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Synthesis of Carbon Quantum Dots (CQDs) from White Turmeric Doped with DMF as an Antioxidant

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Abstract: Carbon quantum dots (CQDs) are carbon-based nanomaterials with excellent optical properties and biocompatibility, making them highly promising for applications in bioimaging, biosensing, and antioxidant therapy. This study aims to synthesize CQDs from white turmeric (*Curcuma zedoaria*) as a natural carbon precursor and to enhance their antioxidant activity through doping with dimethylformamide (DMF). The synthesis was carried out using a hydrothermal method at 180 ℃ for 4 h, followed by purification and characterization using FT-IR, UV-Vis, and photoluminescence (PL) analysis. Antioxidant activity was tested using DPPH and calculated the percentage of scavenging activity (%). FT-IR results confirmed the presence of functional groups such as -OH, C=O, C-N, and -NH, indicating hydrophilic characteristics and active surface functionalities of the CQDs. The UV-Vis spectrum showed an absorption peak at 263 nm corresponding to π–π* transitions, while the PL spectrum exhibited fluorescence emission at 449 nm. Antioxidant activity evaluated using the DPPH method demonstrated that the IC_{50} values of white turmeric extract and CQDs were 0.13% and 5.03%, respectively. Overall, the findings indicated that white turmeric can serve as an environmentally friendly carbon source for CQDs synthesis. This study highlights the potential application of turmeric-derived CQDs in bioimaging and delivery.

Keywords: nanotechnology, hydrothermal, optical properties, IC_{50}, *Curcuma zedoaria*.

Introduction

Carbon quantum dots (CQDs) are carbon-based nanomaterials that have attracted great attention due to their unique optical properties and potential in a wide range of applications [1]. CQDs are very small nanomaterials, usually less than 10 nanometers, which exhibit extraordinary fluorescence properties, water solubility, biocompatibility, low toxicity, and ease of synthesis [2]. These properties make CQDs very promising for various application fields such as bioimaging, biosensing, and nanomedicine [3],[4]. With flexibility in particle size modification and functionalization, CQDs can be optimized to meet specific needs in various applications [5].

One of the most important properties of CQDs is their ability as antioxidant agents, which are compounds that inhibit the oxidation of other molecules and protect the body from the effects of free radicals [6]. Free radicals can be produced by normal cell metabolism or as an effect of pollution and exposure to other external factors, and are responsible for premature aging and play a role in cardiovascular disease, degenerative diseases such as cataracts, Alzheimer's disease, and cancer [7]. Therefore, antioxidants are very important in maintaining health and preventing various diseases.

To increase the antioxidant potential of CQDs, one promising approach is to utilize natural ingredients, such as white turmeric (*Curcuma zedoaria*) which has great potential as a source of bioactive compounds [8]. Several studies have shown that white turmeric contains compounds such as curcuminoids, flavonoids, and essential oils which have antioxidant activity [9]. However, in this research, white turmeric was used not to retain its original bioactive compounds, but as a carbon source for CQD synthesis through a carbonization process. Doping with dimethylformamide

(DMF) aims to introduce nitrogen groups onto the CQDs' surfaces to enhance antioxidant activity.

Nitrogen doping has been widely employed to tailor the electronic structure and surface chemistry of carbon quantum dots. The incorporation of nitrogen-containing functional groups, such as amino, pyridinic-N, and graphitic-N moieties, can increase electron density and facilitate electron- or hydrogen-atom transfer processes involved in free-radical scavenging. Several studies have reported that N-doped CQDs exhibit higher antioxidant activity than undoped CQDs because nitrogen functionalities create additional active sites for reactive oxygen species (ROS) quenching and improve charge-transfer efficiency. Moreover, surface amino groups may contribute to radical stabilization through proton donation mechanisms. Therefore, DMF was selected as a nitrogen source in this study to introduce nitrogen-containing functionalities onto the CQD surface and potentially improve their antioxidant performance, although the final activity also depends on the preservation of bioactive surface groups after carbonization and purification processes.

