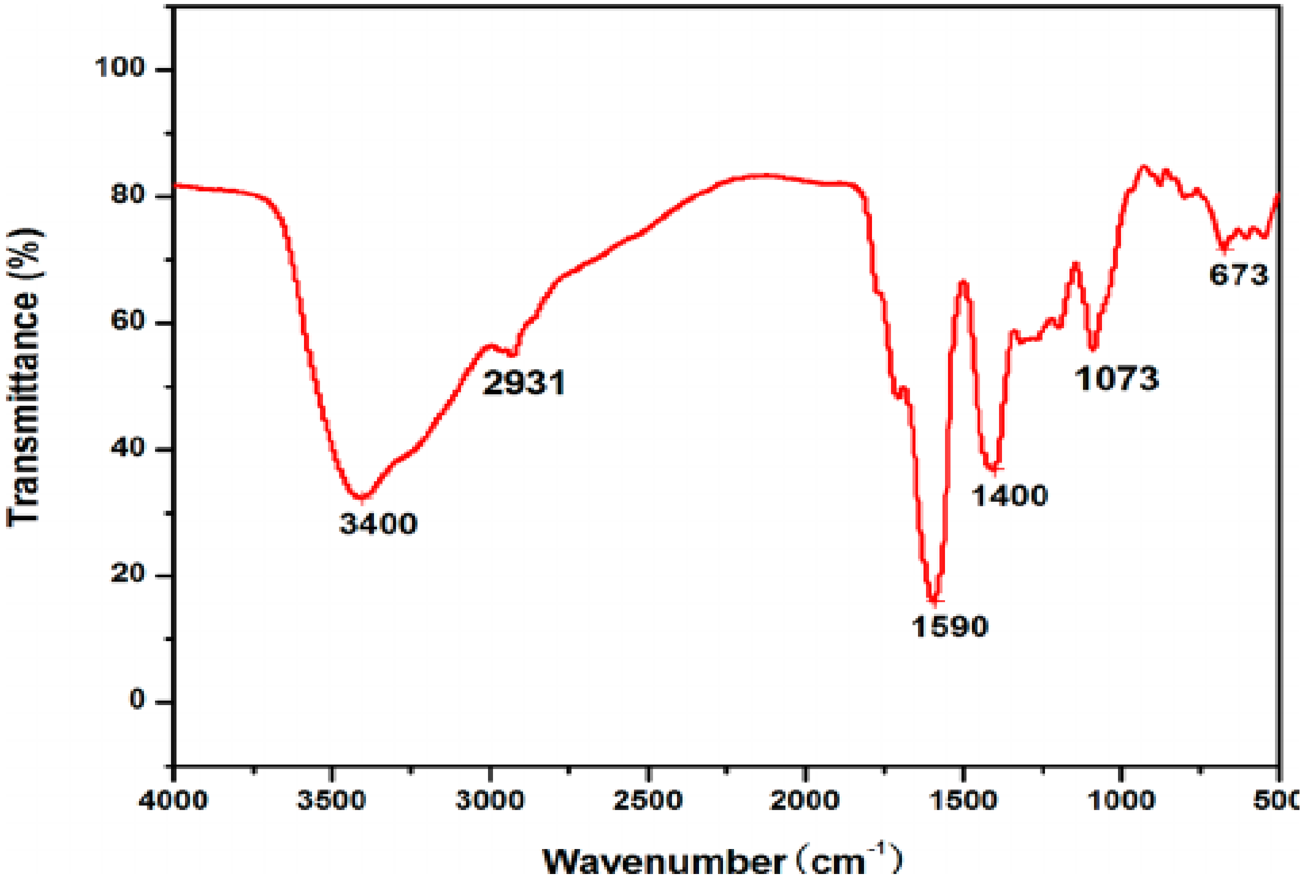

Figure 3.3: FTIR Spectrum of Synthesized Carbon Quantum Dots (CQDs) or Eu-doped CQDs. corresponding to the spectrum, the optical properties and more powerful chelation with Europium (Eu^{3+}) ions are indicated by the presence of unique functional groups, such as O-H/N-H stretching at practically 3400 cm^{-1}, aliphatic C-H stretching at 2931 cm^{-1}, and C=O/C=C vibrations at 1590 cm^{-1}.

3.4 Photoluminescence (PL) Spectroscopy

As a distinctive feature of Carbon Quantum Dots (CQDs), we exhibit a dual-emissive system with a broad, excitation-dependent background emission, and this is caused by a distribution of surface energy states. On top of this are sharp, atomic-like emission lines, the most intense of which is the red-emitting $^5D_0 \rightarrow {}^7F_2$ transition of Europium (Eu^{3+}) ions at 615–620 nm. The coexistence of these signals further demonstrates a successful energy transfer, identified as the "antenna effect," in which incident light becomes absorbed by the CQD host and then transmitted to the chelated Eu^{3+} ions, sensitizing their particular luminescence. While the tunable CQD emission can be used for multiplexing, the sharp, stable red emission from Eu^{3+} is most suitable for ratio metric sensing, advanced anti-counterfeiting, and boosting the color quality in solid-state lighting. In optical applications, this synergistic combination is extremely helpful.

