ECO-FRIENDLY AND ONE POT SYNTHESIS OF FLUORESCENT CARBON QUANTUM DOTS FROM TEAK TREE LEAVES THROUGH HYDROTHERMAL TREATMENT

By

Jackson Barua, M. Phil

18MCHEM008P

A thesis submitted in partial fulfillment of the requirements for the degree of
MASTER of PHILOSOPHY

Department of Chemistry

CHITTAGONG UNIVERSITY OF ENGINEERING & TECHNOLOGY

JUNE 2024

Declaration

I hereby declare that the work contained in this Thesis has not been previously submitted to meet requirements for an award at this or any other higher education institution. To the best of my knowledge and belief, the Thesis contains no material previously published or written by another person except where due reference is cited. Furthermore, the Thesis complies with PLAGIARISM and ACADEMIC INTEGRITY regulation of CUET.

Jackson Barua
18MCHEM008P
Department of Chemistry
Chittagong University of Engineering & Technology (CUET)

Dedication

To my beloved parents especially my mother Minakhi Barua.

List of Publication

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Approval/Declaration by the Supervisor

This is to certify that **Mr. Jackson Barua** has carried out this research work under my supervision, and that he has fulfilled the relevant Academic Ordinance of the Chittagong University of Engineering and Technology, so that he is qualified to submit the following Thesis in the application for the degree of Master of PHILOSOPHY in Chemistry. Furthermore, the Thesis complies with the PLAGIARISM and ACADEMIC INTEGRITY regulation of CUET.

Dr. Arup Kumer Roy
Associate Professor
Department of Chemistry
Chittagong University of Engineering & Technology

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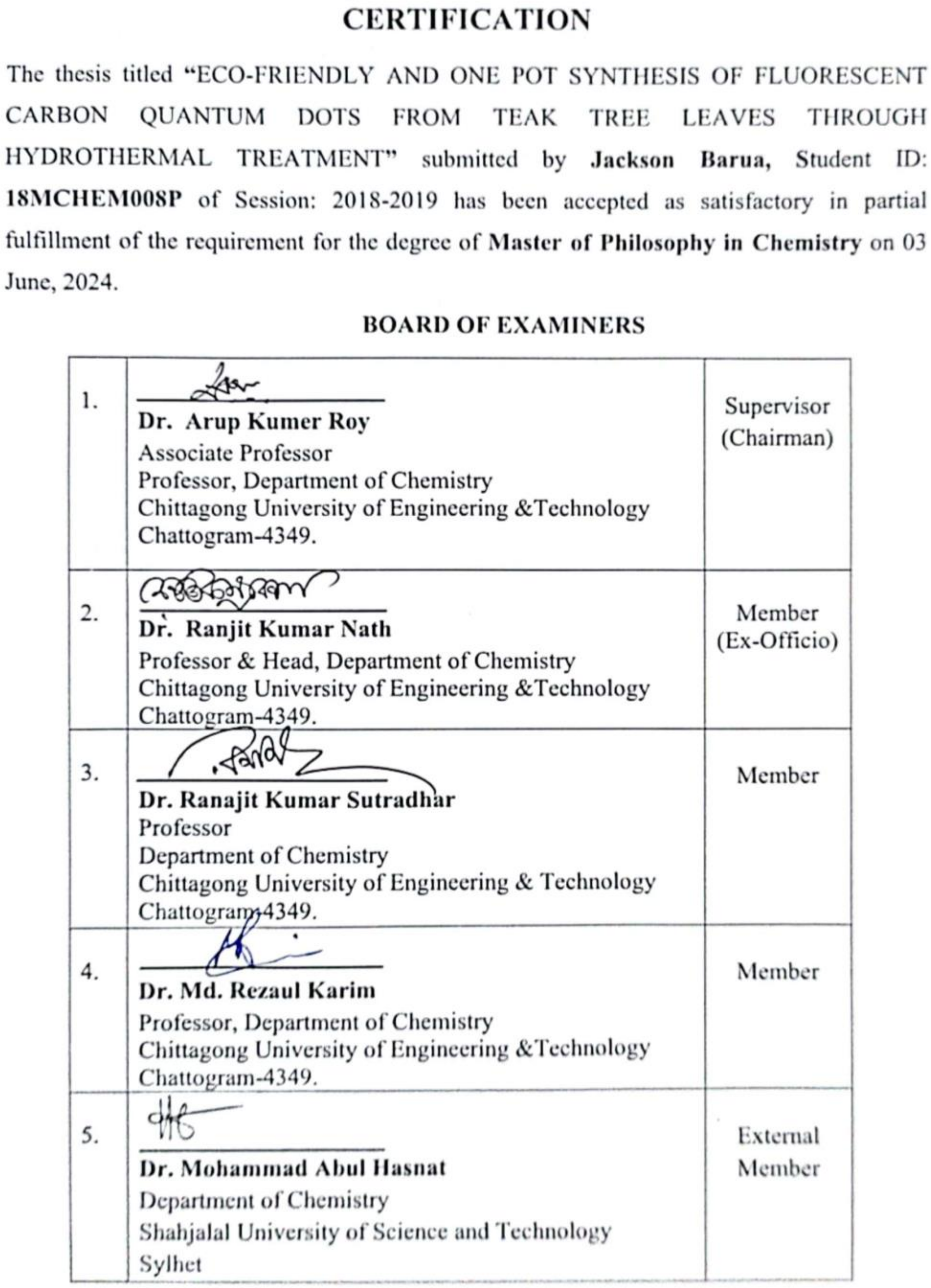

CERTIFICATION

The thesis titled "ECO-FRIENDLY AND ONE POT SYNTHESIS OF FLUORESCENT CARBON QUANTUM DOTS FROM TEAK TREE LEAVES THROUGH HYDROTHERMAL TREATMENT" submitted by **Jackson Barua,** Student ID: **18MCHEM008P** of Session: 2018-2019 has been accepted as satisfactory in partial fulfillment of the requirement for the degree of **Master of Philosophy in Chemistry** on 03 June, 2024.

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Abstract

This study describes the synthesis of environmentally friendly fluorescent carbon quantum dots (CQDs) derived from teak tree leaves (*Tectona grandis*) using a straightforward one-pot hydrothermal method. This method offers a sustainable approach to the synthesis of CQDs by utilizing renewable biomass resources. The synthesized CQDs exhibit nano-sized particles and possess strong fluorescence characteristics. Treatment with H_2O_2 facilitates the breakdown of the leaves structure and the formation of functional groups on their surface which enhanced their potential for the degrading hazardous chemical dyes like methylene blue (MB). The synthesized samples were extensively characterized using UV-Vis spectroscopy, photoluminescence spectroscopy, FTIR for functional group analysis, and Zeta potential measurements. Surface morphology and particle size were analyzed through TEM, SEM, EDX, and Histogram analysis. These CQDs demonstrate outstanding photocatalytic activity, achieving an impressive 98% degradation efficiency when exposed to visible light irradiation. Chemical oxygen demand (COD) analysis confirmed the high efficiency of photodegradation under visible light conditions. The combination of their eco-friendly synthesis method and superior photocatalytic performance underscores the potential of CQDs derived from teak as effective and sustainable materials for applications in environmental remediation. This research contributes to advancing the development of renewable nanomaterials for addressing environmental pollutants, suggesting a promising future for biomass-derived CQDs in various water treatment technologies and beyond.

বিমূর্ত

এই গবেষণাটি সেগুন গাছের পাতা থেকে এক-পাত্র হাইড্রোথার্মাল পদ্ধতিতে প্রাপ্ত পরিবেশবান্ধব কার্বন কোয়ান্টাম ডটের বর্ণনা করে । এই পদ্ধতিতে নবায়নযোগ্য উদ্ভিজ্জ উপাদান ব্যবহার করে কার্বন কোয়ান্টাম ডট তৈরি করা হয়েছে। কার্বন কোয়ান্টাম ডট গুলো ন্যানো-আকারের এবং উজ্জ্বল আলোক বর্ণ প্রদর্শন করে। হাইড্রোজেন পারক্সাইডের সাথে বিক্রিয়ায় সেগুন গাছের কাঠামোর ভেঙ্গে, তাদের পৃষ্ঠে কার্যকরী মূলক যুক্ত করতে সাহায্য করে, যা মিথিলিন ব্লুর মতো বিপজ্জনক রাসায়নিক রঞ্জক গুলো অবক্ষয়ের সম্ভাবনাকে বাড়ায়। কার্বন কোয়ান্টাম ডট ইউ. ভি. বর্ণালীবিক্ষণ যন্ত্র, ফোটোলুমিনেসেন্স বর্ণালীবিক্ষণ যন্ত্র, এফ.টি.আই.আর এবং জিটা পটেনসিয়ালের মাধ্যমে পরীক্ষা করা হয়েছে এছাড়াও টি.ইএ.ম, এস.ই.এম, ই.ডি.এক্স এবং হিস্টোগ্রাম বিশ্লেষণের মাধ্যমে কার্বন কোয়ান্টাম ডটের কণার আকার নিরীক্ষণ করা হয়েছে। এই কার্বন কোয়ান্টাম ডটগুলো দৃশ্যমান আলোতে ৯৮% মিথিলিন ব্লুর গঠন ভেঙ্গে দিয়ে তার কার্যকারিতা নষ্ট করে দেয়, যা খুবই আকর্ষণীয়। এছাড়া রাসায়নিক অক্সিজেন চাহিদা বিশ্লেষণের মাধ্যমেও মিথিলিন ব্লুর ফটোডিগ্রেডেশন নিশ্চিত করা হয়েছে। পরিবেশ-বান্ধব এবং উচ্চ আলোর অনুঘটক কার্মক্ষমতার বিবেচনায় সেগুন থেকে প্রাপ্ত কার্বন কোয়ান্টাম ডট খুবই কার্যকরী এবং টেকসই উপকরণ হিসাবে পরিবেশগত অন্যান্য দূষণকারী দ্রব্যগুলির মোকাবেলা করবে। এই গবেষণাটি নবায়নযোগ্য ন্যানোমেটারিয়ালগুলোর বিকাশে অবদান রাখবে এবং বিভিন্ন জল পরিশোধন প্রযুক্তি এবং এর বাইরেও জৈব উপাদান থেকে প্রাপ্ত কার্বন কোয়ান্টাম ডটগুলোর জন্য একটি আশাবাদী ভবিষ্যতের পরামর্শ দিবে।

