

RESEARCH ARTICLE

Fabrication and Characterization of Carbon Quantum Dots from Waste Fruit Extract and Study their Antibacterial Activity

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ABSTRACT:

CQDs have emerged as encouraging materials for numerous uses due to their exceptional optical and electronic properties. In this study, we explore an eco-friendly approach to fabricate CQDs using waste fruit extract as a precursor. The fabrication process involves simple and cost-effective steps, making it appropriate for scale up. The obtained CQDs are analysed utilizing spectroscopic and microscopic techniques to know the structural and optical properties. Besides, the antibacterial activities of CQDs were screened against aquatic Gram-negative (*Klebsiella pneumoniae* and *Proteus vulgaris*) microbial organisms. This research highlights the innovative use of agricultural waste in nanomaterial synthesis, contributing to sustainable and green chemistry practices.

KEYWORDS: Carbon Quantum Dots, Green Synthesis, TEM, Waste fruit extract, Nanoparticles.

INTRODUCTION:

CQDs are a class of carbon-based nanomaterials which possess and have gained substantial deliberation owing to their exclusive optical properties, such as tunable fluorescence, low toxicity, biocompatibility, and versatility for a diverse applications, especially bioimaging, drug delivery, environmental sensing, and antimicrobial therapies^{1,2,3}. The green synthesis of CQDs using natural precursors, has become increasingly popular due to its simplicity, low cost, and environmental sustainability. Natural sources like plant biomass, including fruit extracts, have been recognized as an excellent precursor for CQD synthesis⁴. These sources are rich in carbon, polyphenolic compounds, vitamins, and sugars, which not only serve as carbon sources but also play important roles as reducing agents and stabilizers in the synthesis process⁵. Fruits such as bananas, apples, pomegranates, and oranges are widely consumed globally, and their waste, including peels, seeds, and pulp, are often discarded, contributing to environmental pollution^{6,7}.

While earlier studies have primarily focused on CQDs derived from a single type of fruit waste such as banana peels⁸, this study explores the use of four different fruit extracts (banana, apple, pomegranate, and orange) thereby broadening the range of natural precursors for CQD synthesis. By comparing the synthesis of CQDs from multiple fruit wastes, this work aims to identify which fruit waste produces CQDs with superior properties, such as enhanced fluorescence, stability, and antibacterial activity. This comparative approach adds significant value to the growing body of literature on green synthesis of CQDs^{9,10}. Banana peels, for instance, are known for their high polyphenolic content, while pomegranate peels contain antioxidants like ellagic acid, both of which have been reported to assist in the synthesis of high-quality CQDs¹¹. Similarly, apple and orange peels are rich in flavonoids and organic acids that can contribute to the fabrication of CQDs with enhanced properties, including high stability and excellent fluorescence¹². The green synthesis of CQDs from fruit waste not only addresses environmental concerns by promoting waste valorization but also offers a sustainable approach to developing nanomaterials with potential antibacterial properties¹³.

The main objectives of this study are to fabricate CQDs from waste fruit extracts (banana, apple, pomegranate, and orange), characterize their physicochemical properties, and evaluate their antibacterial activity. The characterization will include techniques such as UV-Vis

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spectroscopy, electron microscope (SEM & TEM) and XRD to determine the size, morphology, optical properties, and surface functionalization of the CQDs. In addition, the antibacterial activity of the synthesized CQDs will be tested against Gram-negative bacterial strains to assess their potential for use in antimicrobial applications.

MATERIALS AND METHODS:

Materials:

The various fruit waste peel of BOPA used in this study was obtained from a local market in Pallavaram, Chennai.

Synthesis of CQDs utilizing multiple fruit waste extract:

The multiple fruit peel extract was prepared as follows [4]: About 12.5g of individual waste peel was excellently cut into fine parts and washed twice with double distilled water then taken in a 100mL beaker containing 50mL water, mixed well, and heat the mixture gently at 60°C and stir it for 30 minutes to extract soluble organic compounds, such as sugars, polyphenols, and flavonoids, which can act as precursors for CQD synthesis. Transfer a 100mL of the fruit extract solution into an autoclave. Seal the autoclave and heated at 140°C for 6hrs. After the reaction time, allow the autoclave to cool down to room temperature naturally.

