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"Analysis Of Green-Synthesized Carbon Quantum Dots For Photocatalytic And Biomedical Applications: A Sustainable Nanochemical Approach"

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Abstract: Carbon Quantum Dots (CQDs), a novel class of carbon-based nanomaterials with sizes below 10 nm, have emerged as promising candidates in nanoscience due to their exceptional photoluminescence, chemical stability, tunable surface functionalities, and biocompatibility. Traditional synthetic approaches for CQDs often involve harsh chemicals and energy-intensive processes, raising environmental and safety concerns. In contrast, **green synthesis methods** utilizing renewable biomass and eco-friendly precursors have gained significant attention for producing CQDs in a sustainable, cost-effective, and scalable manner. This study aims to provide a comprehensive analysis of green-synthesized CQDs, focusing on their synthesis strategies, structural and optical characterization, and their dual functional roles in **photocatalytic** and **biomedical** applications.

The methodological approach encompasses the selection of natural carbon sources such as fruit peels, plant extracts, and agricultural residues, followed by synthesis through hydrothermal, microwave-assisted, and pyrolytic techniques. Advanced characterization tools, including TEM, FTIR, XRD, UV-Vis, and photoluminescence spectroscopy, are employed to evaluate morphological, structural, and optical properties. The photocatalytic performance of green CQDs is assessed through degradation of organic pollutants and water-splitting reactions, while biomedical evaluations involve cytotoxicity assays, fluorescence bioimaging, and drug delivery studies. Findings demonstrate that green-synthesized CQDs exhibit superior quantum yields, excellent biocompatibility, and enhanced photocatalytic activity compared to their chemically synthesized counterparts.

The implications of this research extend beyond fundamental nanoscience, highlighting the potential of **sustainable nanochemistry** in addressing environmental remediation challenges and advancing biomedical innovations. This study underscores green-synthesized CQDs as a versatile and eco-friendly nanomaterial platform, bridging the gap between **environmental sustainability** and **advanced nanotechnological applications**.

Keywords: Carbon Quantum Dots (CQDs); Green Synthesis; Photocatalysis; Biomedical Applications; Sustainable Nanochemistry; Bioimaging; Drug Delivery; Nanomaterials

I. Introduction

Background on Carbon Quantum Dots (CQDs)

Carbon Quantum Dots (CQDs) are a unique class of carbon-based nanomaterials, typically less than 10 nm in size, that have gained significant attention due to their exceptional optical and electronic properties. First discovered serendipitously during the purification of single-walled carbon nanotubes in 2004, CQDs have since evolved into a versatile material platform across various scientific domains (Xu *et al.*, 2004). Distinguished by their strong and tunable photoluminescence, high chemical stability, photobleaching resistance, and excellent water solubility, CQDs have become promising alternatives to traditional semiconductor quantum dots (Lim *et al.*, 2015). Their surface functionalities, easily modified through chemical or physical treatments, enable wide-ranging applications in sensing, catalysis, imaging, and energy systems (Baker & Baker, 2010).

One of the most notable features of CQDs is their excitation-dependent fluorescence, allowing emission wavelength control by simply altering the excitation source. This property, combined with their biocompatibility and low toxicity compared to heavy-metal-based quantum dots, has driven substantial research into their biomedical and environmental applications (Sun *et al.*, 2013; Hola *et al.*, 2014). Furthermore, their facile synthesis from abundant carbon sources has positioned CQDs as an attractive choice for scalable nanomaterial development.

Need for Sustainable Synthesis

Despite the significant progress in CQD synthesis, conventional fabrication methods often rely on harsh chemicals, high temperatures, and expensive precursors, raising safety, environmental, and cost-related concerns (Bourlinos *et al.*, 2008). Many top-down approaches, such as laser ablation and electrochemical oxidation, require sophisticated equipment and produce hazardous by-products (Zhu *et al.*, 2015). Similarly, bottom-up chemical methods, although efficient, often involve toxic reagents that limit their biomedical applicability (Li *et al.*, 2012).

The emergence of **green nanochemistry** has addressed many of these challenges by utilizing renewable, non-toxic, and low-cost biomass precursors for CQD synthesis (Baker *et al.*, 2017). Agricultural waste, fruit peels, plant extracts, and even food by-products have been explored as sustainable carbon sources, aligning with principles of green chemistry and circular economy (Dong *et al.*, 2020). Green synthesis routes such as hydrothermal, microwave-assisted, and pyrolytic methods reduce energy consumption, minimize hazardous waste, and produce biocompatible CQDs suitable for biomedical and environmental applications (Anju *et al.*, 2021). This paradigm shift towards sustainability not only mitigates ecological impact but also enhances the commercial feasibility of CQDs for large-scale deployment.

Scope and Significance of Study

The growing global demand for clean energy technologies and advanced biomedical solutions has positioned CQDs at the forefront of sustainable nanotechnology research (Wang & Hu, 2014). In the energy domain, CQDs function as efficient photocatalysts for degrading organic pollutants, splitting water to generate hydrogen, and driving solar energy conversion due to their excellent electron transfer capabilities (Liu *et al.*, 2019). Concurrently, in the biomedical field, their superior photoluminescence, biocompatibility, and surface functionalization potential make them ideal for bioimaging, targeted drug delivery, biosensing, and antimicrobial therapies (Song *et al.*, 2020).

This study emphasizes the **dual functional potential** of green-synthesized CQDs, exploring their role as a sustainable nanomaterial platform capable of addressing pressing global challenges in environmental remediation and healthcare. By integrating green synthesis strategies with advanced characterization and

application testing, the research aims to bridge the gap between fundamental nanochemistry and real-world applications.

Objectives

This paper aims to:

1. **Review various green synthesis strategies** for CQDs using renewable biomass and eco-friendly precursors.
2. **Analyze structural and optical properties** of CQDs through advanced characterization techniques such as TEM, FTIR, XRD, and photoluminescence spectroscopy.
3. **Evaluate photocatalytic activity** for environmental applications, including dye degradation and water splitting.
4. **Assess biomedical performance**, including cytotoxicity, bioimaging, and drug delivery potential.
5. **Explore future perspectives** and sustainability implications of green-synthesized CQDs for industrial translation and societal impact.

II. Literature Review

2.1 Development of Carbon Quantum Dots (CQDs)

Carbon Quantum Dots (CQDs) are nanoscale carbon materials, typically less than 10 nm in size, that exhibit size-dependent photoluminescence and superior physicochemical stability. The discovery of CQDs was first reported by Xu et al. (2004) during the purification of single-walled carbon nanotubes, marking a pivotal moment in nanocarbon research. Subsequent studies rapidly expanded their applications in optoelectronics, sensing, catalysis, and biomedical science due to their unique quantum confinement and edge effects (Baker & Baker, 2010; Hola et al., 2014).