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Nomenclature

Symbols	Elaboration
e.g.	For example
etc.	Etcetera
et al.	And others

Acronyms and Abbreviations

Acronyms	Abbreviations
nm	Nanometer
mg/L	Milligram per Liter
mL	Milliliter
CNT	Carbon Nanotube
CQDs	Carbon Quantum Dots
GQDs	Graphene Quantum Dots
BCQDs	Biomass-Derived Carbon Quantum Dots
SiNPs	Silica Nanoparticles
MB	Methylene Blue
UV-Vis	UltraViolet -Visible
PL	Photoluminescence
FTIR	Fourier Transform Infrared
EDX	Energy Dispersive X-Ray Analysis
FE-SEM	Field-Emission Scanning Electron Microscopy
TEM	Transmission Electron Microscopy
PSDH	Particle Size Distribution Histogram
PTFE	Polytetrafluoroethylene
TCSPC	Time-Correlated Single Photon Counting

Chapter 1: INTRODUCTION

1.1 BACKGROUND

Carbon quantum dots (CQDs) have emerged as a fascinating class of carbon-based nanomaterials with unique optical, electronic, and chemical properties (Bhatt et al., 2018). CQDs are typically small carbon nanoparticles with sizes less than 10 nm, possessing quantum confinement effects that lead to tunable photoluminescence. Their size-dependent optical properties, along with their high surface area, chemical stability, and biocompatibility, make them highly versatile in both fundamental research and practical applications. Unlike conventional semiconductor quantum dots, which are typically composed of heavy metals, CQDs are composed solely of carbon and are therefore less toxic and more environmentally friendly, opening up opportunities for safe and sustainable technologies.

CQDs normally exhibit a heterogeneous distribution of sp^2 and sp^3 carbon skeleton with heteroatomic functional groups which leads to alterations in their properties (Pillar-Little et al., 2018). These surfaces can be decorated with a variety of functional groups, including $-NH_2$, $-C=O$, $-OH$ and $-COOH$ **(Figure 1.1)** (Baskar Thangaraj et.al.).

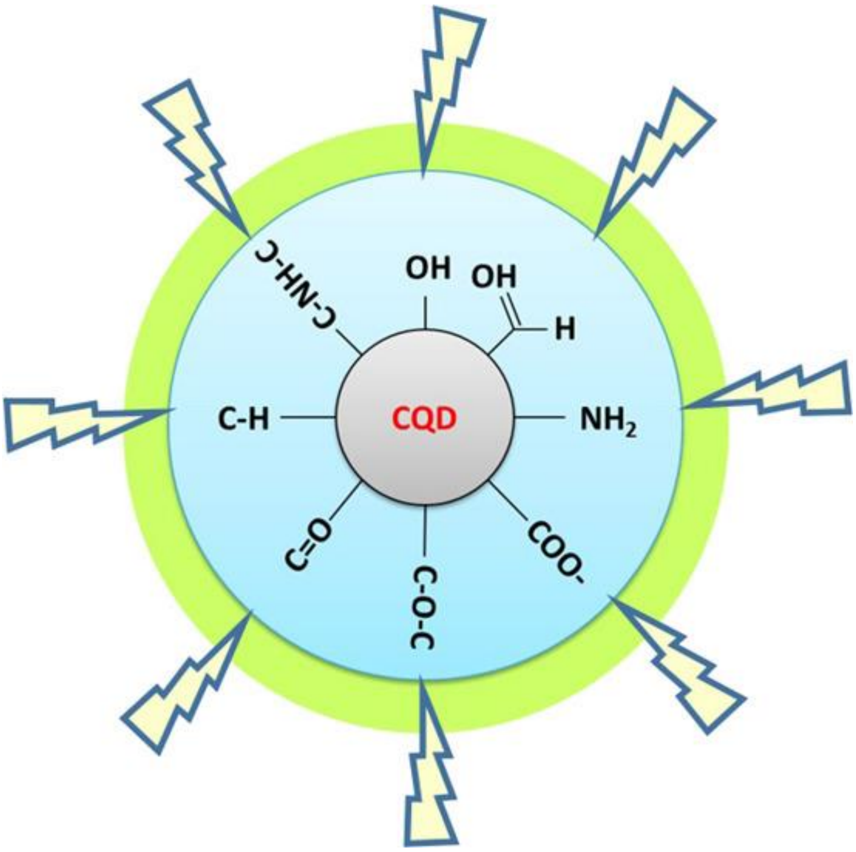


Figure 1.1: Functional groups of CQDs (Lim et al., 2015)

In 2004, Xu et al. accidentally discovery carbon quantum dots (CQDs) while purifying single-walled carbon nanotubes. This finding prompted significant research efforts to explore and capitalize on the fluorescent properties exhibited by CQDs (Xu. et al., 2004). In 2006, Sun et al. reported a significant advancement in the field of CQDs by introducing a method for preparing luminescent CQDs through laser ablation coupled with surface passivation. This pioneering work marked a pivotal moment in CQD research, as it demonstrated a novel approach to synthesizing CQDs with controlled luminescent properties (Sun et al., 2006).

The discovery of graphene quantum dots (GQDs) is attributed to the work of Pan et al. in 2010. In their pioneering study, Pan and colleagues demonstrated a method to produce GQDs from graphene oxide (GO) through a chemical exfoliation process. This method involved oxidizing graphene sheets to GO followed by cutting them into small nanoscale fragments using strong acid treatment. These fragments, known as GQDs, exhibited unique optical and electronic properties distinct from both graphene and graphene oxide (Pan. et al., 2010). In this same year, Wang et al. firstly, developed both water and oil soluble CQDs from citric acid in noncoordinating solvent (Wang et al., 2010).

Next, Sahu et al. achieved the first synthesis of carbon quantum dots (CQDs) directly from biomass product orange juice in 2012. These biomass-based CQDs are environmentally friendly and offer a high utilization of undervalued biomass resources.

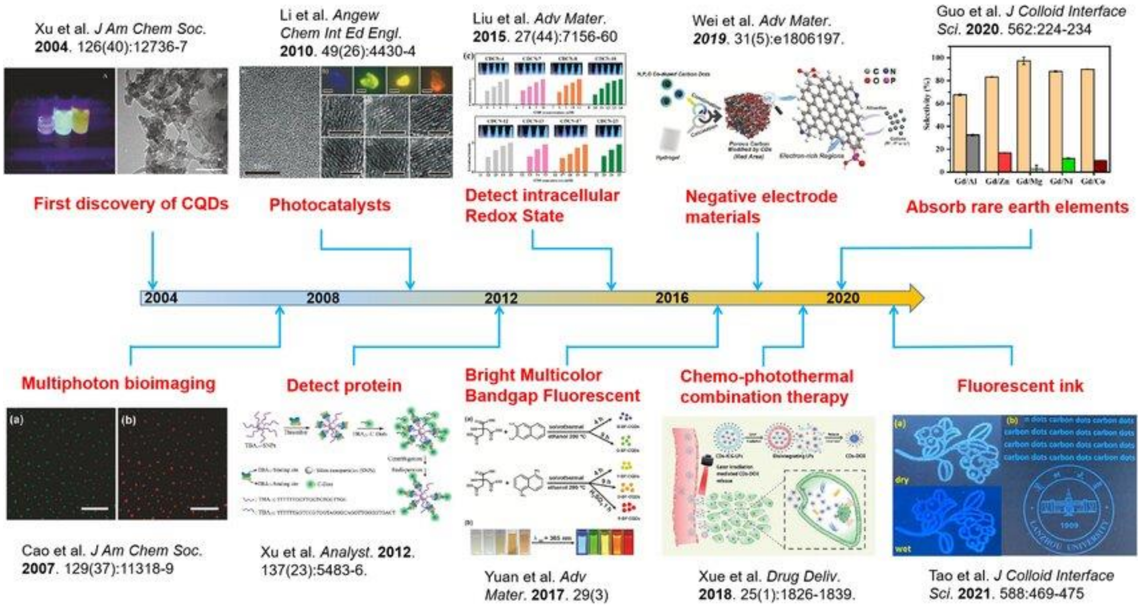


Figure 1.2: The development history of CQDs. (Cai et al., 2021)

The synthesis of CQDs has evolved significantly, encompassing diverse methods such as laser ablation, chemical oxidation, hydrothermal treatment, and microwave-assisted techniques. Each method offers distinct advantages for controlling the size, surface chemistry, and optical properties of CQDs, enabling tailored applications in fields ranging from bioimaging and sensing to optoelectronics and environmental remediation. Moreover, functionalization strategies allow for the modification of CQDs with specific groups, enhancing their stability and enabling targeted applications in biomedicine and nanotechnology.