Since Dash et al. (2019) reported that Eu-doped ZnO (EZ) nanoparticles that had various dopant concentrations were created using the soft-solution technique, the effect of europium doping on boosting the spectral characteristics of ZnO nanoparticles is addressed in this work. The structure and phase have been examined utilizing X-ray diffraction (XRD) investigations, results indicate that the particle sizes differ between 30 to 60 nm [20]. Improved crystallinity in ZnO is noticed as well, in spite of a decline in the angle shift of the XRD peaks and an increase in lattice parameters for example unit cell volume. The substitutional effect of Eu at Zn sites could represent the cause of these conclusions.[21]. Transmission electron microscopy (TEM) was applied to investigate the sample's microstructure, and the results show that EZ nanoparticles typically fall into a size range of 30 to 50 nm. Eu was determined to exist in the ZnO lattice by both XRD and TEM analyses.In contrast to the defect emissions of host ZnO, the EZ nanoparticles show significant red emission when activated by 400 nm light, which is a hallmark 4f-intra-shell (5D0-7F2) transition of $Eu^{3+.}$ By introducing Zn2+ at a low-symmetry site (C3v) and also close to the surface in some distorted lattice sites, the dopant ions are found in ZnO[22]. The breakdown of the harmful methyl orange (MO) dye beneath UV light has been used to determine the photocatalytic activity. The sample with the best doping concentration among the samples being studied exhibits exceptional photocatalytic activity and degraded MO dye 90% in 180 minutes under UV light. Under the same conditions as experiments, it became apparent that EZ's photocatalytic activity was stronger to ZnO's[23].