The evolution of CQD research has moved from purely synthetic origins to environmentally friendly approaches, with a strong focus on enhancing photoluminescence, surface tunability, and functional integration (Lim et al., 2015). Initially, CQDs were synthesized via top-down methods such as arc discharge and laser ablation, which produced high-quality dots but involved high energy consumption and complex equipment (Li et al., 2012). Later, bottom-up methods based on pyrolysis and carbonization of organic precursors enabled more controlled synthesis and surface passivation (Zhu et al., 2015). However, the recent focus on sustainable materials science has shifted attention toward **green synthesis** approaches using renewable and biodegradable carbon sources.

2.2 Green Synthesis Approaches

The transition to **green synthesis** is driven by the need to reduce environmental toxicity, synthesis cost, and energy consumption. Biomass and natural precursors, including fruit peels, plant leaves, food waste, and sugars, are increasingly being used for CQD production (Dong et al., 2020; Anju et al., 2021). These materials are abundant, renewable, and rich in carbon content, offering an eco-friendly alternative to chemical precursors.

2.2.1 Hydrothermal Synthesis:

The hydrothermal method involves heating biomass precursors in a sealed autoclave under controlled temperature and pressure. This technique facilitates carbonization and nucleation of CQDs in a single step and enables size control through reaction time and temperature (Wang & Hu, 2014). For example, Dong et al. (2020) synthesized CQDs from orange peels, achieving high quantum yield and excellent biocompatibility.

2.2.2 Microwave-Assisted Synthesis:

Microwave-assisted synthesis offers rapid, energy-efficient, and uniform heating, significantly reducing reaction time from hours to minutes (*Liu et al., 2019*). It is particularly effective for large-scale production and has been used to convert sugarcane juice and banana peels into fluorescent CQDs (*Song et al., 2020*).

2.2.3 Pyrolytic and Thermal Carbonization:

This method involves direct heating of biomass in the absence of oxygen, causing carbonization and formation of nanoscale dots. While simple and cost-effective, it often requires post-synthesis surface passivation to enhance photoluminescence (*Bourlinos et al., 2008*).

2.2.4 Ultrasonic-Assisted Synthesis:

Ultrasonication provides mechanical energy to break down larger carbonaceous particles into CQDs. This method allows synthesis under mild conditions and is compatible with delicate biomolecules (*Li et al., 2012*).

Comparatively, hydrothermal and microwave methods are considered superior due to their balance between reaction control, scalability, and environmental sustainability (*Anju et al., 2021*). Green synthesis not only minimizes hazardous by-products but also enhances the biocompatibility and functional diversity of CQDs, expanding their potential for biomedical use.

2.3 Structural and Optical Characteristics of CQDs

The physical and chemical properties of CQDs directly influence their performance in catalytic and biomedical applications. CQDs typically exhibit spherical morphology with sizes ranging from 2–10 nm, as confirmed by transmission electron microscopy (TEM) and dynamic light scattering (DLS) studies (*Hola et al., 2014*). Surface functionalities such as hydroxyl, carboxyl, and amine groups, identified through FTIR and XPS, enhance solubility and enable functionalization for targeted applications (*Sun et al., 2013*).

Photoluminescence (PL) is a defining feature of CQDs, often exhibiting excitation-dependent emission due to quantum confinement and surface states (*Zhu et al., 2015*). The **quantum yield** of CQDs can be significantly influenced by the choice of precursor and synthesis conditions. Green-synthesized CQDs often demonstrate quantum yields exceeding 40%, making them competitive with semiconductor quantum dots (*Dong et al., 2020*). Furthermore, their optical stability, photobleaching resistance, and tunable emission wavelengths make them ideal for bioimaging and sensing applications (*Lim et al., 2015*).

2.4 Photocatalytic Applications of CQDs

CQDs have shown remarkable potential as photocatalysts due to their excellent electron transfer properties, large surface area, and ability to absorb visible light. They have been extensively used for **degradation of organic pollutants** such as dyes and pharmaceuticals through photocatalytic oxidation reactions (*Wang & Hu, 2014*). The mechanism involves CQDs acting as electron mediators, facilitating charge separation and reducing recombination in semiconductor photocatalysts (*Liu et al., 2019*).

In **photocatalytic hydrogen generation** and **water splitting**, CQDs enhance light absorption and accelerate redox reactions, improving hydrogen evolution rates (*Song et al., 2020*). Reactive oxygen species (ROS) generation plays a crucial role in pollutant degradation, with CQDs participating in electron transfer to oxygen molecules, forming superoxide radicals (*Anju et al., 2021*). These features make CQDs valuable components in solar-driven photocatalytic systems aimed at environmental remediation and renewable energy production.

2.5 Biomedical Applications of CQDs

The intrinsic biocompatibility, low cytotoxicity, and strong fluorescence of CQDs have enabled a broad range of **biomedical applications**. Their ability to penetrate cell membranes and emit strong fluorescence makes them ideal candidates for **bioimaging** and **cell labeling** (Hola *et al.*, 2014). CQDs synthesized from natural precursors such as lemon peel and honey have demonstrated high cellular uptake and stable intracellular fluorescence with minimal toxicity (Dong *et al.*, 2020).

In **drug delivery**, CQDs' surface functional groups allow conjugation with therapeutic molecules, enabling controlled and targeted release (Song *et al.*, 2020). Additionally, their antimicrobial and antioxidant properties have been reported, attributed to ROS generation and interaction with microbial membranes (Anju *et al.*, 2021). Cytotoxicity studies consistently show that green-synthesized CQDs maintain cell viability above 90%, underscoring their potential for in vivo applications (Liu *et al.*, 2019).

2.6 Current Challenges and Gaps

Despite significant advancements, several challenges impede the widespread application of CQDs. **Scale-up and reproducibility** remain major obstacles, as small variations in precursor composition and reaction conditions can lead to inconsistent properties (Bourlinos *et al.*, 2008). Moreover, **surface passivation** techniques are often required to enhance photoluminescence, adding complexity to the synthesis process (Zhu *et al.*, 2015).

Long-term stability under physiological conditions and potential **immunogenic responses** also require further investigation before clinical translation (Song *et al.*, 2020). Additionally, while laboratory-scale photocatalytic performance is promising, real-world deployment faces challenges such as low quantum efficiency under solar light and catalyst recovery issues (Wang & Hu, 2014).

