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# Jojoba Meal-Derived Carbon Quantum Dots: A Green Synthesis and Biomass Valorization

**Reda A. Elkhyat [1], Mohsen Ghali [2], Mahmoud Nasr [3], Mohamed A. Ghazy [4]**
[1] Biotechnology Program, Basic and Applied Science Institute, Egypt-Japan University of Science and Technology (E-JUST), New Borg El-Arab City, Alexandria 21934, Egypt; Botany and Microbiology Department, Faculty of Science, Alexandria University, Alexandria 21526, Egypt
reda.elkhyat@ejust.edu.eg
[2] Basic and Applied Science Institute, Egypt-Japan University of Science and Technology (E-JUST), New Borg El-Arab City, Alexandria 21934, Egypt; Physics Department, Faculty of Science, Kafrelsheikh University, 33516, Kafr El-Sheikh, Egypt mohsen.ghali@ejust.edu.eg
[3] Environmental Engineering Department, Egypt-Japan University of Science and Technology (E-JUST), New Borg El-Arab City, Alexandria 21934, Egypt; Sanitary Engineering Department, Faculty of Engineering, Alexandria University, Alexandria 21544, Egypt
mahmoud.nasr@ejust.edu.eg
[4] Biotechnology Program, Basic and Applied Science Institute, Egypt-Japan University of Science and Technology (E-JUST), New Borg El-Arab City, Alexandria 21934, Egypt; Biochemistry Department, Faculty of Science, Ain Shams University, Cairo 11566, Egypt
mohamed.ghazy@ejust.edu.eg

## Abstract
Amid escalating environmental pollution and resource depletion, transforming plant waste into high-value functional materials has become a pivotal strategy for advancing circular economies. Among these materials, carbon quantum dots (CQDs), a category of novel carbon nanoparticles, possess significant potential for a wide range of applications owing to their remarkable physical and optical properties, high biocompatibility, low toxicity, and hydrophilicity. Despite multiple methods for producing CQDs, demand is rising for employing cost-effective and environmentally friendly synthetic methods. Thus, this study presents a one-pot hydrothermal synthesis of CQDs using jojoba meal (*Simmondsia chinensis* seed residue as a precursor, denoted as JCQDs), without surface passivation agents or oxidizers. The TEM micrograph revealed that the synthesized JCQDs exhibited uniform morphology with an average diameter of 25.7 nm. Additionally, UV-Vis analysis of JCQDs showed a characteristic absorption peak at 260 nm and emitted bright greenish-blue fluorescence under 350 nm UV excitation. Notably, JCQDs demonstrated a promising antimicrobial activity against Gram-positive (*Staphylococcus aureus*) bacteria, highlighting their potential for biomedical and environmental applications. Therefore, this study revealed the recyclability of jojoba meal as a sustainable and eco-friendly precursor for high-performance fluorescent nanomaterials, enabling a novel approach for plant biomass valorization.

***Keywords***: Carbon quantum dots; Biomass recyclability; Jojoba meal; Antibacterial activity

## 1. Introduction
Carbon Quantum Dots (CQDs) are a novel class of zero-dimensional photoluminescent carbon nanomaterials with typical diameters smaller than 10 nm. CQDs exhibit distinctive visual characteristics, diverse surface functionalities, excellent biocompatibility, low toxicity, hydrophilicity, and notable optical properties [2]. They have recently attracted attention in various fields, including bioimaging, biosensing, food packaging, solar cells, drug delivery, and photodynamic therapy[3, 12]. For example, CQDs exhibit significant antibacterial and anticancer effects when subjected to external energy stimuli, leading to the production of Reactive Oxygen Species (ROS) [11]. CQDs also have antioxidant properties and enhanced UV absorption capabilities, attributed to their remarkable electron acceptor characteristics, along with the abundance of π-π conjugated groups in their core [3].

Various methods for producing CQDs are available; however, there is growing interest in employing low-cost and environmentally sustainable synthetic methods [1]. High-purity chemicals are frequently utilized as precursors in synthesizing CQDs to enhance the efficiency and uniformity of the synthesis process. However, they also necessitate high energy consumption and use toxic and aggressive chemical additives that threaten the biological environment [7]. These factors collectively render the process economically unviable [1]. Therefore, green synthesis has attracted significant interest in recent years, where plant biomass-based CQDs are considered the most sustainable fluorescent nanomaterial.