In recent years, CQDs have gained significant attention due to their potential applications in various fields including optoelectronics, bioimaging, sensing and catalysis. (**Figure 1.3**) Unlike traditional semiconductor quantum dots, such as, Cadmium Selenide (CdSe), (Singh et al., 2018) Zinc Sulfide (ZnS), (Sharma et al., 2021) Zinc Selenide (ZnSe) (Toufanian et al., 2021) which are typically composed of heavy metal elements. On the contrary, CQDs offer several advantages including superior biocompatibility, low toxicity, facile synthesis, and environmental friendliness to make them promising candidates for diverse applications (Zhang et al., 2016).

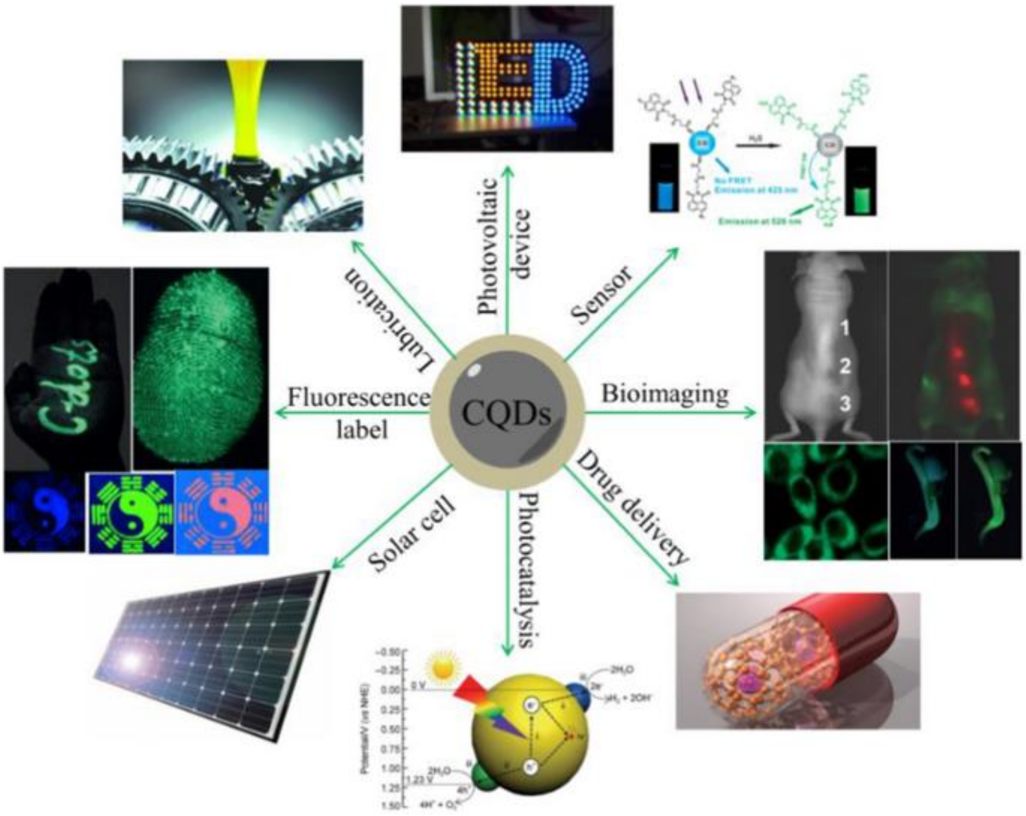


Figure 1.3: Various applications of CQDs. (Tang et al., 2021)

At present, researchers pay attention biomass derived materials to prepare CQDs. Biomass is an excellent carbon sources and eco-friendly natural products compared to other carbon related sources. They have various advantages, including low cost, easy to obtain, eco-friendly, low toxic and abundant in nature. To prepare biomass based CQDs various sources, including fruits (Meng et al., 2019) and vegetables, leaves, agricultural and forestry wastes etc. **Figure 1.4.**

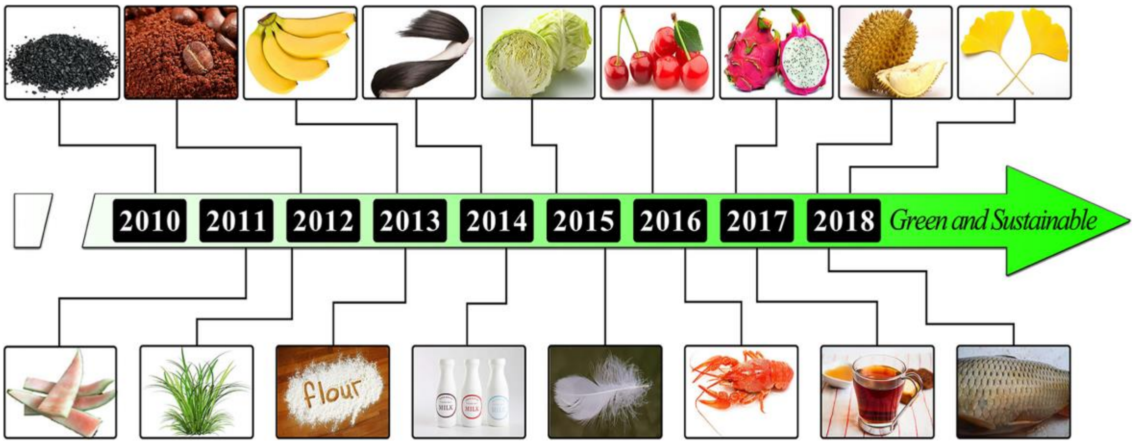


Figure 1.4: Development map of CQDs in recent year.

To date, numerous methods have been proposed for the preparation of CQDs, including microwave irradiation, electrochemical oxidation, laser ablation, thermal oxidation and pyrolysis. However, these methods often have several limitations such as restricted spectral efficiency, low yield, lack of size control and the requirement for toxic chemicals or high temperatures.

To overcome this, we prepared environmentally friendly and high catalytic efficiency CQDs with the assistance of H_2O_2 and applied for the degradation of methylene blue.

1.2 AIMS AND OBJECTIVES

- To Utilize teak tree leaves as a sustainable source to produce CQDs via hydrothermal treatment.
- Perform comprehensive characterization including spectroscopic (UV-Vis absorption, PL spectroscopy), structural (TEM, SEM), and chemical (FTIR) analyses to understand the size, morphology, chemical composition, and optical properties of the CQDs.

- Study the photocatalytic activity of teak-derived CQDs by quantifying the degradation efficiency (%) of methylene blue under visible light irradiation.
- Contribute novel insights and methodologies for the synthesis of eco-friendly fluorescent CQDs from biomass sources, promoting green chemistry principles and sustainable material development.

1.3 RESEARCH GAP

Despite the numerous studies on synthesizing carbon quantum dots (CQDs) from various biomass sources, there remains a significant gap in the literature regarding the synthesis of CQDs specifically from teak leaves using H_2O_2 as a key reagent. While several articles have explored CQD synthesis from biomass derivatives, such as sugarcane bagasse, rice husk, and other plant sources, the utilization of teak leaves for CQD synthesis with H_2O_2 has received limited attention.

Teak leaves possess distinct chemical compositions that offer potential for producing functionalized carbon structures which making them an underexplored resource for enhancing the properties of CQDs. Utilizing H_2O_2 in this context serves to break down the carbon framework of teak leaves and introduce functional groups. These additions not only enhance fluorescence but also activate the degradation capabilities crucial for applications such as the photodegradation of methylene blue (MB). This innovative approach represents a novel direction within the realm of carbon nanomaterial research.

Chapter 2: LITERATURE REVIEW

2.1 LITERATURE BACKGROUND

Quantum dots (QDs) are nanoscale semiconducting particles with unique electronic and optical properties. They are typically made of materials such as cadmium selenide (CdSe), cadmium sulfide (CdS) or indium phosphide (InP) and are only a few nanometers (nm) in size (Kumar et al., 2018).

The history of quantum dots (QDs) can be traced back to the early 1980s when the term "quantum dot" was first introduced by Russian physicist Alexei Ekimov and American chemist Louis Brus while studying the optical properties of semiconductors (Kovačova et al., 2020) and observed that when the size of a semiconductor crystal was reduced to a few nms, it exhibited unique properties not found in bulk materials. During that time, they were able to produce CdSe QDs with sizes ranging from 2 to 10 nm. The CdSe QDs were found to have a unique electronic structure, with quantized energy levels that could be tuned by varying the size of the QD (Badawi et al., 2013).