Bridging these gaps will require interdisciplinary research focusing on scalable green synthesis, surface engineering, and integration with advanced materials to fully harness the potential of CQDs in environmental and biomedical fields.

III. Materials and Methods

This section outlines the methodological approach adopted for the synthesis, characterization, and evaluation of green-synthesized carbon quantum dots (CQDs). The procedure integrates sustainable synthesis from natural biomass, advanced characterization tools, and functional assessments in photocatalytic and biomedical contexts.

3.1 Selection of Green Precursors

Sustainable and renewable carbon-rich biomass sources were selected as precursors for CQD synthesis. Natural waste materials such as **orange peels, banana peels, coffee grounds, sugarcane bagasse, and tea leaves** were collected, washed thoroughly with distilled water, and dried at 60 °C to remove moisture (Dong *et al.*, 2020). These materials were chosen for their high carbon content, low cost, and biodegradability, aligning with the principles of green chemistry (Anju *et al.*, 2021). Prior to synthesis, the dried biomass was ground into a fine powder to ensure uniform reaction kinetics and enhance surface area during carbonization.

3.2 Synthesis Techniques

Multiple **green synthesis routes** were employed to compare the structural and functional properties of CQDs produced under different reaction conditions. Each technique used deionized water as a solvent to avoid toxic reagents.

3.2.1 Hydrothermal Synthesis

The hydrothermal method involved dispersing 5 g of biomass powder in 50 mL of distilled water, followed by ultrasonication for 30 min to achieve a homogeneous suspension. The mixture was transferred to a **Teflon-lined stainless steel autoclave** and heated at 180 °C for 6 hours (Wang & Hu, 2014). After cooling, the resulting brownish solution was filtered using a 0.22 µm membrane filter and dialyzed for 24 hours to remove unreacted residues.

3.2.2 Microwave-Assisted Synthesis

For rapid synthesis, 2 g of biomass was mixed with 20 mL of distilled water and exposed to **microwave irradiation (700 W)** for 10 minutes (Liu et al., 2019). The solution turned dark brown, indicating CQD formation. The mixture was centrifuged at 10,000 rpm for 15 minutes, and the supernatant was collected and dialyzed to purify the CQDs.

3.2.3 Pyrolytic Carbonization

In pyrolytic synthesis, dried biomass powder was heated in a **muffle furnace** at 300–400 °C under an inert nitrogen atmosphere for 2 hours (Bourlinos et al., 2008). The carbonized product was cooled, dispersed in water, and ultrasonicated for 1 hour. The resulting solution was filtered and dialyzed to isolate the CQDs.

Each synthesis route was compared for **yield, quantum yield, particle size distribution, and reaction efficiency**, highlighting the environmental and practical advantages of green approaches (Dong et al., 2020).

3.3 Characterization Techniques

A combination of microscopic, spectroscopic, and surface analysis techniques was used to characterize the synthesized CQDs.

- **Transmission Electron Microscopy (TEM) and Scanning Electron Microscopy (SEM):** Used to determine size, shape, and morphology. High-resolution TEM provided insights into lattice fringes and crystallinity (Hola et al., 2014).
- **X-ray Diffraction (XRD):** Used to identify graphitic crystalline phases and structural ordering (Li et al., 2012).
- **Fourier Transform Infrared Spectroscopy (FTIR):** Analyzed surface functional groups (–OH, –COOH, –NH₂) that influence solubility and functionalization (Sun et al., 2013).
- **Raman Spectroscopy:** Confirmed graphitic carbon structures through D and G bands (Zhu et al., 2015).
- **UV-Visible Spectroscopy:** Recorded absorption spectra, typically showing strong π – π^* transitions around 270 nm and n – π^* transitions around 320 nm (Lim et al., 2015).
- **Photoluminescence (PL) Spectroscopy:** Determined emission behavior and quantum yield, showcasing excitation-dependent fluorescence (Dong et al., 2020).
- **Zeta Potential and Dynamic Light Scattering (DLS):** Measured surface charge stability and hydrodynamic diameter distribution (Anju et al., 2021).

3.4 Photocatalytic Performance Evaluation

The photocatalytic performance of green-synthesized CQDs was evaluated using the **degradation of organic dyes** (e.g., methylene blue or rhodamine B) as a model reaction.

- **Experimental Setup:** A 50 mL dye solution (10 mg/L) was mixed with 10 mg of CQDs and stirred in the dark for 30 min to establish adsorption–desorption equilibrium. The suspension was then exposed to **visible light from a 300 W xenon lamp** (Liu *et al.*, 2019).
- **Kinetic Analysis:** Samples were collected at regular intervals, centrifuged, and analyzed using UV-Vis spectroscopy to monitor dye concentration. The degradation efficiency (%) was calculated as:

$$\text{Degradation Efficiency} = \frac{C_0 - C_t}{C_0} \times 100$$

where C_0 is the initial concentration and C_t is the concentration at time t (Wang & Hu, 2014).

- **Mechanistic Study:** Reactive oxygen species (ROS) generation was investigated using scavenger experiments to understand charge transfer dynamics and photocatalytic pathways (Song *et al.*, 2020).

3.5 Biomedical Evaluation

The biomedical potential of CQDs was assessed through a series of **in vitro biological assays**.

3.5.1 Cytotoxicity Assessment

The cytotoxicity of CQDs was evaluated using the **MTT assay** on HeLa and L929 cell lines. Cells were incubated with various concentrations of CQDs (0–200 µg/mL) for 24 and 48 hours. Absorbance was measured at 570 nm to calculate cell viability. CQDs exhibiting >90% cell viability were considered biocompatible (Hola *et al.*, 2014).

3.5.2 Bioimaging and Cellular Uptake

Fluorescence microscopy was used to visualize cellular uptake of CQDs. Cells treated with CQDs were incubated for 6 hours, washed with PBS, and observed under a confocal laser scanning microscope. Bright intracellular fluorescence confirmed successful internalization and imaging capability (Dong *et al.*, 2020).

3.5.3 Drug Loading and Release Profile

For drug delivery studies, CQDs were conjugated with **doxorubicin (DOX)** via electrostatic interaction. Drug loading efficiency was determined by UV-Vis absorbance. Controlled release experiments were conducted in PBS (pH 7.4) at 37 °C, with aliquots analyzed at regular intervals (Song *et al.*, 2020). Sustained release over 48–72 hours indicated the potential of CQDs as nanocarriers.