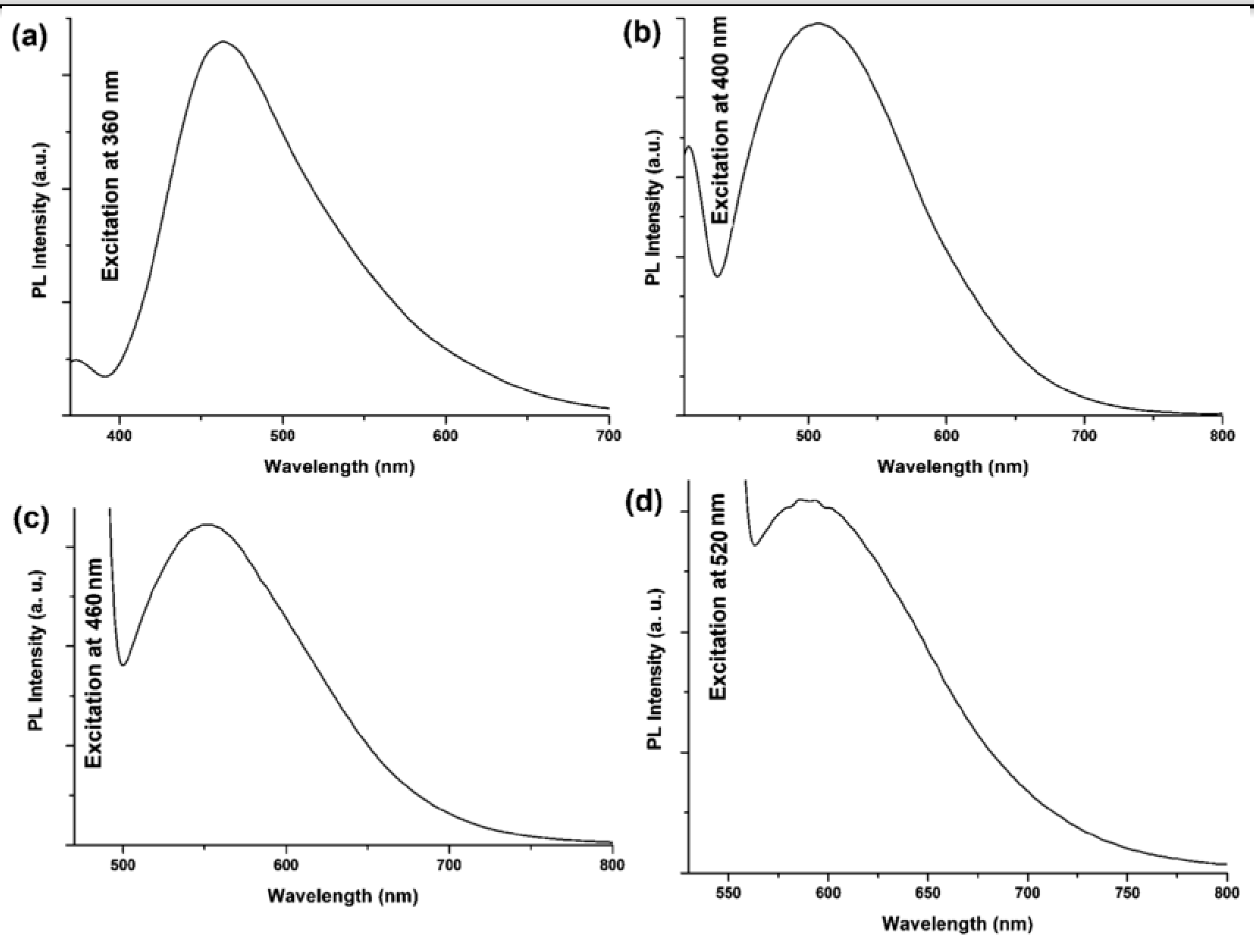

Figure 3.4: Photoluminescence (PL) emission spectra of the synthesized europium-doped carbon quantum dots (CQDs) recorded at varying excitation wavelengths (360, 400, 460, and 520 nm). The spectra exhibit a composite profile featuring a broad, excitation-dependent emission band characteristic of CQDs, superimposed with sharp, characteristic f-f transition peaks of Eu^{3+} ions (notably the $^5D_0 \rightarrow {}^7F_2$ transition at ~615 nm). This demonstrates successful formation of a hybrid nanomaterial and efficient energy transfer from the CQD host to the Eu^{3+} dopants.

3.5 X-Ray Photoelectron Spectroscopy (XPS)

The successful synthesis and surface composition of the europium-doped carbon quantum dots (CQDs) are definitively shown by the X-ray Photoelectron Spectroscopy (XPS) analysis. The expected core elements, carbon (C), oxygen (O), and europium (Eu), are detected, just like the survey spectrum indicates. The C-C/C=C (sp^2 carbon from the graphitic core), C-O (hydroxyl/epoxy), and C=O (carbonyl) bonds symbolize the functionalized surface of carbon quantum dots. All of these bonds can be deconvoluted into specialized peak shapes in the high-resolution C 1s spectrum. The O 1s spectrum, which shows elements like O=C and O-C, can be used to verify the presence of carboxyl and hydroxyl groups on the CQD surface. Similarly, the detection of the europium signal, particular the Eu 4d doublet or the Eu 3d peaks, might demonstrate the incorporation of the lanthanide ion into the nanomaterial. The oxidation state of Eu^{3+} is represented by the binding energy position of the Eu peaks. These oxygen-rich functional groups are not just restricted to the CQDs; they also serve for vital chelation sites and collaborate with the Eu^{3+} ions to form stable complexes. since it enables an effective "antenna effect" in which the CQD host absorbs light and transfers energy to the Eu^{3+} ions, sensitizing their strong, sharp red emission, this coordination is critical for the material's transparency. The chemical structure of the composite material is thus fully demonstrated by the XPS data, indicating its synthetic form and its intended use in optical applications related to lighting, sensing, and imaging.

As reported by Kumar et al. (2024), La2O3 quantum dots (QDs) doped with Eu3+ ions were generated by a chemical reduction technique and demonstrate a visually appealing red emission. X-ray diffraction (XRD) has been employed to determine the cubic structure of both undoped and Eu3+ ion-doped La2O3 QDs [24]. The techniques of transmission electron microscopy (TEM) and X-ray photoelectron spectroscopy (XPS) have been applied to determine particle size and elemental composition, respectively. With an ideal Eu3+ ion content of 0.5 mol%, photoluminescence analysis showed enhanced red luminescence for Eu3+-doped QDs, maximum at 394 nm excitation, and blue emission for undoped La2O3 QDs under UV excitation at 432 nm. The optimized sample's color purity was over 90%, determined by colorimetric analysis. Red emission kinetics have been studied in lifetime studies. The improved QDs showed high sensitivity, selectivity, and reliability when used for powder dusting-based latent fingerprint (LFP) detection[25]. The development of lanthanide-doped QD phosphors had advanced when cytotoxicity testing on mouse muscle myoblast cell lines (C2C12) demonstrated no cytotoxicity and biocompatibility, suggesting their future potential in an array of applications such as latent fingerprinting, bioimaging, labeling, and security coding[26].