One of the key features of quantum dots is that they exhibit quantum confinement, which means that the electronic properties of the particle are influenced by its small size. This leads to unique properties such as a discrete energy spectrum and tunable fluorescence emissions, which depend on the size, shape, and composition of the quantum dots. Due to their unique properties, quantum dots have found applications in a wide range of fields, including electronics (Kim et al., 2017) , biomedical imaging (Gil et al., 2021) , photovoltaics (Nozik et al., 2010), and lighting (Anc et al., 2012).

They can be used as fluorescent labels for imaging biological structures or as light emitters in electronic displays. They have also been investigated for their potential use in quantum computing and quantum cryptography.

However, the use of these types of quantum dots has raised environmental and safety concerns due to their potential toxicity. Efforts are underway to develop safer and more sustainable materials for quantum dots those made of silicon or carbon-based materials.

2.2 TYPES OF QUANTUM DOTS

There are various types of quantum dots, each with its unique properties and advantages (Zhang et al., 2015). (**Figure 2.1)**

2.2.1 Alloy or Core type Quantum Dots (QDs): Alloy or Core type quantum dots are semiconductor nanoparticles generally composed of Cadmium Selenide (CdSe) or Zinc Sulfide (ZnS). They are characterized by their narrow emission spectra, high quantum yield and long photobleaching lifetime. Due to the distinct fluorescence spectra, they are widely used in biological imaging, nano-sensor-based device and so on.

2.2.2 Fluorescent Silica Nanoparticles (SiNPs): Silica nanoparticles consist of ultra-monodisperse spherical silica nanoparticles surrounded by a fluorescent dye. They are extensively used in a broad range of biocompatible applications and by functionalizing with targeting ligands making them useful candidates in drug delivery and biomedical imaging**.**

2.2.3 Carbon Quantum Dots (CQDs): Carbon quantum dots are small carbon-based fluorescent nanoparticles. They are generally less than 10 nm in size and exhibit unique optical properties such as high quantum yield and photostability. The unique biological properties such as good biocompatibility, low toxicity entrust them with promising applications in biosensor, bioimaging, drug delivery and catalytical applications.

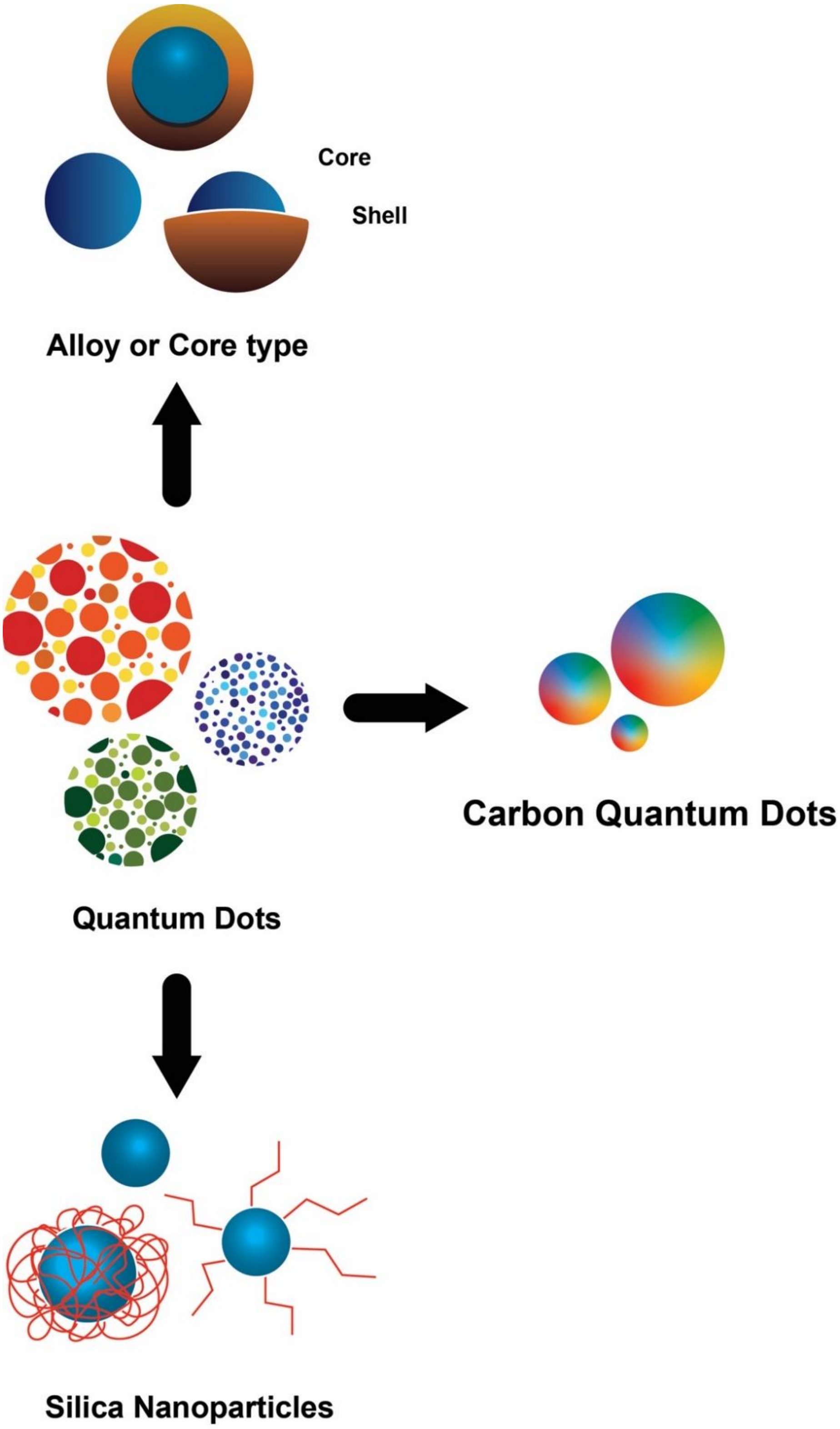


Figure 2.1: Different types of quantum dots.

2.3 TYPES OF CARBON-BASED DOTS

Depending on their structure, carbon-based dots are categorized into three distinct classes as depicted in **Figure 2.2** (Han et al., 2018).

a) Graphene Quantum Dots

b) Carbon nano Dots or Carbon Quantum Dots

c) Polymer Dots

2.3.1 Graphene Quantum Dots: Graphene quantum dots (GQDs) are composed of one or a few layers of graphene and are characterized by chemical groups located on their edges. They are less than 100 nm in size. They are highly biocompatible and photostable. (Wang et al., 2015)

2.3.2 Carbon Quantum Dots: Carbon quantum dots (CQDs) are zero-dimensional fluorescent nanomaterials. They are usually amorphous in structure. (Lim et al., 2015)

CQDs can be synthesized from a variety of carbon sources, including:

a) **Carbonaceous materials:** It can be synthesized from carbonaceous materials such as carbon black, graphite, activated carbon, and carbon nanotubes (CNT).

b) **Biomass:** It can be synthesized from biomass sources such as sugarcane bagasse, coffee grounds, and fruit peels.

The carbon nanoparticles consist of various molecules such as, oxygen (O), nitrogen (N), sulfur (S), phosphorus (P), and chlorine (Cl) into their carbon skeletons.

2.3.3 Polymer Dots: Polymer Dots are comprised of linear polymer or polymer chains into the carbon structure through either cross-linking or aggregation process (Tomczak et al., 2009).

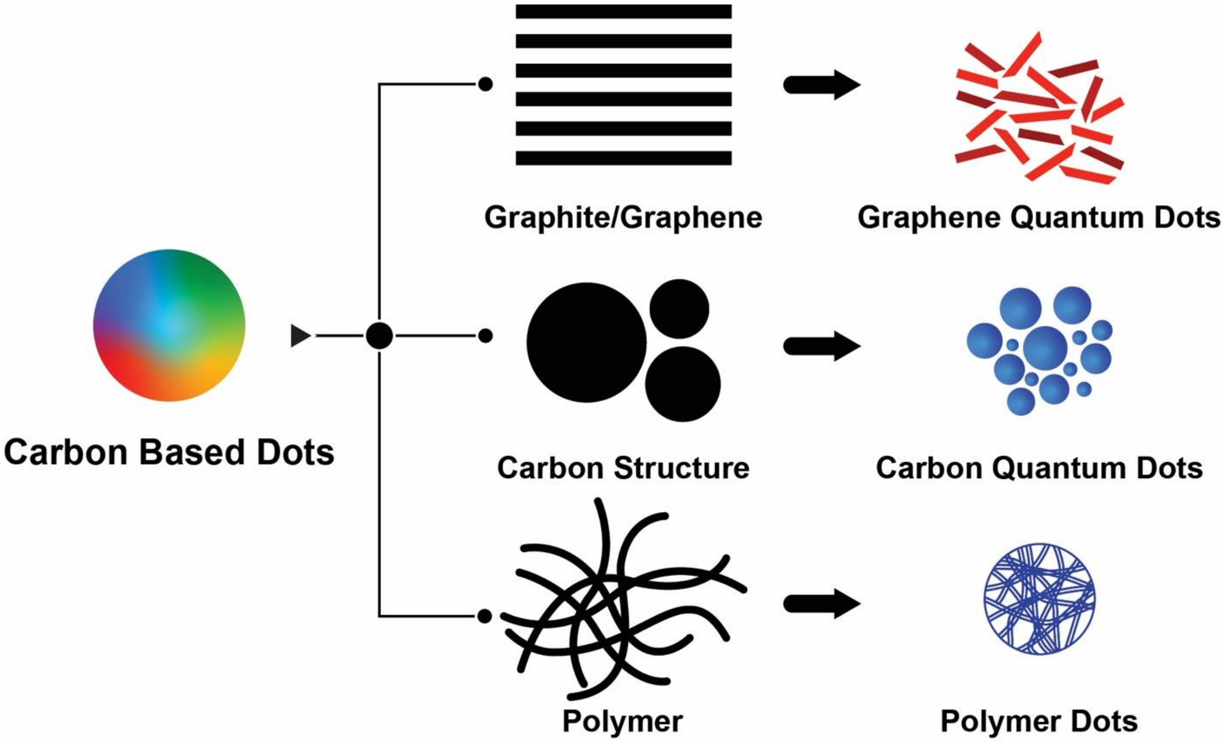


Figure 2.2: The three types of carbon-based dots.