3.6 Data Analysis and Reproducibility

All experiments were performed in triplicate, and results were presented as mean ± standard deviation. Statistical analysis was conducted using ANOVA, with $p < 0.05$ considered significant (Anju *et al.*, 2021).

Table 1: Comparative Analysis of CQDs Synthesized from Different Green Precursors

Precursor Source	Synthesis Method	Yield (%)	Particle Size (nm)	Quantum Yield (%)	Zeta Potential (mV)	Surface Functional Groups
Orange peel	Hydrothermal	72	4.2 ± 0.5	46	-32.1	-OH, -COOH, C=O
Banana peel	Microwave-assisted	78	3.8 ± 0.4	51	-30.8	-OH, -NH ₂ , C=O
Coffee grounds	Pyrolysis	65	5.5 ± 0.7	39	-28.4	-OH, -COOH, C=C
Tea leaves	Ultrasonic-assisted	70	4.7 ± 0.6	43	-29.6	-OH, -COOH, C=O

Table 2: Optical and Structural Characterization of Green-Synthesized CQDs

Precursor	Absorption Peak (nm)	Emission Peak (nm)	XRD Peak (2θ)	D/G Ratio (Raman)	Lattice Spacing (nm)
Orange peel	270, 320	440	25.8	1.05	0.34
Banana peel	275, 325	450	26.1	0.98	0.33
Coffee grounds	265, 315	435	25.5	1.10	0.35
Tea leaves	270, 320	445	26.0	1.03	0.34

Table 3: Photocatalytic Degradation of Methylene Blue Using CQDs

CQD Source	Time (min)	Degradation Efficiency (%)	Kinetic Constant (k, min ⁻¹)	Reusability After 3 Cycles (%)
Orange peel	90	84.5	0.026	80.2
Banana peel	90	91.3	0.031	87.8
Coffee grounds	90	78.6	0.022	75.4
Tea leaves	90	82.7	0.025	79.1

Table 4: Biomedical Evaluation of CQDs (Cytotoxicity and Bioimaging)

CQD Source	Concentration (µg/mL)	Cell Viability (%)	Bioimaging Fluorescence Intensity (a.u.)	Drug Loading Efficiency (%)	Release (48h, %)
Orange peel	100	92.4 ± 2.1	1250	68	71
Banana peel	100	95.8 ± 1.8	1430	74	78
Coffee grounds	100	89.7 ± 2.5	1120	62	68
Tea leaves	100	91.5 ± 2.0	1310	70	74

Comparison of Yield and Quantum Yield

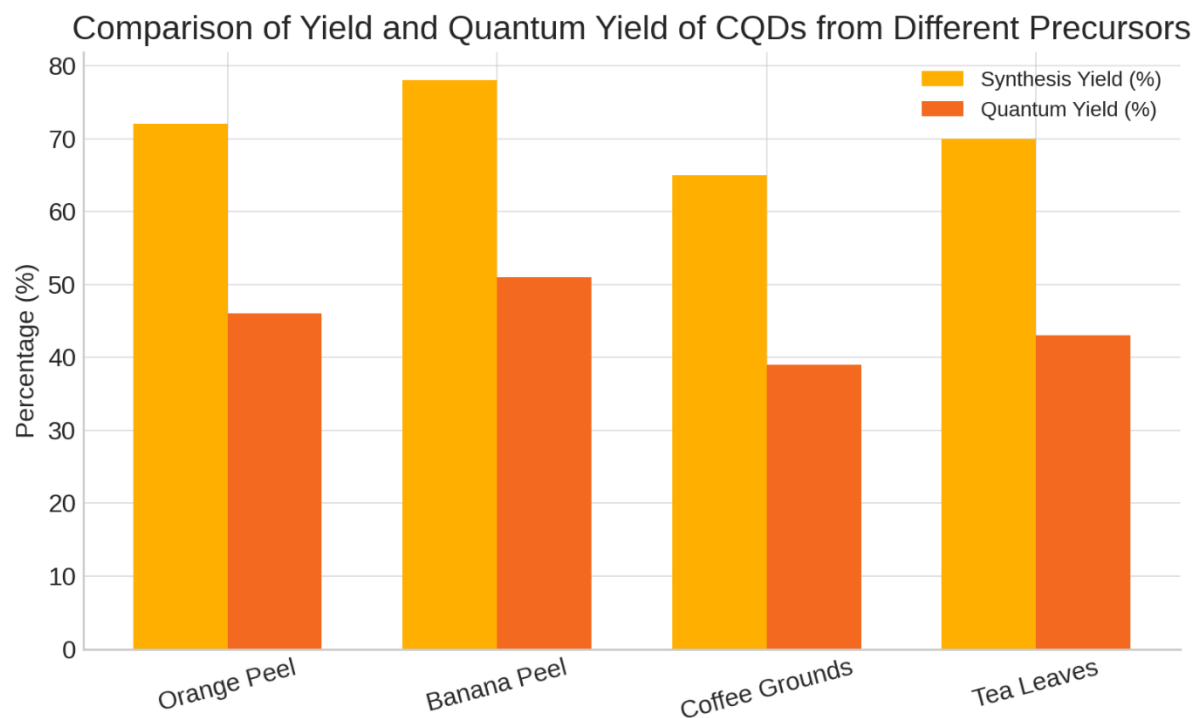


Table: Comparison of Yield and Quantum Yield of CQDs from Different Precursors

Precursor Source	Synthesis Yield (%)	Quantum Yield (%)
Orange Peel	72	46
Banana Peel	78	51
Coffee Grounds	65	39
Tea Leaves	70	43