Although CQDs from natural materials such as white turmeric offer many advantages, the main challenges faced are the efficiency and sustainability of the synthesis process. Traditional synthesis methods often involve the use of hazardous chemicals and extreme reaction conditions. Therefore, the development of more environmentally friendly and economical synthesis methods is crucial. Utilizing natural materials such as white turmeric as CQD precursors is a promising step to overcome these challenges [10],[11]. In addition, doping CQDs with certain compounds such as DMF can improve their properties, including antioxidant activity.

DMF is a polar aprotic solvent commonly used in organic synthesis. DMF can serve as a doping agent for CQDs, which can modify the surface structure and electronic properties of CQDs, thereby enhancing their antioxidant activity. Doping with heteroatoms such as nitrogen, residual DMF will be removed through a stepwise purification process, including centrifugation and filtration.

Dimethylformamide (DMF) was selected as a nitrogen source because of its high nitrogen content, excellent miscibility with carbonaceous precursors, and its proven effectiveness in introducing nitrogen-containing functional groups onto carbon nanomaterials. Nitrogen incorporation can modify the electronic structure and surface chemistry of CQDs, leading to improved optical and redox-related properties. Although DMF is recognized as a hazardous solvent, its use in this study was limited to the synthesis stage as a nitrogen precursor rather than as a constituent of the final material. To minimize potential toxicity, the synthesized CQDs were subjected to purification steps including filtration and centrifugation to remove unreacted DMF and low-molecular-weight by-products. Alternative nitrogen sources such as urea, ethylenediamine, and amino acids have been reported in the literature; however, DMF was selected because it simultaneously acts as a solvent and an efficient nitrogen donor, enabling facile surface functionalization under relatively mild condition.

It should be noted that DMF was not expected to become fully incorporated into the carbon core of CQDs under the relatively mild post-synthesis doping conditions (60–80 °C for 2 h). Instead, DMF primarily served as a nitrogen precursor that could introduce nitrogen-containing surface functionalities through interactions with oxygenated surface groups already present on the CQDs. Therefore, the resulting material is more appropriately described as surface-functionalized or nitrogen-modified CQDs rather than CQDs with extensive substitutional nitrogen incorporation into the graphitic framework.

The novelty of this research lies in the use of white turmeric as a natural material for CQD synthesis, DMF doping to enhance its antioxidant properties, and its potential application in antioxidant therapy. This research offers an innovative solution in the development of safe, effective, and environmentally friendly natural-based nanomaterials, opening up opportunities for more efficient and sustainable medical and cosmetic products.

Method

The research procedures can be described as follows:

CQDs Synthesis

CQDs synthesis was carried out based on previous research [12]. A total of 500 g of white turmeric was chopped and extracted with 5 L of ethanol at room temperature for 24 h. The resulting extract was filtered and evaporated to remove the ethanol, leaving a liquid white turmeric extract. The white turmeric extract was then hydrothermally processed at 180°C for 4 h to produce CQDs. After the synthesis process, the resulting CQDs were purified by filtration and centrifugation, then dried using a freeze dryer.

After ethanol evaporation, the obtained concentrated white turmeric extract was directly subjected to hydrothermal treatment without further dilution. Therefore, no additional water was added during CQD synthesis, and the extract-to-water ratio was 1:0 (v/v). This information is provided to improve the reproducibility of the synthesis procedure.

DMF Doping

A total of 20 mg of synthesized CQDs was mixed with 10 mL of DMF in a reaction vessel. This mixture was heated at 60-80°C for 2 h to ensure DMF bonding with the CQDs surface, enhancing their antioxidant properties and optical stability.

Following the doping process, the CQDs were thoroughly purified by repeated centrifugation and filtration to remove residual DMF. The objective of using DMF was to introduce nitrogen-containing surface functionalities rather than retaining DMF molecules within the final product. Therefore, the final CQDs were expected to contain nitrogen-doped surface groups while minimizing residual solvent content.