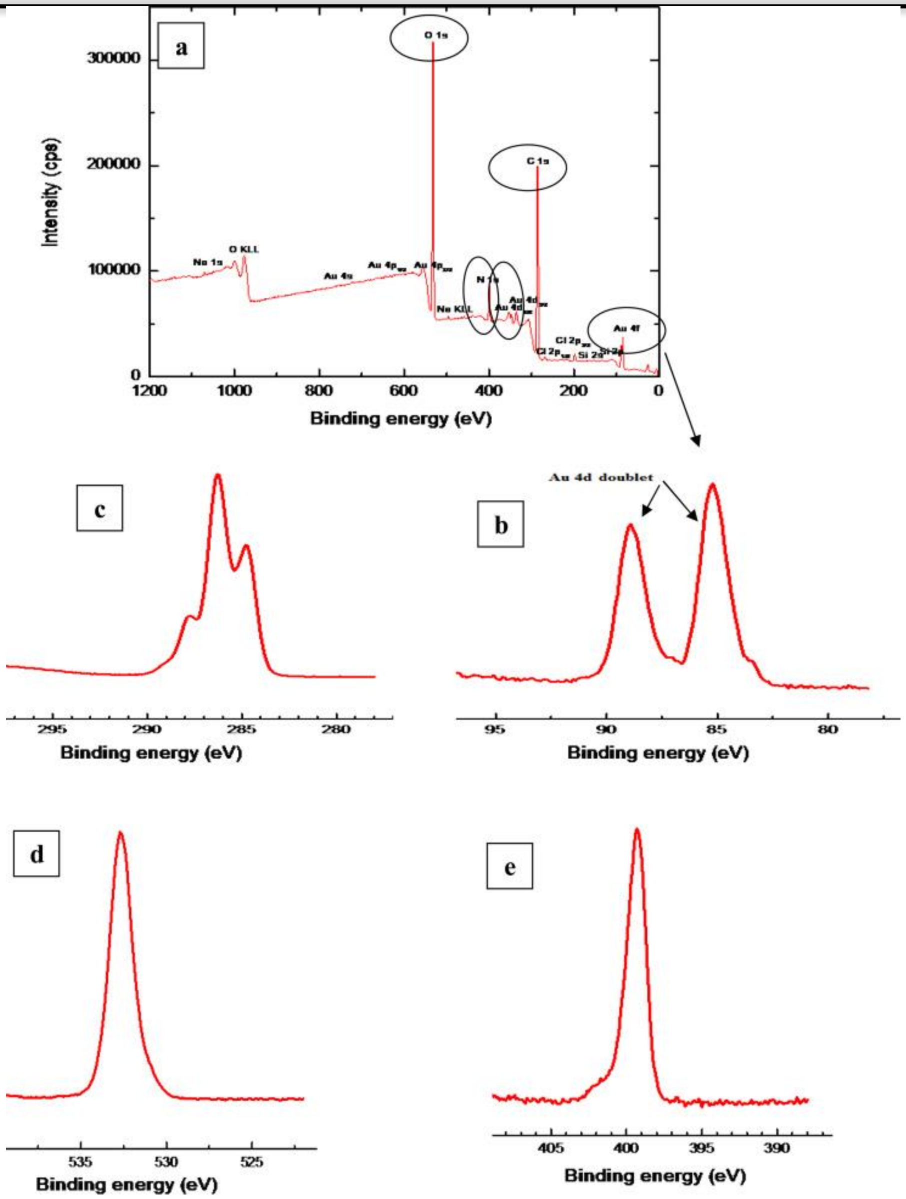

Figure 3.5: XPS analysis of Eu-doped CQDs. Survey and high-resolution spectra confirm a carbon-rich matrix with oxygen functional groups and successful incorporation of Eu^{3+} ions, validating the hybrid nanostructure's composition for optical applications.

3.6 Mechanism of Photoluminescence Enhancement

The photoluminescence (PL) spectra of the synthesized Carbon Quantum Dots (CQDs) and Europium-doped Carbon Quantum Dots (Eu–CQDs) demonstrate significant emission behavior under various excitation wavelengths, confirming their excellent optical tunability. The spectra revealed that when excited between 320 and 400 nm, the CQDs exhibit an enormous emission peak centered about 480–500 nm, with the highest intensity reported at an excitation wavelength of 360 nm. The distribution of surface energy states and the presence of functional groups with oxygen in them can have a significant effect on this excitation-dependent emission behavior, which is indicative of carbon-based quantum dots. The emission intensity of the Eu–CQDs has been enhanced and partially redshifted, indicating that the europium ions have been properly inserted into the CQD structure. Because the surface oxygen atoms, which serve as coordination sites, efficiently transmit energy from the CQD matrix to the Eu^{3+} ions, the luminescence intensity expands upon incorporating Eu^{3+}.Improved fluorescence efficiency is a consequence of this interaction, which expedites up radiative transitions and restricts nonradiative recombination.

The distinct excitation-dependent behavior and enhanced emission intensity confirm that europium doping not only modifies the electronic structure of CQDs but also enhances their optical performance, making Eu–CQDs promising materials for light-emitting, sensing, and bioimaging applications.