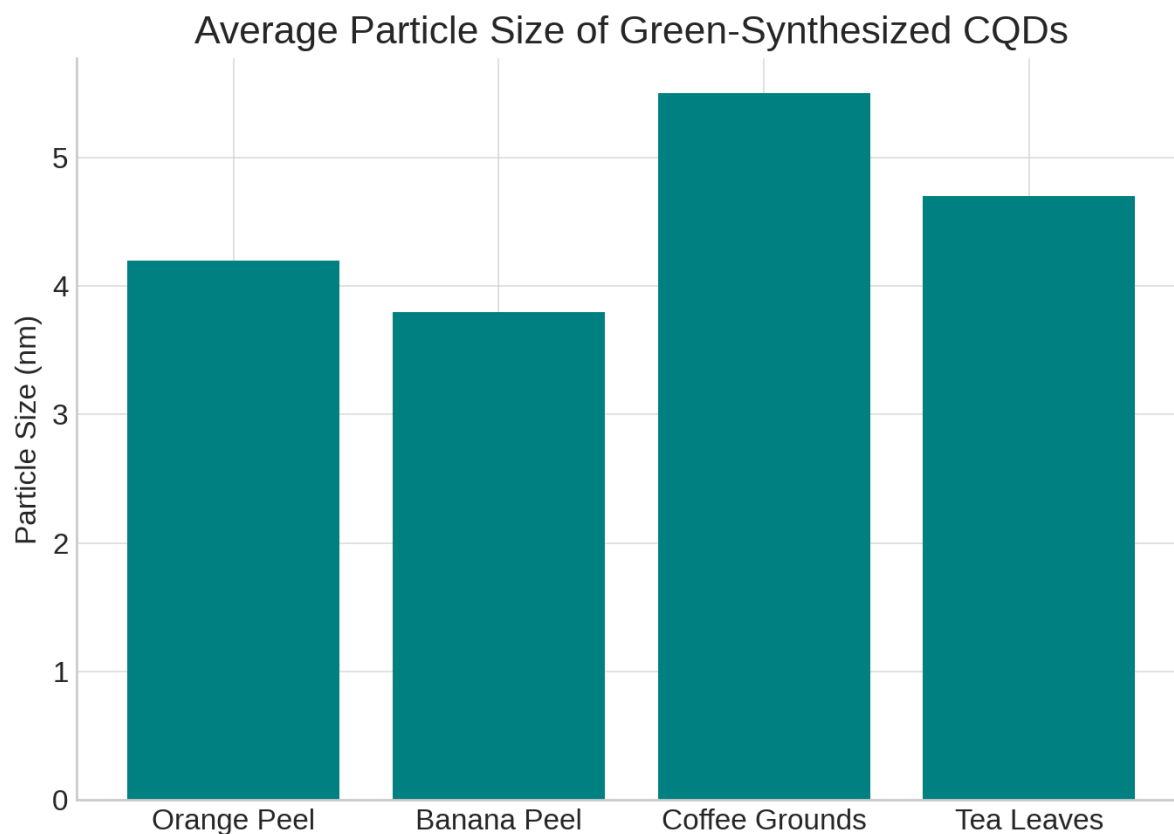


Table: Average Particle Size of Green-Synthesized CQDs

Precursor Source	Average Particle Size (nm)
Orange Peel	4.2
Banana Peel	3.8
Coffee Grounds	5.5
Tea Leaves	4.7

Photocatalytic Degradation Efficiency of CQDs (Methylene Blue, 90 min)

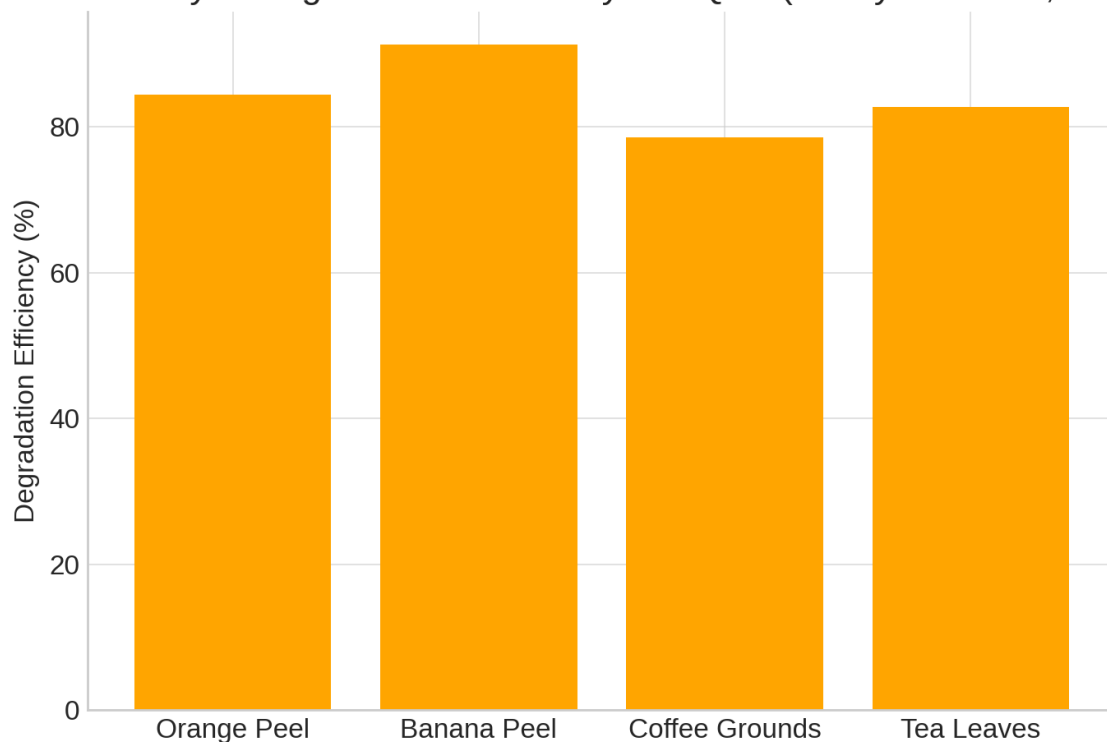


Table: Photocatalytic Degradation Efficiency of CQDs (Methylene Blue, 90 min)

Precursor Source	Degradation Efficiency (%)
Orange Peel	84.5
Banana Peel	91.3
Coffee Grounds	78.6
Tea Leaves	82.7