Antioxidant Testing

The percentage of DPPH radical scavenging activity (%) inhibition was calculated using Equation (1):

$$\%Inhibition = \frac{A_o - A_s}{A_o} x100 \qquad (1)$$

where A0 is the absorbance of the DPPH control solution and As is the absorbance in the presence of the sample. The IC_{50} value was subsequently determined from the linear regression plot of percentage inhibition versus sample concentration. IC_{50} represents the concentration required to inhibit 50% of DPPH radicals and was obtained from the regression equation.

$$IC_{50} = \left(\frac{A_{517\ control} - A_{517\ sample}}{A_{517\ control}}\right) \text{x } 100 \qquad (2)$$

Data analysis and evaluation

Data from PL, UV-Vis, and FT-IR measurements were analyzed to assess the absorbance and structure of the CQDs after doping with DMF.

Results and Discussion

CQDs from white turmeric extract were synthesized by hydrothermal method as carbon precursor. At the beginning of hydrolysis, dehydration and decomposition of various carbohydrates occur in the presence of ascorbic acid and produce soluble compounds such as furfural aldehyde, ketone and some organic acids such as acetic, levulinic, formic acid, etc. which act as acid sources for various acid catalytic reactions. Polymerization and condensation of these products convert them into various soluble polymer products. Aromatization and carbonization then take place through condensation and cycloaddition reactions [13]. The formed CQDs were doped with DMF to improve their antioxidant and optical properties. Finally, the white turmeric CQDs doped with DMF were analyzed by FT-IR, PL, and UV-Vis.

The FTIR spectrum of DMF-modified white turmeric CQDs is shown in **Figure 1**. The main absorption bands were observed at approximately 3446, 2926, 1637, 1387, and 705 cm^{-1}. The broad band around 3446 cm^{-1} is attributed to O–H and/or N–H stretching vibrations, indicating the presence of hydroxyl and amine-containing surface groups. The peak at 2926 cm^{-1} corresponds to aliphatic C–H stretching vibrations. The band at 1637 cm^{-1} is assigned to C=O stretching and/or conjugated C=C vibrations within the carbonized structure. The absorption at 1387 cm^{-1} is associated with C–N stretching and/or O–H bending vibrations, suggesting the presence of oxygen- and nitrogen-containing functionalities on the CQD surface. The weak band near 705 cm^{-1} may be related to out-of-plane bending vibrations of aromatic C–H groups. These oxygenated and nitrogen-containing surface groups contribute to the hydrophilic nature and aqueous dispersibility of the CQDs. The observation of N-containing functional groups is also consistent with surface modification by DMF.

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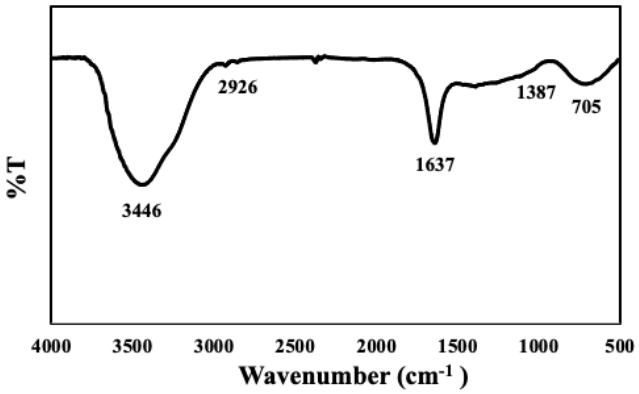

Figure 1. FTIR spectrum of DMF-doped white turmeric CQDs.