2.4 SYNTHETIC APPROACHES OF CARBON QUANTUM DOTS

CQDs are synthesized based on top-down (cutting bulk carbon materials) and bottom-up (fusing tiny or atomic size molecules). The top-down approach including hydrothermal synthesis, laser ablation, ultrasonic-assisted treatment to generate CQDs. The bottom-up approach including Arc discharge, electrochemical method and microwave-assisted have been developed to utilize nanoscale structure (Zuo et al., 2016). (**Figure 2.3**)

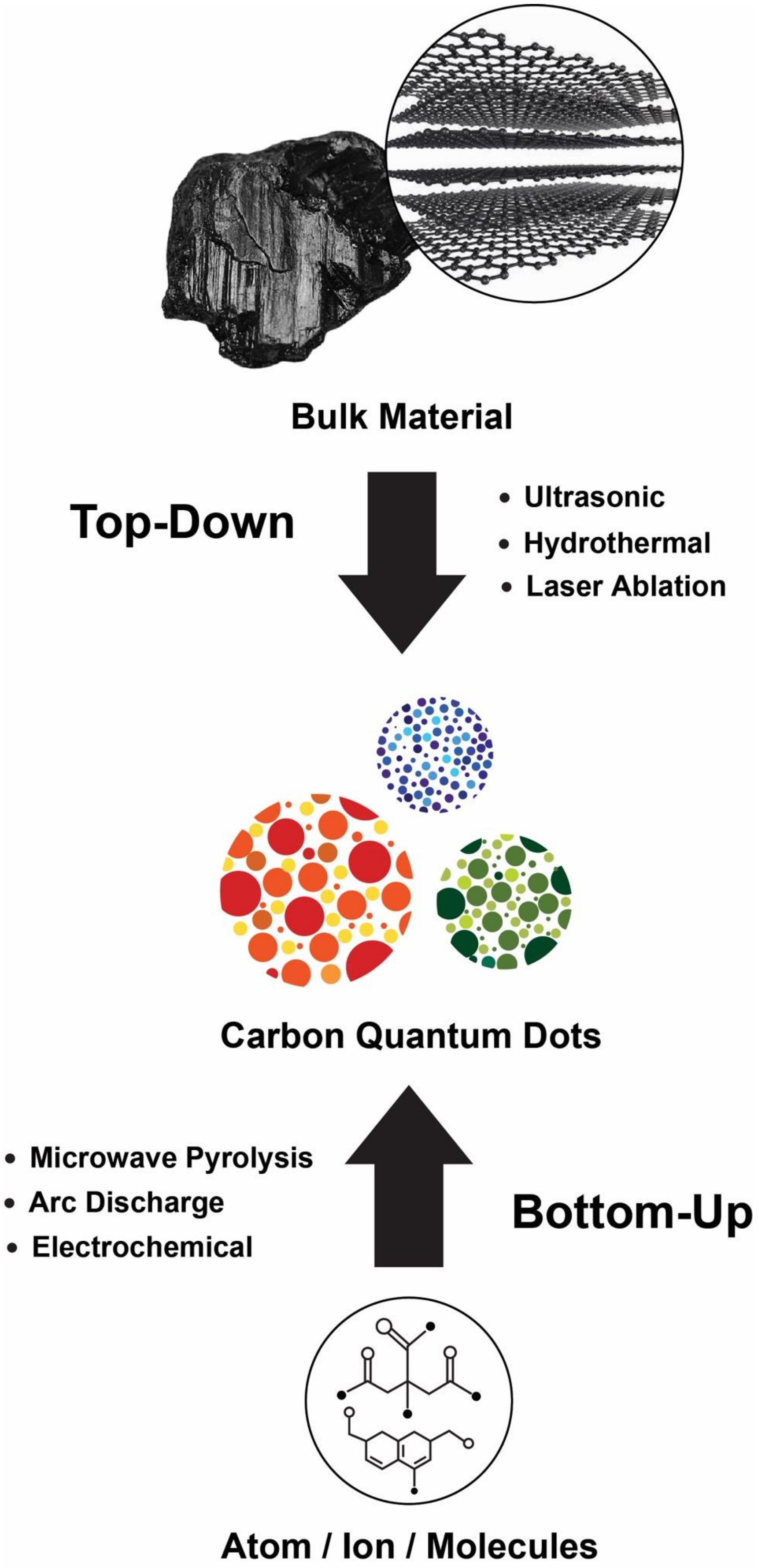


Figure 2.3: The synthetic approach of carbon quantum dots.

2.5 SYNTHESIS METHODS OF CARBON QUANTUM DOTS

There are several methods for synthesizing carbon quantum dots (CQDs), including:

2.5.1 Hydrothermal synthesis: This strategy involves heating a carbon source under high pressure and temperature in the water solution. This method is a low-cost, non-toxic, and environmentally friendly synthesis route to produce CQDs. The resulting CQDs show high quantum yield and good photoluminescence properties. (Hu et al., 2010)

2.5.2 Microwave-assisted synthesis: In this method, a carbon material such as an organic compound is mixed with a solvent and then heated using microwave irradiation. The reaction generates CQDs with good photoluminescence properties in a short time. (Feng et al., 2015)

2.5.3 Electrochemical synthesis: Electrochemical synthesis is a controlling method to prepare CQDs using various large carbon materials as precursors. This method involves using an electrode to oxidize a carbon source in a solution. The resulting reaction generates CQDs with good photoluminescence properties. (Li et al., 2010)

2.5.4 Laser ablation: In this method, CQDs are prepared by the laser ablation of a carbon target in the presence of water vapor with inert gas at different temperatures and pressures. The resulting CQDs have good photoluminescence properties and can be easily functionalized (Hu et al., 2011).

2.5.5 Pyrolysis method: In the pyrolysis approach, macroscopic carbon precursors are heated to a high temperature in the presence of inert gas. The resulting reaction is conducted in a short time and is easy to operate with scalable production (Wang et al., 2016).

2.5.6 Ultrasonic-assisted synthesis: This method involves using ultrasonic waves to break down a bulky, agglomerate carbon source into CQDs without changing intrinsic properties. The ultrasonic treatment is widely used to disperse nanoparticles into liquid and homogenize NPs dispersions (Park et al., 2014).

The choice of synthesis method depends on the desired properties of the CQDs and the intended application. Each method has its advantages and limitations as well as optimization of the reaction conditions is critical to achieve the desired properties of the CQDs.