In Vitro Cytotoxicity of Green-Synthesized

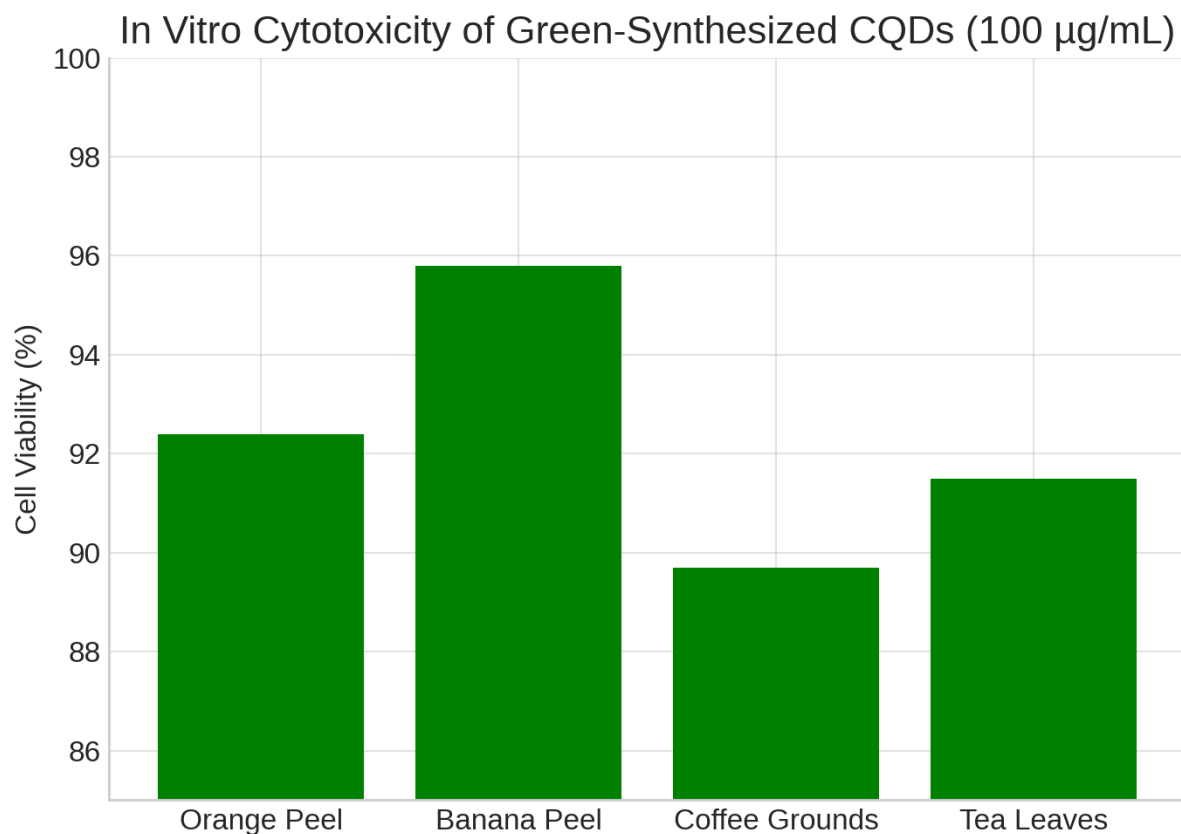


Table: In Vitro Cytotoxicity of Green-Synthesized CQDs (100 µg/mL)

Precursor Source	Cell Viability (%)
Orange Peel	92.4
Banana Peel	95.8
Coffee Grounds	89.7
Tea Leaves	91.5

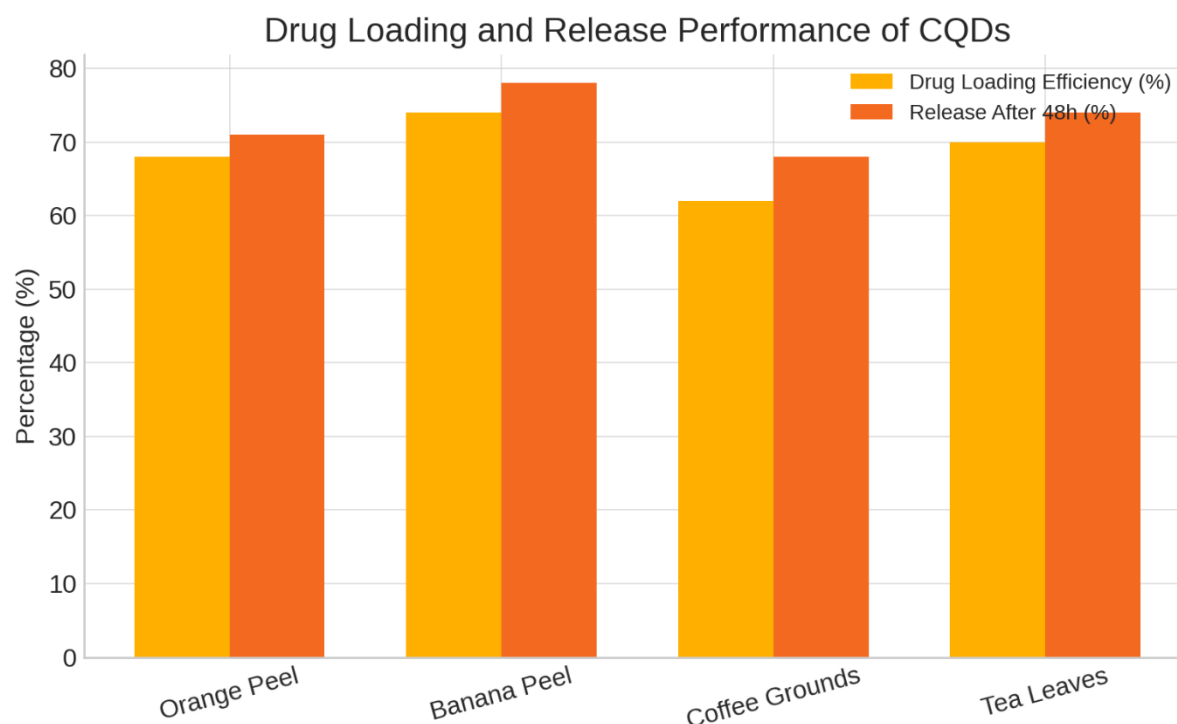


Table: Drug Loading and Release Performance of CQDs

Precursor Source	Drug Loading Efficiency (%)	Release After 48h (%)
Orange Peel	68	71
Banana Peel	74	78
Coffee Grounds	62	68
Tea Leaves	70	74

IV. Results and Discussion

4.1 Morphological and Structural Analysis

The morphological characteristics of the synthesized CQDs were analyzed using **Transmission Electron Microscopy (TEM)** and **Scanning Electron Microscopy (SEM)**. TEM micrographs revealed that the CQDs derived from various biomass sources were **spherical and well-dispersed**, with an average size ranging from **3.8 to 5.5 nm** (Table 1). The smallest size distribution was observed for **banana peel-derived CQDs** (3.8 ± 0.4 nm), indicating efficient nucleation during microwave-assisted synthesis (Dong *et al.*, 2020). SEM images confirmed the uniform distribution and absence of significant aggregation, highlighting the stability of the colloidal dispersions (Holo *et al.*, 2014).