The plant biomass exhibits significant biocompatibility owing to the presence of naturally occurring stabilizing and reducing agents within its tissues [7]. In addition, plant biomass comprises various organic compounds such as carbohydrates, proteins, amino acids, and secondary metabolites, which provide essential elements for the surface functionality of CQDs [8]. The green synthesis route of CQDs facilitates the conversion of plant waste into valuable biomass-based CQDs, reducing waste generation and enhancing resource reutilization [4]. This, in turn, mitigates the carbon footprint associated with traditional synthesis methods and meets the circular economy and sustainable approach. Therefore, this study aims to (i) recycle the jojoba meal, one of the agricultural wastes, to produce jojoba-derived carbon quantum dots (JCQDs) and (ii) examine the antimicrobial efficiency of the produced JCQDs.

## 2. Materials and Methods

### 2.1. JCQDs fabrication

The fluorescent CQDs were synthesized from jojoba meal using a hydrothermal method(Fig. 1). Prior to synthesis, the jojoba meal was dried and finely ground into a powder. A mixture of 0.5 g of jojoba meal and 50 mL of deionized water was transferred into a Teflon-lined stainless-steel autoclave and heated at 180 °C for 12 hours. After completion, the solution was allowed to cool naturally to room temperature. The resulting brown-coloured solution was centrifuged at 8000 rpm for 30 minutes and filtered with a 0.45 μm membrane filter to remove large particles. Further purification was performed via dialysis using a membrane (MWCO: 3 kDa). The purified supernatant was kept at 4 °C for further characterization and analysis.

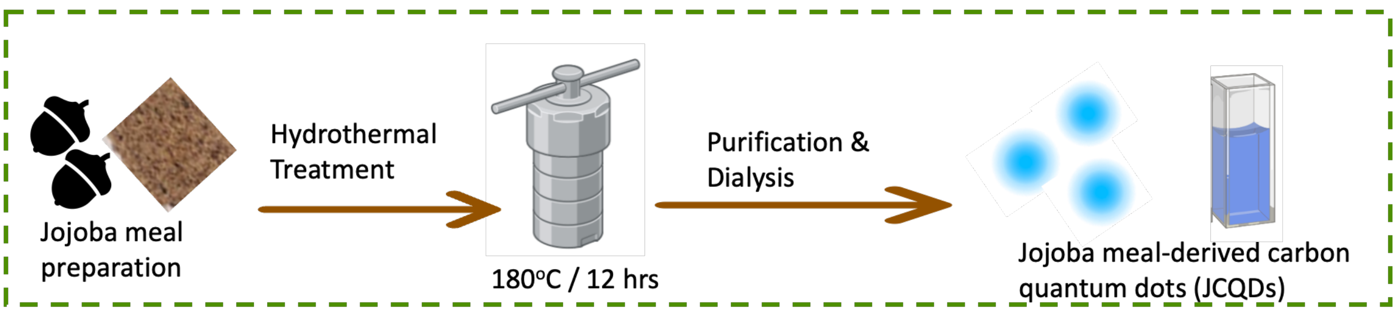


Fig. 1: Schematic abstract of the main steps included in the practical work.

### 2.2. JCQDs Characterization

The fluorescence emission properties of the synthesized JCQDs were examined using a fluorescence spectrophotometer (Hitachi F-7100 FL, Japan). Emission spectra were recorded across excitation wavelengths from 250 to 500 nm to identify the peak fluorescence intensity. Optical absorption spectra were measured spectrophotometrically with a UV-visible spectrophotometer (Hitachi U-3900, Japan) at 25 °C, with scans conducted between 220 and 700 nm. Morphological analysis was performed using transmission electron microscopy (JEOL JEM-2100, Japan) to assess CQD size and shape. ImageJ software assessed particle size (Version 1.53k, NIH, USA).

### 2.3. Antibacterial activity

The antibacterial effectiveness of JCQDs against Gram-positive *Staphylococcus aureus* was assessed using the conventional disk diffusion method. A bacterial suspension calibrated to the 0.5 McFarland standard (~1 x $10^8$ CFU/mL) was evenly distributed on agar plates. Sterile filter paper disks (6 mm in diameter) impregnated with different concentrations of JCQDs (e.g., 10 and 20 µg/mL) were aseptically positioned onto the inoculated agar. Positive control (jojoba meal) and negative control (sterile distilled water) were incorporated. Plates were incubated at 37 °C for 24 hours, after which the diameters of the inhibition zones surrounding the disks were determined in millimeters. Zone diameters indicated the extent of antibacterial action.