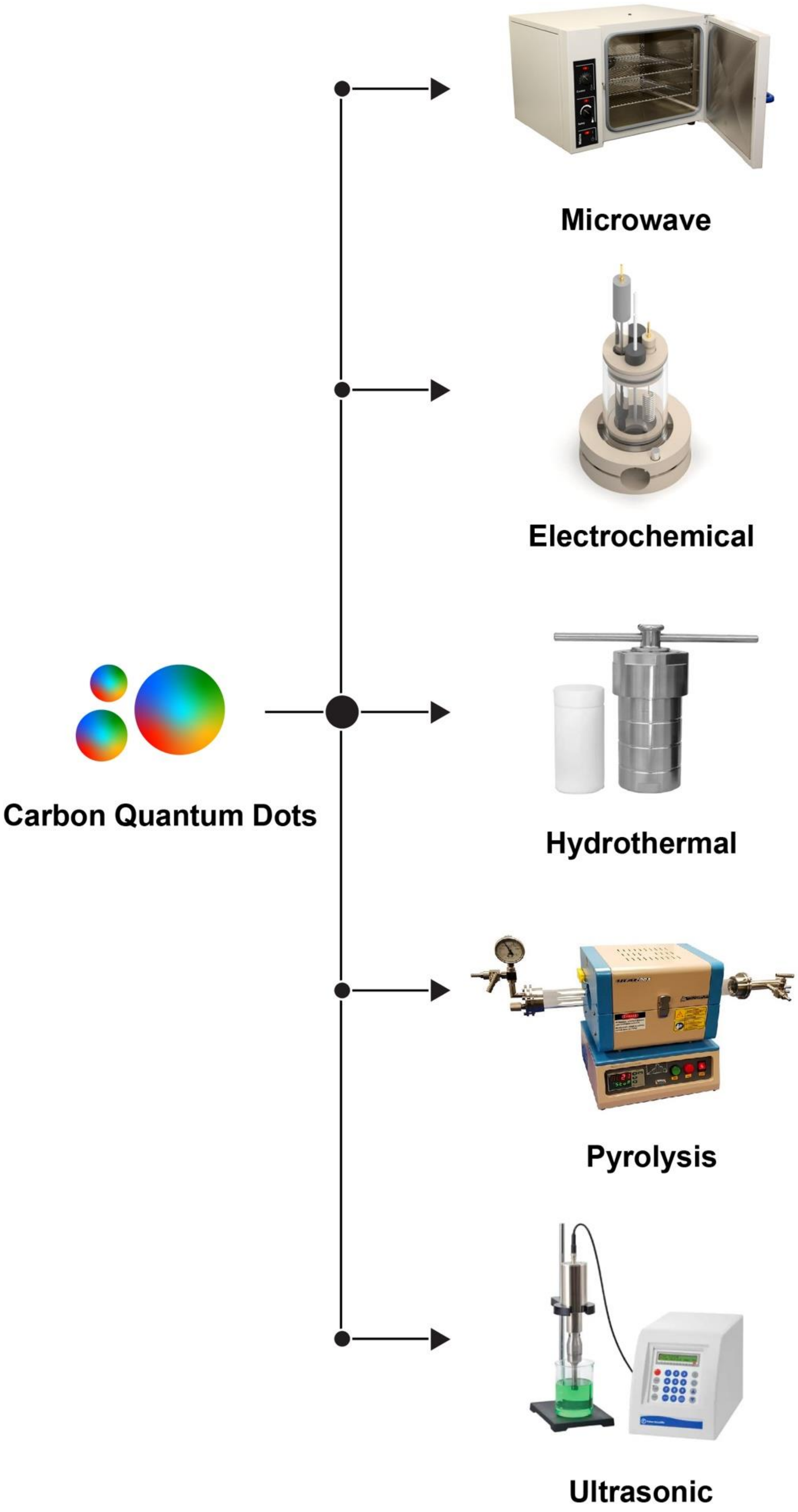


Figure 2.4: Different pathways of preparation of carbon quantum dots.

2.6 BIOMASS-DERIVED CARBON QUANTUM DOTS

Biomass plays a vital role in the synthesis of CQDs on a large scale. Due to their environmentally friendly, low-cost, and renewable nature, biomass-derived CQDs (BCQDs) are promising candidates for a wide range of applications. To date, various biomass-based starting materials have been developed for preparing CQDs. Such as,

2.6.1 Leaves-derived CQDs:

Leaves-derived CQDs performed as a promising candidate in the realm of the quantum dots family.

2.6.2 Vegetable-derived CQDs:

Vegetable-derived CQDs offer a sustainable and environmentally friendly route for the synthesis of BCQDs with diverse applications. The synthesis process typically involves the pyrolysis or hydrothermal assisted synthesis by vegetable precursors including carrots, (Liu et al., 2017) cabbage, (Alam et al., 2015) sweet potato, (Shen et al., 2017) cucumber juice, (Wang et al., 2014) and so on. Due to their biocompatibility, low toxicity, and abundance, vegetable-derived CQDs hold immense potential in various fields including bioimaging (Li et al., 2019) , sensing (Xu et al., 2015), drug delivery (Mehta et al., 2017) and photocatalysis (Yu et al., 2019).

2.6.3 Fruit-derived CQDs:

CQDs derived from fruit precursors are used for mass production and low-cost materials. Fruit contains a significant amount of water, sugar and many health-promoting vitamins and essential other components. Fruit-based CQDs are synthesized by a simple hydrothermal method with various fruits as carbon sources, such as lemon (Oza et al., 2015), pomegranate (Kasibabu et al., 2015), durian (Wang et al., 2018), apple (Mehta et al., 2015), dragon fruit (Arul et al., 2021) and so on.

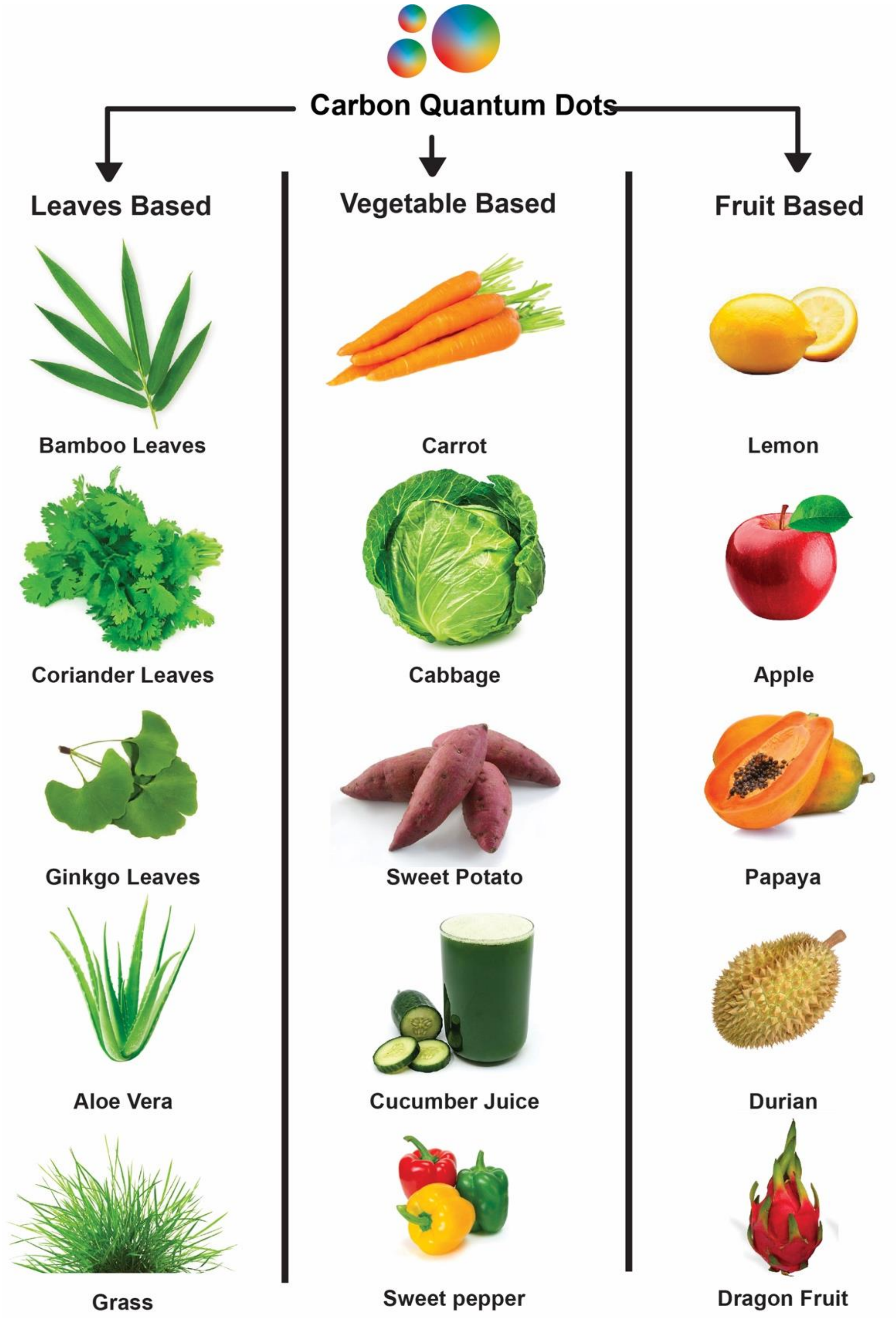


Figure 2.5: Carbon quantum dots derived from different biomass products.

2.7 GENERAL APPLICATIONS OF CARBON QUANTUM DOTS

Carbon quantum dots (CQDs) have a range of potential applications due to their unique optical and physical properties, as well as their biocompatibility and low toxicity. Some of the applications of CQDs include:

2.7.1 Bioimaging: CQDs have excellent photoluminescence properties and can be used as fluorescent probes for bioimaging applications. Due to low cytotoxicity, biocompatibility and high-water solubility CQDs can be functionalized for targeted imaging of specific cells or tissues. These CQDs can also serve as bright and stable probes for visualizing biological structures and processes (Subramania et al., 2023).

2.7.2 Sensing: The outstanding photoluminescence properties of CQDs offer significant potential in sensing applications. It can be used as a sensing agent due to its potential sensing signal for the detection of various analytes such as metal ions, biomolecules, and pollutants (Nazri et al., 2021).

2.7.3 Photocatalysis: CQDs have gained considerable attention in the field of photocatalysis owing to their ability to absorb visible light, exhibit up-conversion luminescence, and rich functional groups. As a photocatalyst, CQDs have been shown to have excellent photocatalytic activity for the degradation of organic pollutants and making them a promising candidate for use in environmental remediation (Gao et al., 2022).

2.7.4 Energy storage: CQDs can be used as electrode materials in photovoltaic energy storage devices such as supercapacitors and batteries due to their high surface area and conductivity (Sikiru et al., 2023).