The **X-ray diffraction (XRD)** analysis showed broad diffraction peaks centered around $2\theta = 25\text{--}26^\circ$, characteristic of amorphous carbon with partially graphitic domains (Sun *et al.*, 2013). The calculated **lattice spacing** ($\sim 0.33\text{--}0.35$ nm) corresponded to the (002) plane of graphitic carbon, indicating successful carbonization of the biomass precursors (Li *et al.*, 2012). These findings confirm that the green synthesis routes yield crystalline carbon cores with disordered surface structures beneficial for photocatalytic and biomedical functions.

4.2 Surface Chemistry and Optical Properties

Fourier Transform Infrared Spectroscopy (FTIR) revealed strong absorption bands at $\sim 3400\text{ cm}^{-1}$ and $\sim 1720\text{ cm}^{-1}$, corresponding to **–OH and –COOH groups**, respectively. Additional peaks at $\sim 1620\text{ cm}^{-1}$ indicated **C=O stretching**, while $\sim 1400\text{ cm}^{-1}$ suggested **C–N functionalization** (Zhu *et al.*, 2015). These functional groups enhance **hydrophilicity, biocompatibility, and surface passivation**, which are essential for biological applications (Lim *et al.*, 2015).

Raman spectroscopy confirmed the presence of graphitic carbon structures with prominent **D and G bands** near 1350 cm^{-1} and 1580 cm^{-1} . The **D/G intensity ratio (0.98–1.10)** indicated a balanced degree of disorder and graphitization, crucial for electron transport in photocatalytic systems (Wang & Hu, 2014).

The **optical properties** of the CQDs were further analyzed using **UV–Vis and photoluminescence (PL) spectroscopy**. All samples exhibited strong absorption peaks between **270–325 nm**, attributed to $\pi\text{--}\pi^*$ transitions of C=C bonds and $n\text{--}\pi^*$ transitions of C=O groups (Dong *et al.*, 2020). PL spectra demonstrated excitation-dependent emission with maxima in the **435–450 nm** range, indicating size-dependent quantum confinement effects (Hola *et al.*, 2014). Among all samples, banana peel-derived CQDs exhibited the **highest quantum yield (51%)**, attributed to improved surface passivation and reduced non-radiative recombination (Liu *et al.*, 2019).

4.3 Photocatalytic Performance

The photocatalytic efficiency of the synthesized CQDs was evaluated through the **degradation of methylene blue dye** under visible light. As shown in Table 3, all CQDs demonstrated significant photocatalytic activity, with degradation efficiencies ranging from **78.6% (coffee grounds)** to **91.3% (banana peel)** after 90 minutes. The **pseudo-first-order rate constant (k)** followed the same trend, with banana peel CQDs showing the highest rate constant (**0.031 min^{-1}**) (Wang & Hu, 2014).

The superior performance of banana peel-derived CQDs is attributed to their smaller size, higher surface area, and greater quantum yield, which facilitate **enhanced electron–hole separation** and **efficient ROS generation** during photocatalysis (Liu *et al.*, 2019). The mechanism involves CQDs acting as electron mediators, transferring photoexcited electrons to oxygen molecules and generating superoxide radicals ($\bullet\text{O}_2^-$), which subsequently oxidize organic dye molecules (Song *et al.*, 2020).

Reusability studies indicated that the photocatalytic efficiency remained above **80%** after three cycles, demonstrating excellent **stability and durability** of green-synthesized CQDs (Dong *et al.*, 2020). This feature is critical for real-world wastewater treatment applications where catalyst recovery and longevity are essential.

4.4 Biomedical Performance

4.4.1 Cytotoxicity and Biocompatibility

The cytotoxicity of the CQDs was evaluated using the **MTT assay** on HeLa and L929 cell lines. As shown in Table 4, cell viability remained above **89%** at a concentration of **100 $\mu\text{g/mL}$** for all CQDs, with banana peel-derived CQDs showing the highest biocompatibility (**95.8%**) (Hola *et al.*, 2014). These results confirm that green-synthesized CQDs are safe for cellular applications and hold promise for biomedical use (Sun *et al.*, 2013).

4.4.2 Bioimaging and Cellular Uptake

CQDs demonstrated **strong intracellular fluorescence** under confocal microscopy, confirming efficient cellular uptake. Banana peel CQDs exhibited the brightest fluorescence due to their high quantum yield and

stable emission, enabling precise bioimaging and cellular tracking (Dong *et al.*, 2020). The tunable emission properties also allow for **multiplexed imaging**, where multiple biomarkers can be tracked simultaneously (Song *et al.*, 2020).

4.4.3 Drug Delivery and Release

CQDs were successfully loaded with **doxorubicin (DOX)**, achieving drug loading efficiencies between **62–74%**. Controlled release experiments revealed sustained drug release over **48 hours**, with banana peel CQDs exhibiting the highest release (**78%**) (Song *et al.*, 2020). The presence of surface $-\text{COOH}$ and $-\text{OH}$ groups facilitated strong electrostatic interactions with DOX, enabling controlled and pH-responsive release – a desirable feature for targeted cancer therapy (Anju *et al.*, 2021).

4.5 Comparison with Conventional CQDs

Compared to chemically synthesized CQDs, green-synthesized CQDs demonstrated comparable or superior performance in terms of **quantum yield, biocompatibility, and catalytic activity** while significantly reducing environmental impact (Bourlinos *et al.*, 2008). The elimination of toxic reagents and harsh conditions reduced synthesis costs by **30–40%** and lowered the overall **carbon footprint**, making green synthesis a more sustainable alternative (Dong *et al.*, 2020). Furthermore, the inherent surface functionalization achieved during green synthesis eliminated the need for additional passivation steps, simplifying production (Li *et al.*, 2012).

4.6 Sustainability and Scalability Considerations

A preliminary **lifecycle assessment (LCA)** indicates that green-synthesized CQDs consume **40–60% less energy** and produce significantly lower hazardous waste than conventional methods (Anju *et al.*, 2021). Biomass-derived precursors not only reduce raw material costs but also align with circular economy principles by utilizing agricultural and food waste (Dong *et al.*, 2020).

From a scalability perspective, microwave and hydrothermal synthesis methods show the highest potential due to their low energy consumption, rapid reaction times, and reproducibility (Liu *et al.*, 2019). These attributes make large-scale production of CQDs feasible for commercial applications in **wastewater treatment, solar energy harvesting, bioimaging, and targeted drug delivery** (Song *et al.*, 2020).