Characterization:

The XRD pattern of CQD samples were measured using *Rigaku SmartLab* high-resolution XRD equipped with a liquid N₂ cooled germanium solid-state detector using Cu-K α radiation. An aqueous solution of CQD was analysed by UV-Visible spectroscopy (Jasco, Japan). To identify the crystalline size and structure of the CQDs, a FEI Technal 20 Plus was employed in a TEM. The graphitization of the CQDs were recorded with a Confocal Raman Spectroscopy Alpha300R WiTech GmbH, Germany.

Antibacterial Studies:

MIC determination utilizing micro broth dilution method. The test material is dispersed in 10% of DMSO solution. The primary concentration of the sample was consecutively thinned in a 96 well plate and incorporated with 5 μ l of suspension contains about 10⁸ CFU ml bacterial growth. The plates have kept under 24hrs incubation at 37°C. The intensity of culture from each well was monitored at 600 nm and the results were compared with control. The MIC of synthesised gold nanoparticles was determined at the least concentration leads to inhibit the microbial growth¹⁴.

RESULT AND DISCUSSION:

UV-Visible Spectroscopy of BOPA mediated CQDs

Figure 1 below illustrates the UV-Visible absorption

spectra of CQDs synthesized from BOPA peel extracts. The characteristic peak around 278nm which corresponds to the π - π^* transition of the C=C bond in the aromatic carbon framework¹⁵. Additionally, a second broad peak appeared around 318 nm is ascribed to the n- π^* transition, which can result from the interaction of functional groups (such as oxygen-containing groups) on the CQD surface with the surrounding medium¹⁶. This suggests that the nature and concentration of surface groups, such as polyphenols and flavonoids, could vary depending on the fruit waste used, influencing the optical properties of the CQDs. The position of the absorption peak shifts towards shorter wavelengths (blue-shift) as the size of the CQDs decreases due to quantum confinement effects.

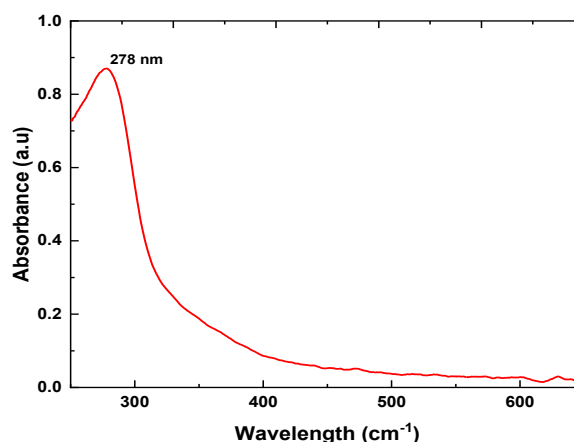


Figure 1: UV-Visible Spectroscopy of BOPA mediated CQDs

XRD of CQDs synthesised from BOPA:

XRD is a powerful technique for analyzing the crystallinity, size, and phase of nanomaterials, and it can provide important information about the nature of the carbon structure in CQDs. Figure 2 below illustrates the XRD patterns of CQDs synthesized from BOPA peel extracts. The XRD patterns of CQDs synthesized from each fruit waste extract exhibited a broad peak centered at $2\theta = 26^\circ$ and 42.98° which is typically associated with the (002) and (001) plane of the graphite-like carbon structure^{17,18}. The broadness of this peak indicates the relatively low degree of crystallinity, which is typical for carbon quantum dots, as they usually possess an amorphous or semi-graphitic structure.