2.7.5 Drug delivery: CQDs are used in a wide range of biological applications in ocular diseases, drug delivery in cancer, brain disorders, and infectious diseases. CQDs are eco-friendly, biocompatible, and less toxic making them excellent nanocarrier systems for targeted delivery (Kaurav et al., 2023).

The unique properties of CQDs have led to intense research and development in both academia and industry, and they are expected to have a wide range of applications in the future.

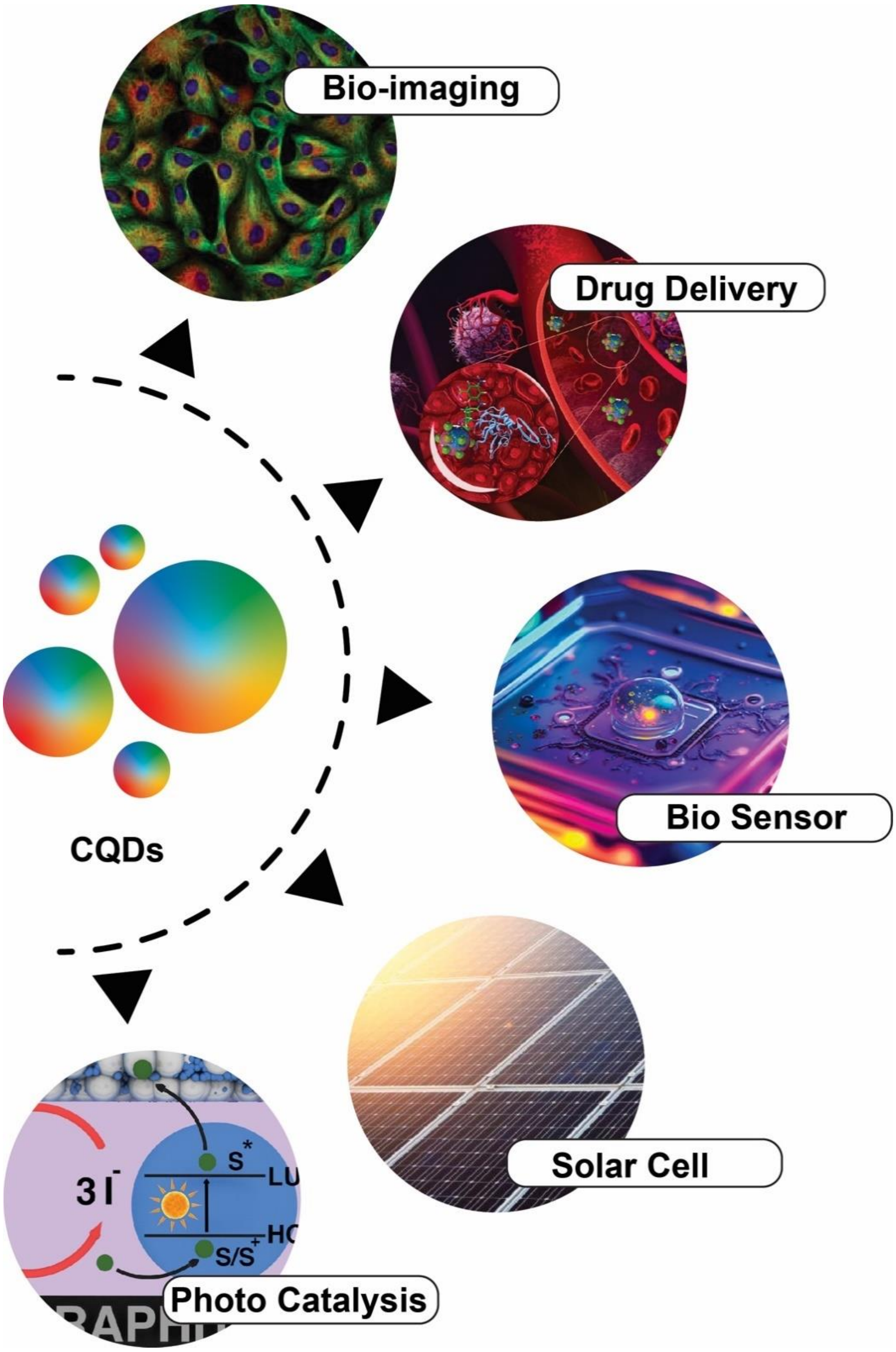


Figure 2.6: Various applications of carbon quantum dots.

Chapter 3: MATERIALS AND METHODOLOGY

3.1 CHEMICALS AND REAGENTS

Analytical grade hydrogen peroxide (H_2O_2) (30%) was purchased from Sigma Aldrich. Dried teak tree (*Tectona grandis L. f*) leaves were collected near the Chittagong University of Engineering and Technology area in the Chattogram region of Bangladesh. Acetone (C_3H_6O) and ethanol (C_2H_5OH) were purchased from Sigma-Aldrich and were used without further purification. Methylene Blue (MB) was purchased from PT. SMART LAB.DI water was used throughout all segments in this experiment.

3.2 APPARATUS

- Polypropylene (PPL) lined Hydrothermal Autoclave
- 0.3 mm Stainless Steel Sieve
- Digital Balance Machine
- Hot Plate Magnetic Stirrer (MS-H380-Pro, USA)
- Centrifuge Machine (CTF-TH16, China)
- Bath Sonicator (Powersonic 405, South Korea)
- LyoQuest laboratory freeze dryers (Telstar)
- Muffle Furnace (Carbolite, ELF 11/14B)
- Laboratoy Drying Oven (Lenton Thermal Designs WF60)
- Vacuum Filtration
- High Power Xenon Light Source (PLS-SXE300E, China)

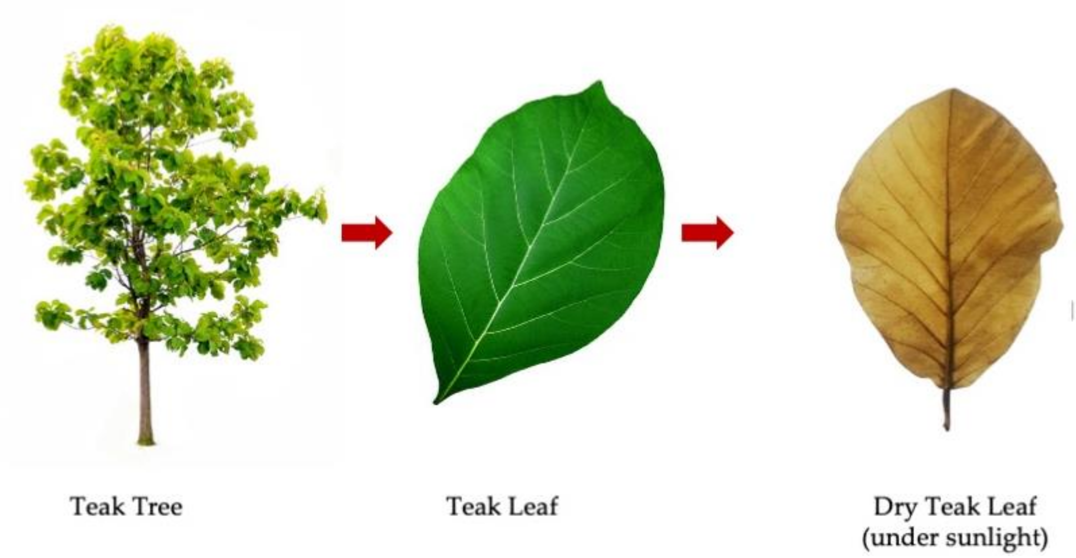
3.3 EXPERIMENTAL

3.3.1 Collection of Plant Leaves

The teak tree (*Tectona grandis)* leaves were collected near the Chittagong University of Engineering and Technology area in the Chattogram region of Bangladesh.

3.3.2 Sample Preparation

The teak leaves were washed with deionized water and then dried under the sunlight. (**Scheme 3.1**) Next, they were finely meshed and sieved through 0.3 mm stainless steel sieve apparatus to remove the vein and midrib. Subsequently, the resulting powder was collected for the synthesis of CQDs.



Scheme 3.1: Collecting Process of Dried Teak Leaf.

3.3.3 Synthesis of Carbon Quantum Dots

CQDs was synthesized using dried teak leaves as a carbon source through a hydrothermal method. For the synthesis of CQDs, 1 g fine teak leaves powder was mixed with 5 mL H_2O_2 and 95 mL DI water, sonicated, and transferred into a PPL-lined autoclave for heating at 200°C for 5 hours. After cooling down, the resulting light-yellow solution was purified and dialyzed against deionized water to remove excess H_2O_2. Then the obtained sample was collected as a powder form by freeze drying. (**Scheme 3.2**)

Scheme 3.2: Schematic illustration and synthesis procedure of CQDs.

3.4 CHARACTERIZATION

The fluorescent nanoparticles and the sensitized film's morphology were assessed using field emission scanning electron microscopy (Model FESEM: JSM-7100FA JEOL USA, Inc.). Absorption spectroscopy was conducted using UV-3600 Plus from Shimadzu, MD, USA, while emission spectroscopy measurements were performed with RF-5301PC from Shimadzu, MD, USA. Zeta potentials of the samples were determined using SZ-100 series Dynamic Light Scattering Particle Size Distribution Analyzer, HORIBA Instruments Inc., Irvine, CA, USA. Transmission Electron Microscopy (TEM) images were obtained using JEM-1400 PLUS (JEOL USA, Peabody, Massachusetts, USA).