## 3. Results and Discussion

### 3.1. Characterization of JCQDs

The surface morphology of the synthesized JCQDs was observed by TEM (Fig. 2A). The TEM image demonstrates that JQDs were uniform in shape with an average diameter of 25.7 nm. Figure 1B shows an optical property of JCQDs that exhibited an absorption peak observed at 260 nm. This absorption spectrum is possibly ascribed to the π–π* transitions [13].

Fig. 2C shows the excitation-dependent emission spectra of JCQDs from 260 to 500 nm. As the excitation wavelength increased, the fluorescence emission spectra of JCQDs showed a distinct wavelength dependence and shifted toward longer wavelengths. Moreover, JCQDs exhibited maximum fluorescence emission at 430 nm at the optimal excitation wavelength of 350 nm, emitting a bright greenish-blue fluorescence. This excitation-dependent emission behavior could be influenced by parameters that vary with particle dimensions, surface functional groups, and energy traps [13].

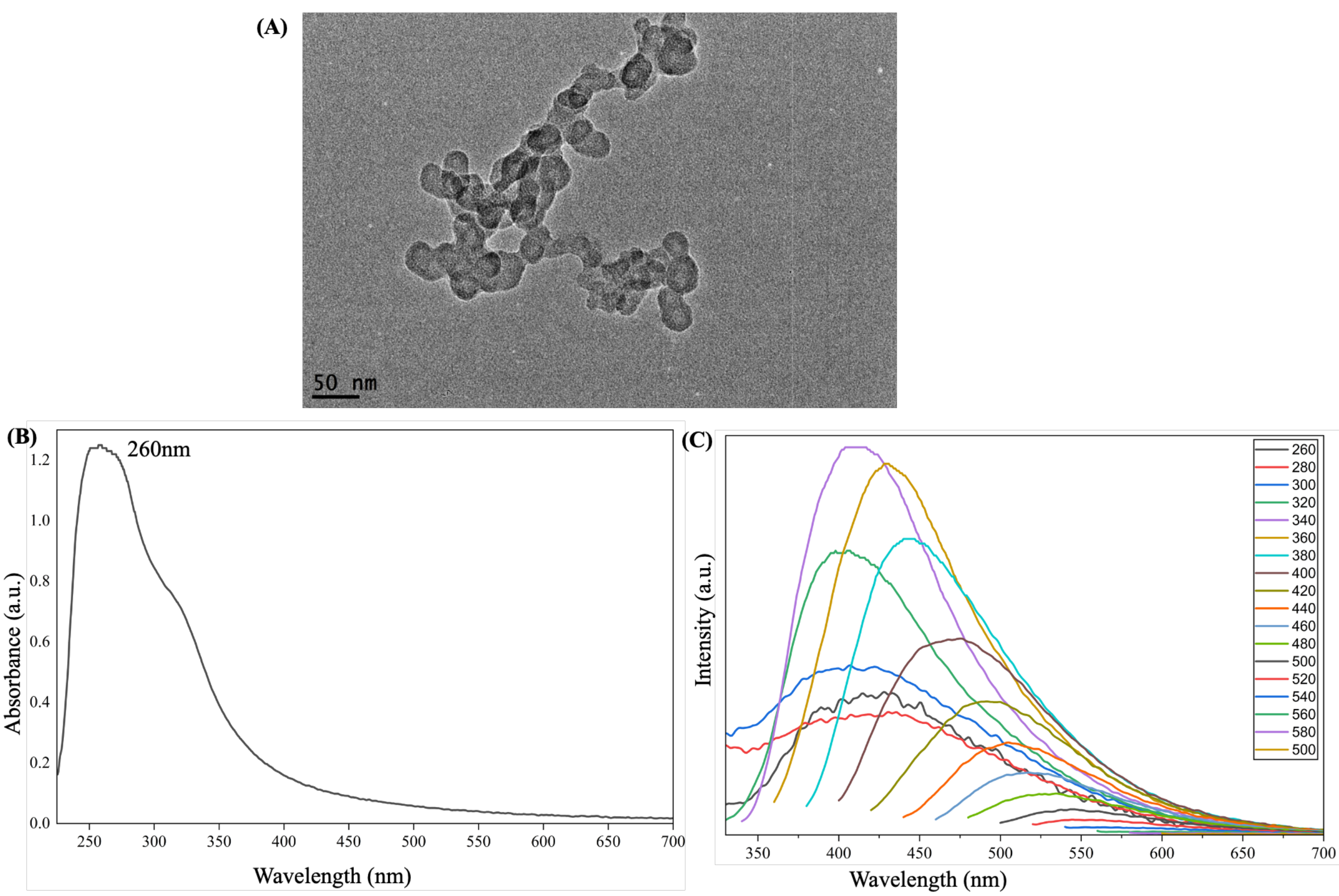

Fig. 2: Characterization of Jojoba meal-derived carbon quantum dots (JCQDs): (A) TEM analysis, (B) UV–Visible absorption spectrum, and (C) Fluorescence emission spectra under excitation wavelengths from 260 to 500 nm at 20 nm intervals.