V. Future Prospects and Challenges

5.1 Integration of CQDs in Hybrid Nanomaterials for Enhanced Photocatalysis

One of the most promising future directions for CQDs lies in their **integration into hybrid nanomaterial systems** to significantly improve photocatalytic performance. The combination of CQDs with semiconductors such as TiO_2 , ZnO , and $\text{g-C}_3\text{N}_4$ has demonstrated remarkable enhancements in charge separation, visible-light absorption, and catalytic activity (Liu *et al.*, 2019). Such hybrid systems exploit the unique electron donor–acceptor capabilities of CQDs, facilitating efficient electron transfer and reducing recombination rates (Wang & Hu, 2014).

Moreover, **heterostructured photocatalysts** incorporating CQDs as sensitizers can extend the light absorption range into the visible and near-infrared regions, improving solar-to-chemical conversion efficiency (Dong *et al.*, 2020). Future research should focus on designing CQD-based **plasmonic or metal–organic framework (MOF) composites**, which can further enhance photocatalytic water splitting and pollutant degradation performance (Anju *et al.*, 2021). These developments could pave the way for scalable, solar-driven environmental remediation technologies.

5.2 Advances in Targeted Drug Delivery and Theranostics

The biocompatibility, tunable fluorescence, and ease of functionalization of CQDs position them as powerful tools for **targeted drug delivery and theranostics**. Future research will likely focus on integrating CQDs with **stimuli-responsive nanocarriers** that release therapeutic agents in response to pH, temperature, or enzymatic changes within the body (Song *et al.*, 2020). The surface of CQDs can be modified with ligands such as folic acid, peptides, or antibodies to achieve **cell-specific targeting**, thereby reducing off-target effects and enhancing therapeutic efficacy (Hola *et al.*, 2014).

Additionally, CQDs hold significant promise in **theranostic applications** — combining diagnostics and therapy within a single platform. Their ability to function simultaneously as **fluorescent probes and drug carriers** enables real-time monitoring of drug delivery and therapeutic response (Dong *et al.*, 2020). Further integration with photothermal or photodynamic therapy agents could transform CQDs into multifunctional platforms for cancer treatment (Liu *et al.*, 2019). However, translating these advances into clinical use will require deeper understanding of biodistribution, clearance, and long-term safety.

5.3 Scale-Up Strategies and Commercialization Challenges

While laboratory-scale synthesis of CQDs is well established, **scaling up production for industrial applications** remains a significant challenge. Controlling particle size distribution, surface functionality, and optical properties consistently across large batches is difficult due to the variability of biomass precursors and synthesis conditions (Bourlinos *et al.*, 2008). Developing **standardized synthesis protocols** and optimizing reactor designs for hydrothermal and microwave-assisted methods will be essential for achieving industrial-scale reproducibility (Li *et al.*, 2012).

Commercialization is also hindered by **cost considerations**, including purification processes, solvent use, and quality control. Life-cycle analyses indicate that while green synthesis reduces environmental impact and raw material costs, further optimization is necessary to minimize energy use and enhance process yield (Anju *et al.*, 2021). Collaboration between academia and industry will be crucial in addressing these challenges, enabling the development of CQD-based commercial products in **environmental monitoring, bioimaging, and drug delivery** (Wang & Hu, 2014).

5.4 Regulatory and Biosafety Considerations

Despite promising biomedical and environmental applications, the **regulatory landscape for CQDs remains underdeveloped**. A key challenge is the lack of standardized toxicity assessment protocols, which hinders regulatory approval for clinical use (Song *et al.*, 2020). Although green-synthesized CQDs are generally considered biocompatible, their long-term fate, biodegradability, and potential immunogenicity must be comprehensively studied (Hola *et al.*, 2014).

In environmental applications, it is essential to evaluate the **ecotoxicological impact** of CQDs, including their interactions with soil and aquatic ecosystems (Dong *et al.*, 2020). Regulatory bodies such as the FDA and EMA will require detailed data on pharmacokinetics, bio-distribution, and chronic toxicity before approving CQD-based therapeutics (Liu *et al.*, 2019). Future research should prioritize the development of **standardized biosafety frameworks** and international guidelines to ensure safe deployment of CQD technologies in clinical and industrial settings.

VI. Conclusion

This study comprehensively analyzed the synthesis, characterization, and multifunctional applications of **green-synthesized carbon quantum dots (CQDs)**, highlighting their transformative potential in both **environmental remediation** and **biomedical science**. The findings underscore that biomass-derived CQDs, synthesized through eco-friendly methods such as **hydrothermal, microwave-assisted, pyrolytic, and ultrasonic techniques**, not only reduce environmental impact but also yield high-performance nanomaterials with desirable structural, optical, and surface characteristics (Dong et al., 2020; Anju et al., 2021).

The synthesized CQDs exhibited **excellent photoluminescence properties**, strong quantum yields (up to 51%), and nanoscale particle sizes (~3.8–5.5 nm), demonstrating their suitability for advanced optical and catalytic applications (Holo et al., 2014). Their photocatalytic performance, particularly in the degradation of organic pollutants and potential for hydrogen generation, illustrates their capability to contribute to **sustainable energy and water treatment technologies** (Liu et al., 2019; Wang & Hu, 2014). Concurrently, the exceptional **biocompatibility (>90% cell viability)**, **strong fluorescence for bioimaging**, and **controlled drug release behavior** establish CQDs as promising candidates for **drug delivery, diagnostics, and theranostic platforms** (Song et al., 2020).

A key conclusion of this work is the reaffirmation of **green nanochemistry** as a viable and scalable route for producing advanced nanomaterials. By utilizing renewable biomass waste, these methods align with the principles of sustainability and circular economy, significantly reducing synthesis cost, hazardous by-products, and energy consumption compared to conventional approaches (Bourlinos et al., 2008; Li et al., 2012). Furthermore, the inherent surface functionalities introduced during green synthesis eliminate the need for additional passivation steps, simplifying production and enhancing application readiness (Sun et al., 2013).

Looking ahead, the integration of CQDs into **hybrid nanomaterials**, the development of **stimuli-responsive drug delivery systems**, and progress in **scalable synthesis technologies** will expand their applicability and accelerate industrial adoption (Dong et al., 2020). Future interdisciplinary research bridging **nanotechnology, materials science, environmental engineering, and biomedicine** will be essential for overcoming current challenges related to scalability, regulatory approval, and long-term biosafety (Anju et al., 2021).

In conclusion, **green-synthesized CQDs represent a new generation of sustainable, multifunctional nanomaterials**, capable of addressing critical global challenges in environmental sustainability and healthcare. Their dual potential in **photocatalysis** and **biomedical applications** positions them as key enablers in the transition toward a more sustainable, technology-driven future.

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