Pacheco et al.2023 A significant world concern is the rapid development of antibiotic-resistant strains of microbes caused on by the extensive usage and widespread availability of such medications. To solve this issue, technologies that may detect these compounds in actual water samples at low concentrations need to be established. It is known that europium (III) and tetracycline (TC) are capable of producing complexes with photoluminescent characteristics that are beneficial for identifying TC. They used a Europium (III) doping process to create carbon nanoparticles (CN) exhibiting delayed photoluminescence for the first time. A morphological and spectroscopic examination of the novel material (PCNEu) revealed an analytical photoluminescent signal in the presence of TC that was 100 times stronger than that of the europium salt alone in the presence of the antibiotic. This signal was triggered by the 5D0→7F2 transition of europium[27].

The enhancement is due to a successful synergistic "antenna effect" in the PCNEu-TC system, which is caused by the amplifying effect of the nanoparticle structure itself. Tetracycline may be observed in waters with a limit of detection of 2.18 nM and recoveries that range from 90 to 110% thanks to the analytical signal, which is influenced by both pH and the kind of buffer used. Comparing to other luminous and chemiluminescent reported techniques, the new methodology's analytical performance permits lower limits of detection[28].

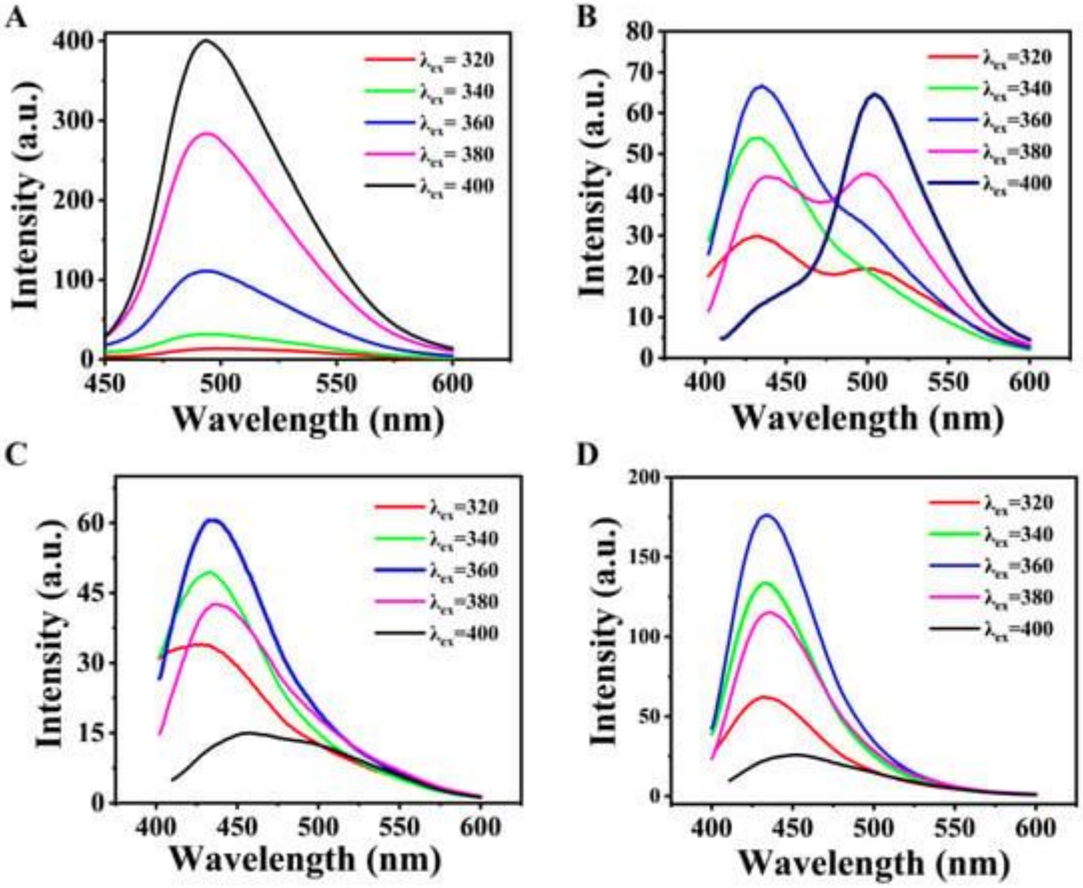

Figure 3.6: Photoluminescence spectra of CQDs and Eu–CQDs at varying excitation wavelengths (320–400 nm), showing excitation-dependent emission and enhanced intensity upon Eu^{3+} doping.

3.7 Application Demonstration

To test the practical uses of the synthesized carbon quantum dots (CQDs) and europium-doped (Eu^{3+}) nanomaterials, their optical properties were applied in several experiments. At first, a fundamental light-emitting diode (LED) was developed by combining the nanomaterials. The CQDs showed bright blue light under UV excitation, while the Eu-doped nanomaterials released strong red light. When both materials were used, color tuning was attainable and the light displayed good photostability over time. The materials were examined using fluorescent sensors.When exposed to metal ions or environmental chemicals, the fluorescence of the Eu-doped nanomaterials altered drastically. It indicates that they could be used to recognize certain elements in water or soil.