The optical absorption spectrum of the CQDs is shown in **Figure 2**. Based on the spectrum, the most prominent absorption feature is observed in the ultraviolet region at approximately 263 nm, which is commonly attributed to the π–π* transition of sp^2-hybridized C=C bonds within the carbon core. No distinct absorption peak at 347 nm can be clearly identified in **Figure 2**. The absorption behavior is consistent with reports of biomass-derived CQDs, where strong UV absorption is mainly associated with conjugated carbon domains and surface oxygen-containing functional groups. Variations in absorption position compared with CQDs derived from garlic peel, tea leaves, coconut shell, or banana peel may arise from differences in precursor composition, carbonization degree, and surface functionalization.

The DPPH assay is based on the reduction of the stable free radical DPPH•, which exhibits a characteristic purple color and strong absorbance at 517 nm. When an antioxidant is present, DPPH• can accept either an electron or a hydrogen atom, resulting in the formation of the reduced species DPPH-H and a corresponding decrease in absorbance. For CQDs, radical scavenging activity is generally attributed to oxygen- and nitrogen-containing surface functional groups, including hydroxyl (–OH), carboxyl (–COOH), carbonyl (C=O), and amino (–NH) groups. These surface functionalities can participate in hydrogen atom transfer (HAT) and single-electron transfer (SET) mechanisms, which neutralize DPPH radicals. In addition, the conjugated sp^2 carbon domains of CQDs may facilitate electron delocalization and stabilize radical intermediates formed during the scavenging process. The observed antioxidant activity of the white turmeric-derived CQDs is therefore likely associated with the combined contribution of surface functional groups and the electronic structure of the carbon core. However, because carbonization can degrade naturally occurring phenolic and flavonoid compounds originally present in white turmeric, the radical scavenging activity of the resulting CQDs may be lower than that of the parent extract. This interpretation is consistent with the antioxidant results obtained in the present study.

A comparison between white turmeric extract and the synthesized CQDs reveals that the extract exhibited substantially stronger antioxidant activity. White turmeric is naturally rich in curcuminoids, flavonoids, phenolic compounds, and other phytochemicals that are well-known hydrogen- and electron-donating antioxidants, which can directly neutralize free radicals and contribute significantly to DPPH scavenging activity. In contrast, the hydrothermal conversion of white turmeric into CQDs involves carbonization and structural transformation processes that may partially degrade or eliminate these bioactive phenolic constituents. Although the resulting CQDs retain oxygen- and nitrogen-containing surface groups capable of participating in radical scavenging reactions, their antioxidant activity is primarily governed by surface chemistry and electronic structure rather than by the original phytochemical composition of the plant extract. Therefore, while CQDs possess measurable antioxidant properties, their radical scavenging performance is lower than that of the parent white turmeric extract. These results suggest that white turmeric extract is a more potent antioxidant source, whereas the CQDs may offer additional advantages such as fluorescence, aqueous dispersibility, and potential applications in bioimaging or delivery systems.

Antioxidant activity was evaluated using the DPPH assay. The IC_{50} values of white turmeric extract and CQDs were 0.13% and 5.03%, respectively (Table 1) [9]. The lower IC_{50} of white turmeric extract indicates stronger antioxidant activity compared to the synthesized CQDs.

Although Vitamin C was used as a reference antioxidant during the DPPH assay, its quantitative results were not included in the present study. Therefore, the comparison with Vitamin C is limited to its role as a standard antioxidant control. Future studies should report the concentration-response data and IC_{50} value of Vitamin C alongside CQDs to enable a more rigorous evaluation of antioxidant performance.

Although nitrogen doping has been reported to enhance the antioxidant performance of CQDs by increasing electron-donating capability and introducing nitrogen-containing

active sites, the present study did not show an improvement in antioxidant activity compared with the original white turmeric extract. This result suggests that the loss of naturally occurring phenolic and flavonoid compounds during hydrothermal carbonization had a greater influence on antioxidant capacity than the potential contribution of nitrogen doping. Therefore, while DMF-derived nitrogen functionalities were successfully introduced as indicated by the presence of C–N and N–H groups in the FTIR spectrum, their effect was insufficient to compensate for the degradation of highly active antioxidant compounds originally present in white turmeric.