FT-IR Spectroscopy of CQDs:

The FT-IR (Fourier Transform Infrared) spectroscopy of carbon quantum dots (CQDs) provides valuable information about their chemical composition, surface functional groups, and structural characteristics (Figure 3). The peak at 3353 cm^{-1} indicate the presence of hydroxyl groups (-OH) from surface functionalization or residual water. The peaks at 1630 cm^{-1} and 1072 cm^{-1} suggest carbonyl groups (C=O), which could originate

from carboxyl groups or ketones^{19,20}.

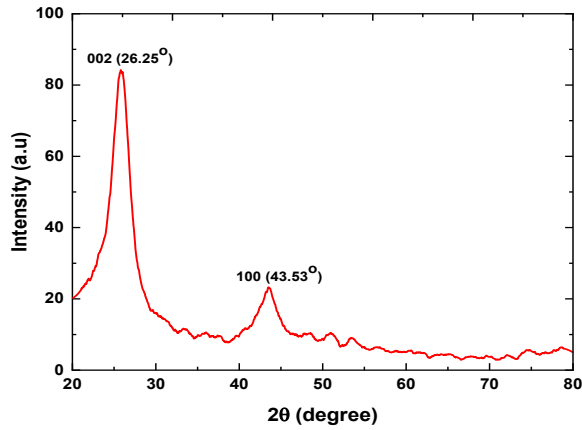


Figure 2: XRD of CQDs from BOPA

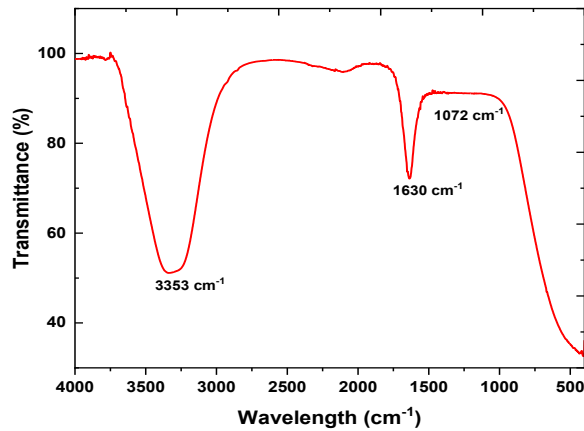


Figure 3: FTIR of CQDs from BOPA

TEM analysis of CQDs synthesised from mixed fruit waste:

The TEM analysis of CQDs synthesized from mixed fruit waste (BOPA) reveals that the CQDs remain predominantly spherical in shape, with an average size ranging from 3 to 6 nm. The results from this study are comparable to those in the literature¹¹. Figure 4 which clearly indicate the distinct structural state of a material with interplanar spacing (d-spacing) of 0.21nm aligned with the graphene structure (1 0 0)plane^{12,21,22}. The blended fruit waste could lead to synergistic effects during the synthesis process, where the combined fruit waste creates a unique environment that modulates the growth kinetics of the CQDs, resulting in nanoparticles that are more uniform in size than those derived from individual fruit sources. This could explain the relatively narrow size distribution observed in the TEM images (Figure 4). The uniform size distribution and the presence of surface functional groups make these CQDs highly suitable for diverse applications especially imaging, drug delivery, and antibacterial treatments.

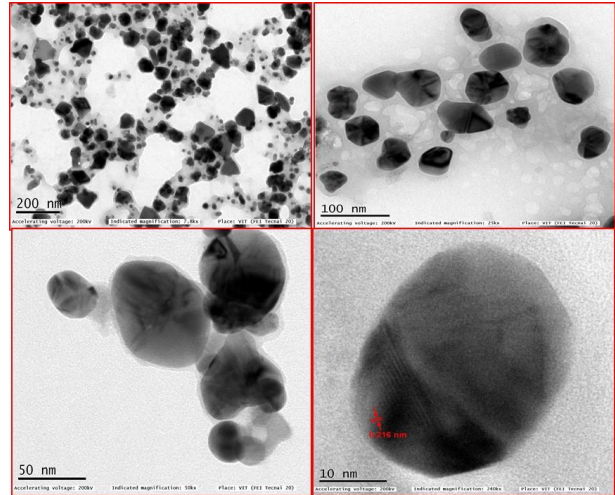


Figure 4: TEM analysis of CQDs synthesised from BOPA

Raman Spectroscopy of CQDs:

The Raman spectrum shown in Figure 5 which show distinct peaks at 1366 cm⁻¹ associated with structural disorder in graphene (D-band) while G-band (at 1586 cm⁻¹) arises from the stretching of sp² carbon bonds, representing the presence of an ordered graphitic structure. The good graphitization of CQDs were confirmed by the I_D/I_G¹².