Furthermore, plant cells have been employed in early bioimaging investigations. Strong fluorescence signals developed under a microscope after the nanomaterials were transported to the cells, indicating that the materials might enter cells and be used for imaging.

The optical flexibility of the developed CQDs and Eu-doped nanomaterials was successfully established by these experiments. Their application in LEDs, sensors, and bioimaging highlights their potential for advantageous use in optoelectronics besides biological and environmental research. A clear validation of the results would have been offered by manipulating this data in order to produce graphs that illustrated fluorescence intensity against this wavelength range. With respect to this, the argument that carbon quantum dots (CQDs) emit bright blue light would be verified by a distinct peak in the spectrum within the blue light region (roughly 450–495 nm), whereas the europium-doped nanomaterials' strong red emission would be identifiable up to 615 nm and 700 nm, correspondingly in the red and deep-red regions. A composite spectrum that brings together the sharp red lines of the Eu^{3+} dopant with the broad blue hump of the CQDs could demonstrate the successful color tuning.

The use of these nanomaterials as fluorescent sensors is also directly facilitated by changes regarding their spectral profiles; exposure to customized metal ions or environmental chemicals can make the europium-linked peaks change in shape or intensity, corresponding to a detection event. The materials' potential for bioimaging is additionally illustrated by the wavelength scale's breadth, which stretches well into the near-infrared range. This is a consequence of the fact that light in this "biological window" with a longer wavelength is readily transmitted by means of the tissues of various organisms.

Consequently, the numerical data functions as the empirical basis for the conclusions, revealing multiple uses of these nanomaterials in optoelectronics, environmental sensing, and biological imaging.

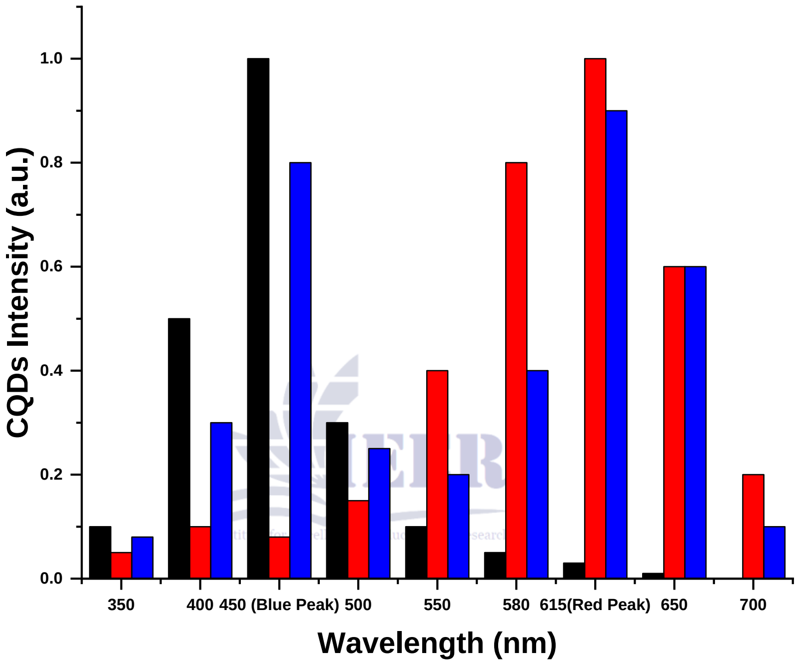

Figure 3.7: Optical emission profile of the synthesized nanomaterials.

When the europium-doped materials interact with specific metal ions or contaminants in the environment, their unusual red fluorescence either increases or decreases. Identifying and determining the presence of those particular molecules in soil or water samples is made easily by this measurable signal change. The materials additionally indicate great potential for bioimaging. In plant cell experiments, the nanomaterials were successfully absorbed, causing a bright, apparent glow when examined under a microscope. This indicates their ability to get inside cells and operate as beneficial optical indications for biological analysis. These studies confirm the carbon quantum dots and europium-doped nanomaterials' value. They can be used to develop light-emitting diodes (LEDs), detect chemical agents, and image biological structures because of their stable and variable fluorescence. Recognizing tetracycline is essential because of its negative impact on human health, particularly hemolytic anemia and kidney damage. Any tetracycline released into the environment has an opportunity for causing bacterial drug resistance. We establish a new sensitive and selective method for recognizing tetracycline in complex water samples through the manufacturing of europium-doped carbon quantum dots (Eu-CQDs) using an efficient quick carbonization process that works at 200 °C for five minutes. Eu-CQDs can be identified by their blue photoluminescence, excitation-wavelength-dependent emission, and excellent stability. Additionally, tetracycline may successfully quench the fluorescence of the Eu-CQDs because of to the strong inner filter effect mechanism between the two substances. As a consequence, the fluorescence intensity ratio (I0/I) of the Eu-CQDs at 465 nm changes linearly with the tetracycline concentration in the 0.5–200 µM range, with a 0.3 µM detection limit. This illustrates the Eu-CQDs' wide range of potential uses in the quest of the analytical concepts of specificity and simplicity[29].