### 3.2. Anti-microbial Activity

Fig. 3 illustrates that JCQDs effectively limit *S. aureus* growth to approximately 3.5 mm ±0.1 at 20 µg/ml. This growth inhibition possibly results from membrane lysis caused by interactions between JCQD surfaces and bacterial cell membranes. Indeed, nitrogen heteroatoms in CQDs produce positively charged groups, boosting electrostatic attraction to the negatively charged peptidoglycan in bacterial cell walls and intracellular components [6, 10]. This adhesion leads to physical and mechanical damage of the bacterial barrier, facilitating the penetration of CDs into the interior membranes [9], consequently disrupting essential biological functions [6]. Additionally, Gupta, Priyadarshi, Tammina, Rhim and Agrawal [5]proposed that the antibacterial mechanism of CQDs involves the generation of ROS, including superoxide anions (O2-•), singlet oxygen (1O2), and hydroxyl radicals (•OH). These radicals trigger oxidative stress within bacterial cells, damaging cell membranes, denaturing proteins, and fragmenting nucleic acids, ultimately leading to cell death[6]. Although JCQDs exhibit antimicrobial potential, higher concentrations are necessary to improve their effectiveness as antimicrobial agents.

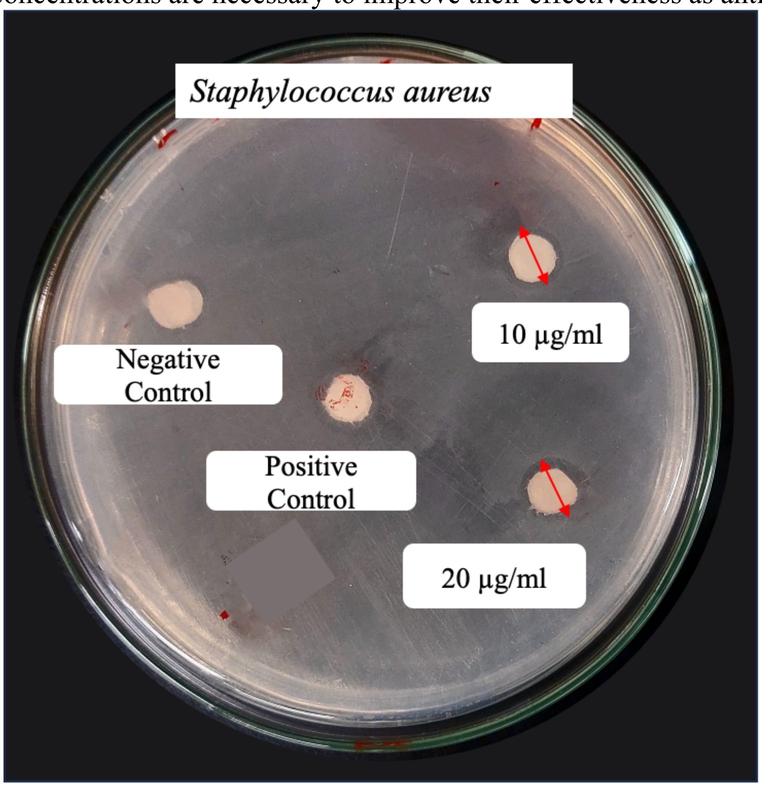


Fig. 3: Photograph of Staphylococcus aureus culture dishes treated with different Jojoba meal-derived carbon quantum dots (JCQDs) concentrations.

## 4. Conclusion

This study presented a novel approach for plant biomass valorization by recycling jojoba meal to synthesize fluorescent CQDs using a one-pot hydrothermal method, reducing the demand for surface passivators or oxidizers. The JCQDs emit bright greenish-blue fluorescence when excited at 350 nm. Moreover, JCQDs demonstrated potent antimicrobial activity against *S. aureus*. These results highlighted jojoba waste as a green, eco-friendly precursor for high-performance nanomaterials and also provided a blueprint for the circular utilization of plant waste. Further research is required to optimize

JCQD concentration to enhance antimicrobial potency and examine its effects against multidrug-resistant strains, along with potential biomedical and environmental applications.

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