The absorption and emission spectra of CQDs are shown in **Figure 3**. From the results, it can be seen that CQDs exhibit a well-resolved peak at around 371 nm, which originates from the C=O bond of carbonyl and/or carboxyl groups in the carbogenic core or COOH group. The PL spectrum in **Figure 3** obtained after UV excitation shows an emission peak at 449 nm. Based on previous studies, this emission can be attributed to the n-σ* (such as C-O-C, C-OH, or C-N), n–π* (in C=O), and π–π* transitions in the graphite core [14].

A limitation of the present study is that the fluorescence quantum yield (QY) of the synthesized CQDs was not experimentally determined. QY is an important parameter for evaluating the efficiency of photon emission and for comparing fluorescent nanomaterials reported in the literature. Although photoluminescence emission at 449 nm confirmed the fluorescent nature of the CQDs, the absence of QY measurements prevents a quantitative assessment of their fluorescence performance. Future studies should include QY determination using an appropriate reference fluorophore to enable a more comprehensive evaluation of the optical properties and potential bioimaging applications of the synthesized CQDs.

Table 1. IC_{50} CQDs of natural-based

No	Sample	IC_{50} (%)	Reference
1	White turmeric extract	0.13	This study
2	White turmeric CQDs	5.03	This study
3	Tea leaves	0.5	[15]
4	Coconut waste	0.75	[16]
5	Ascorbic acid	1.5	[17]
6	Vitamin E	1.3	[18]

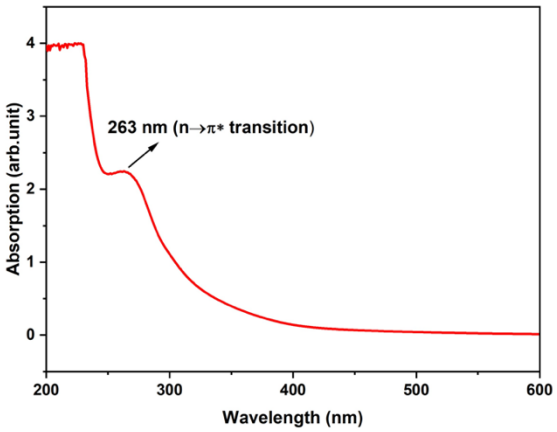

Figure 2. UV-vis DMF-doped white turmeric CQDs.

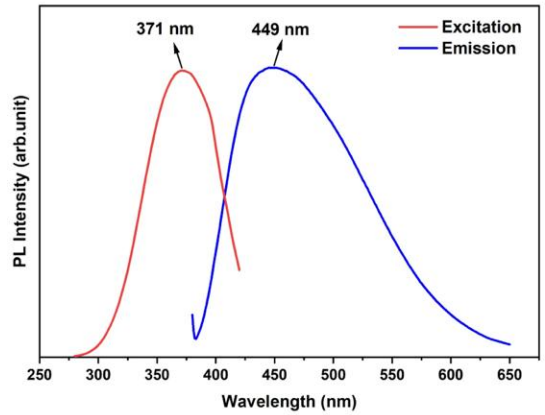

Figure 3. PL DMF-doped white turmeric CQDs.

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Conclusions

This study successfully synthesized CQDs from white turmeric through a hydrothermal method and doping using DMF. FT-IR analysis showed the presence of functional groups such as hydroxyl, carbonyl, amine, and C-N which play a role in increasing the water solubility and surface activity of CQDs. Meanwhile, the UV-Vis and PL characteristics showed typical optical transitions of the C=O and C=C bands which confirmed the formation of carbogenic CQDs with fluorescence emissions at a wavelength of around 449 nm. In the antioxidant test, an increase in IC_{50} was caused by the degradation of active compounds such as flavonoids during carbonization. A limitation of this work is that the fluorescence quantum yield was not measured; therefore, future studies should include QY determination to allow quantitative comparison with other fluorescent CQDs.

Conflicts of interest

"There are no conflicts to declare".

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