Antimicrobial Activity of CQDs:

The antibacterial activity of CQDs has been evaluated against gram-negative strains. A significant finding in this area is the ability of CQDs to inhibit bacterial growth by disrupting the bacterial membrane and generating ROS. CQDs demonstrate a concentration-dependent antibacterial effect²³. A study by Cai²⁴ showed that CQDs synthesized from glucose exhibited strong antibacterial action against *Klebsiella* and *Proteus*, with inhibition zones of 8.1mm and 6.5 mm, respectively. Gram-negative bacteria have an outer membrane that is more easily penetrated by CQDs due to their smaller size and negative surface charge^{25,26}.

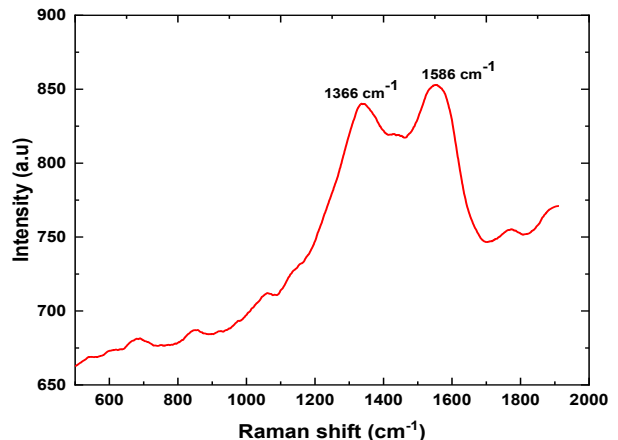


Figure 5: Raman Spectrum of CQDs

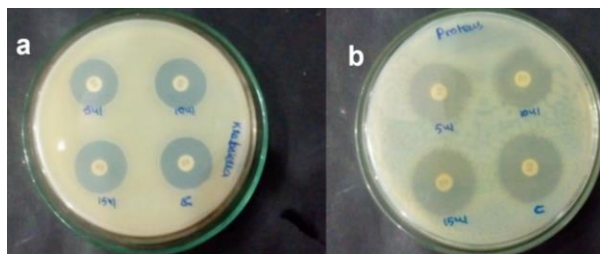


Figure 6: Antibacterial activity against *Klebsiella pneumoniae* and *Proteus vulgaris*

CONCLUSION:

In this study, carbon quantum dots (CQDs) were successfully synthesized from waste fruit extract, demonstrating an innovative and sustainable approach to utilizing food waste for the production of nanomaterials. The fabricated CQDs were characterized through different physicochemical analysis such as UV-Visible spectroscopy, FTIR, XRD, TEM. These investigations endorsed the efficacious formation of CQDs with a size range of 3-6nm. The CQDs exhibited excellent dispersibility in water, further enhancing their potential for biomedical applications. The results showed that the CQDs had significant antibacterial effects, with larger inhibition zones and lower minimum inhibitory concentrations (MIC) observed for Gram-negative bacteria like *Klebsiella* and *Proteus*. The antibacterial action was likely due to the generation of ROS and the ability of CQDs to disrupt bacterial cell membranes. The surface charge and size of the CQDs also contributed to their efficient interaction with bacterial cells. Overall, this study highlights the promising potential of CQDs derived from waste fruit extract as effective, eco-friendly antibacterial agents. The use of waste materials not only addresses environmental concerns but also contributes to the development of sustainable nanomaterials with biomedical and environmental applications.

CONFLICT OF INTEREST:

The authors have no conflicts of interest regarding this investigation.

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