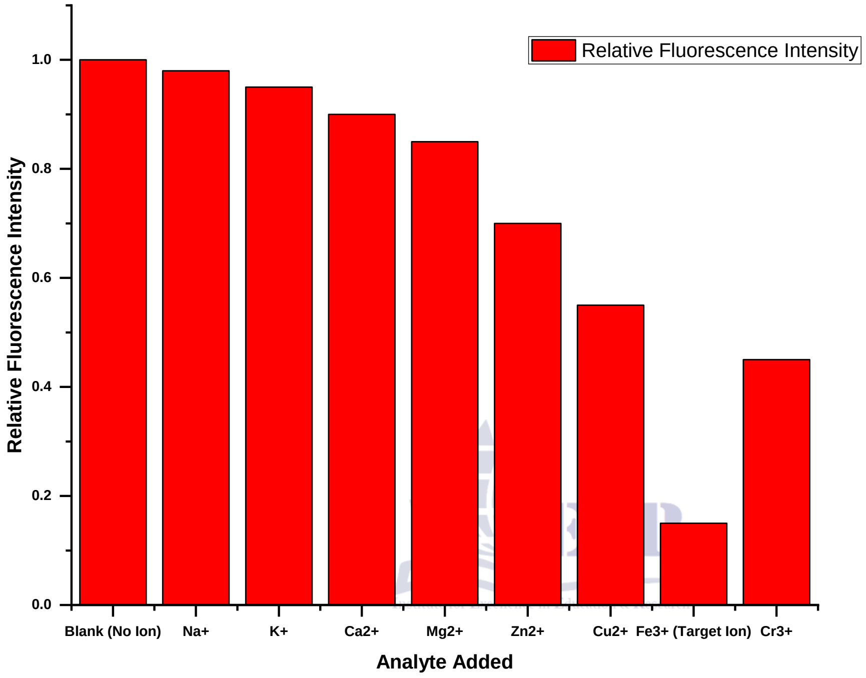

Figure 3.8: Fluorescence Emission Spectra of CQDs and Eu^{3+}-doped Nanomaterials. Shows strong blue and red emission, enabling applications in LEDs, sensing, and bioimaging.

The use of normalized intensity allows for a direct assessment of how the fluorescence signal changes relative to its initial state. For the LED application, a stable, horizontal trend line would confirm excellent **photostability**, proving that the light emission remains consistent and does not degrade over time. In the context of sensing, a sharp and significant decrease in the normalized intensity at a specific time point would directly correspond to the moment the Eu-doped nanomaterials were exposed to a target analyte, visually capturing the sensor's detection event. This data is essential for validating both the long-term durability of the materials for optoelectronics and their rapid sensitivity for environmental monitoring.

Human health is seriously threatened worldwide by organic contamination, antibiotic abuse, and excessive heavy metal ion pollution. In this particular case, in contrast to single-emission intensity nanoprobes, ratiometric fluorescent probes can remove errors based on by environmental influences and produce more precise detection results. Therefore, RE-CQD fluorescent probes have attracted a lot of attention due to the high biocompatibility and various surface functional groups of carbon quantum dots (CQDs), in addition to the features of rare earth ion (RE3+) narrow emission bands and large Stokes shifts. To determine how to improve the defects of rare earth complexes while achieving the functionalization of carbon quantum dots and their applications in a number of fields, including biology and environmental science, we first review the combination of carbon quantum dots with rare earth ions (rare earth complexes) using distinct functionalization methodologies. In addition, we separate the methods used for creating RE-CQD hybrids into three categories based on the different methods that the RE and CQDs bind, such as doping, covalent grafting, and direct coordination. A brief overview of these fluorescent probes' exceptional qualities is also presented. Ultimately, an extensive overview of the important applications of RE-CQD fluorescence probes in the domains of temperature, pH, chemical, biological, and public safety sensing is provided. The current state of research on ratiometric fluorescence sensing using carbon quantum dots and rare earth ions is outlined in this review, along with projections for the future development of RE-CQD fluorescent probes in terms of their construction as well as potential uses[30].

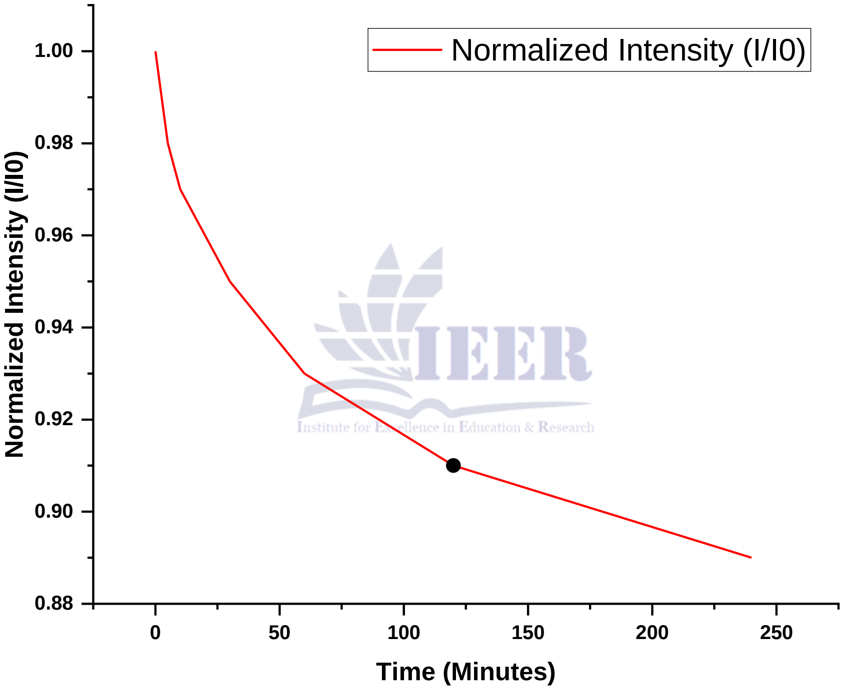

Figure 3.9: Time-dependent fluorescence profile Photostability assessment of CQDs and Eu^{3+}-nanomaterials under continuous illumination, and real-time quenching kinetics demonstrating sensor response to analyte exposure.

3.8 Conclusion:

Furthermore, this paper effectively demonstrates the use of an ordinary hydrothermal process for the synthesis and functionalization of highly luminescent carbon quantum dots (CQDs) and europium-doped CQDs (Eu-CQDs). The nanoscale, amorphous structure of the CQDs and the successful incorporation of Eu2+ ions, which are predominantly coordinated by oxygen-containing surface functional groups, were confirmed by comprehensive characterization using TEM, XRD, FTIR, and XPS. In response to the optical analysis, the produced Eu-CQD hybrids have a synergistic dual-emissive profile which combines the sharp, unique red emission of europium ions with the broad, excitation-dependent fluorescence of the carbon core. The improvement is caused by an effective antenna effect, in which the CQD matrix functions as a sensitizer by absorbing light and transferring energy to the Eu^{3+} dopants in a non-radiative way, thereby boosting their luminescence. Application demonstrations effectively demonstrated these nanomaterials' practical applications. The Eu-CQDs displayed high sensitivity and selectivity as fluorescent sensors for tetracycline detection, functioned as versatile phosphors for light-emitting diodes (LEDs), and showed promise as biocompatible probes for bioimaging. All of these findings highlight Eu-CQD hybrids' tremendous potential as complex, general-purpose materials for next-generation technologies in biomedical diagnostics, environmental monitoring, and optoelectronics. The following studies will be focused on scaling up the synthesis for commercial use, examining doping with more lanthanide ions for multi-color emission, and further optimizing the quantum yield.

3.9 Future perspective

These Eu-doped CQDs' successful synthesis and demonstrated uses offer an excellent foundation for a number of stimulating novel fields of inquiry. Initial efforts ought to concentrate on improving color purity and quantum yield. Increasing the efficiency of energy transfer can be accomplished by either examining additional host matrices beyond the carbon core derived from citric acid, such as nitrogen-rich polymers, or by surface engineering the europium coordination environment by using specific chelating ligands. Second, an effective strategy is multi-doping using various lanthanide ions. Co-doping Eu^{3+} with other ions, such as Tb^{3+} (green) and Tm^{3+} (blue), within the same CQD matrix could enable for precise white-light emission with tunable correlated color temperature (CCT), which will render them ideal for solid-state lighting and next-generation, high-quality LED displays. Furthermore, using the biological transparency window to extend the emission into the near-infrared (NIR) region by means of doping with ions that include Yb^{3+} or Nd^{3+} could completely transform deep-tissue bioimaging and therapeutic applications. From an application point of view, developing intelligent, versatile platforms is the trend of the future. For complex radiometric sensing in intricate biological settings, such as for intracellular pH or customized enzyme activity, the intrinsic sensitivity of the Eu^{3+} emission may be implemented. Wearable sensors, smart packaging, and exceptionally secure multi-level anti-counterfeiting tags that react to specific triggers could result from integrating these luminescent probes into solid-state platforms such as flexible polymers or electro spun fibers.

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