3.5 SAMPLE PREPARATION FOR ANALYSIS

3.5.1 UV-VIS Spectroscopy:

To conduct UV-Vis spectroscopy on the CQDs sample with a concentration of 0.1 mg/L using a Shimadzu UV-3600 Plus spectrophotometer, the following procedure was implemented.

First, a quartz cuvette with a path length appropriate for the UV-Vis measurement (typically 1 cm) was thoroughly cleaned with DI water and ethanol to remove any residues that could interfere with the measurement. A small volume of the CQD solution (approximately 1 mL) was prepared by diluting the stock solution to achieve the desired concentration of 0.1 mg/L. The cuvette was then filled with the diluted CQD solution, ensuring no air bubbles were present. The cuvette was carefully placed into the sample holder of the UV-Vis spectrophotometer, aligning it with the light beam path. A baseline spectrum of DI water was initially recorded for reference. Subsequently, the absorbance spectrum of the CQD solution was measured over the desired wavelength range (typically 200-800 nm), with scanning parameters optimized for the detection of CQD absorption features. Data acquisition and analysis were performed using software provided by origin pro, ensuring accurate determination of absorbance peaks.

3.5.2 Photoluminescence (Pl) Spectroscopy

To perform Photoluminescence (PL) spectroscopy on the CQDs sample with a concentration of 0.1 mg/L using a Shimadzu RF-5301PC spectrofluorometer, the following procedure was followed.

Initially, a quartz cuvette with a standard path length (typically 1 cm) was meticulously cleaned with DI water and ethanol to eliminate any contaminants that could affect the spectroscopic measurements. A small volume (typically 1 mL) of the CQD solution was prepared by diluting the stock solution to achieve the desired concentration of 0.1 mg/L. The cuvette was then filled with the diluted CQD solution, ensuring that no air bubbles were trapped inside. Next, the cuvette was carefully placed into the sample compartment of the spectrofluorometer, ensuring proper alignment with the excitation and emission light paths.

For the emission spectroscopy measurements, the excitation wavelength was set to an appropriate value based on the absorption spectrum of the CQDs, typically around their absorption maximum. The emission spectrum was recorded by scanning the wavelength range from the emission onset to a higher wavelength, with parameters optimized to detect the photoluminescence peaks efficiently. The integration time and slit widths were adjusted to achieve an optimal signal-to-noise ratio. Data acquisition and analysis were conducted using origin pro software allowing for the determination of excitation and emission maxima and other photoluminescence characteristics of the CQDs in solution.

3.5.3 Fourier transform infrared (FTIR) spectroscopy

To conduct Fourier Transform Infrared (FTIR) spectroscopy on the CQDs sample with a concentration of 0.1 mg dispersed in anhydrous potassium bromide (KBr), the following procedure was employed. First, approximately 1 mg of anhydrous KBr powder was thoroughly dried and placed in a mortar. Next, a small amount (0.1 mg) of the CQD powder was added to the KBr and mixed homogeneously using a pestle to ensure uniform dispersion. The mixture was then pressed into a thin, transparent pellet using a hydraulic press under controlled pressure to form a solid sample for FTIR analysis.

The prepared KBr pellet containing the CQDs was securely mounted onto the sample holder of the FTIR spectrometer. The background spectrum of an empty KBr pellet was initially recorded for baseline correction. Subsequently, the FTIR spectrum of the CQD-loaded KBr pellet was acquired over the desired spectral range (typically 4000-400 cm^{-1}), with appropriate resolution and number of scans to enhance spectral quality. Spectral interpretation and analysis were performed using FTIR software to identify characteristic vibrational modes and functional groups present in the CQDs and KBr matrix.

3.5.4 Zeta Potential

To determine the zeta potential of the carbon quantum dot (CQD) sample at a concentration of 0.1 mg/L in DI water, a SZ-100 series Dynamic Light Scattering Particle Size Distribution Analyzer from HORIBA Instruments Inc. was utilized following this procedure.

First, the CQD solution was prepared by diluting the stock solution to achieve the desired concentration of 0.1 mg/L in DI water. The sample was then thoroughly vortexed or gently mixed to ensure uniform dispersion.

Next, the SZ-100 instrument was calibrated according to manufacturer specifications, ensuring optimal performance. A small volume (typically 1 mL) of the prepared CQD solution was transferred into a suitable cuvette designed for zeta potential measurements, taking care to avoid introducing air bubbles. The cuvette was securely placed into the instrument's sample chamber, and measurements were conducted at a controlled temperature to maintain sample stability.

The zeta potential measurement was performed based on electrophoretic mobility using laser Doppler velocimetry. The instrument applied an electric field to the sample, causing the CQDs to migrate, and their velocity was measured via the Doppler shift of scattered light. Multiple measurements were taken and averaged to ensure accuracy.

Data analysis was conducted using dedicated software provided by HORIBA, which calculated the zeta potential based on the electrophoretic mobility of the CQDs in the DI water medium.

3.5.5 Field-Emission Scanning Electron Microscopy (FE-SEM)

To prepare CQDs sample at a concentration of 0.1 mg/L for FESEM imaging using a JEOL JSM-7100FA instrument, the following procedure was followed.

A clean silicon wafer was selected for its flat surface and compatibility with electron microscopy. Initially, the silicon wafer was thoroughly cleaned using sequential rinsing with acetone, ethanol, and deionized water, followed by drying under a stream of nitrogen gas. Using tweezers, the cleaned silicon wafer was carefully handled to avoid contamination. A small aliquot (typically 5-10 μL) of the CQD solution was pipetted onto the center of the silicon wafer, ensuring uniform distribution over the surface. After allowing sufficient time (about 1 minute) for the solution to adhere, excess liquid was gently removed by blotting the wafer against clean filter paper. The wafer was then air-dried at room temperature to ensure the formation of a thin, uniform layer of CQDs on the silicon surface. No additional staining was applied to preserve the natural characteristics of the CQDs. Subsequently, the prepared silicon wafer was securely mounted onto a sample holder and inserted into the JEOL JSM-7100FA FESEM instrument. Imaging was conducted at an appropriate accelerating voltage (typically 10-30 kV) under high vacuum conditions to capture high-resolution images of the CQDs deposited on the silicon wafer.

3.5.6 Energy Dispersive X-Ray Analysis (EDX)

Energy Dispersive X-Ray Analysis determined from FE-SEM measurement (**Section 3.5.5**).

3.5.7 Transmission Electron Microscopy (TEM)

To prepare the CQDs sample at a concentration of 0.1 mg/L for Transmission Electron Microscopy (TEM) imaging using a JEOL JEM-1400 PLUS instrument, the following procedure was employed.

First, a clean copper TEM grid (200 mesh) was glow discharged briefly to enhance sample adhesion. A drop of the CQD solution was then pipetted onto the grid, allowing it to adhere for approximately 1 minute. Excess liquid was carefully blotted using filter paper without touching the grid directly. Subsequently, the grid was air-dried at room temperature to ensure the formation of a thin, uniform film of CQDs on the grid surface. For contrast enhancement, no additional staining was applied due to the inherent fluorescence of CQDs. Finally, the prepared grid was securely placed into the TEM holder and imaged using the JEOL JEM-1400 PLUS TEM instrument operating at an appropriate accelerating voltage (typically 100 kV) under high vacuum conditions.

3.5.8 Particle Size Distribution Histogram (PSDH)

Particle Size Distribution Histogram determined from TEM measurement (**Section 3.5.7**)

3.5.9 Photoluminescence (Pl) Lifetime

To measure the Photoluminescence (PL) lifetime of CQDs at a concentration of 0.1 mg/L in DI water, the following procedure was followed.

First, a clean quartz cuvette with a standard path length of 1 cm was thoroughly cleaned using DI water and ethanol to eliminate any potential contaminants. The CQD stock solution was then appropriately diluted to achieve the desired concentration of 0.1 mg/L in DI water. Subsequently, the cuvette was filled with the diluted CQD solution, ensuring the absence of air bubbles. The cuvette was carefully inserted into a time-resolved fluorescence spectroscopy system equipped with a pulsed laser excitation source, a sensitive detection system (such as a photomultiplier tube), and a time-correlated single photon counting (TCSPC) module. The excitation wavelength was set to match the absorption peak of the CQDs to optimize excitation efficiency. Laser repetition rate, excitation power, and detector settings were adjusted to ensure optimal signal-to-noise ratio during measurement. The pulsed laser was triggered to excite the CQDs, and emitted photons were recorded over time using the TCSPC module. Data analysis involved fitting the decay curve of emitted photons to extract the PL lifetime(s) using dedicated TCSPC software.

Chapter 4: RESULTS AND DISCUSSION

4.1 UV-VIS SPECTROSCOPY

The UV-Vis spectra of CQDs have been investigated and presented in **Figure 4.1**. The spectrum showed a weak absorption in the UV region at around 220 nm attributed to the π-π* electronic transition of sp^2 conjugated carbon (C=C) bond and a weak absorption peak at around 285 nm (n-π*) due to the functional groups (C=O) present on the surface of CQDs. (John et al., 2021)

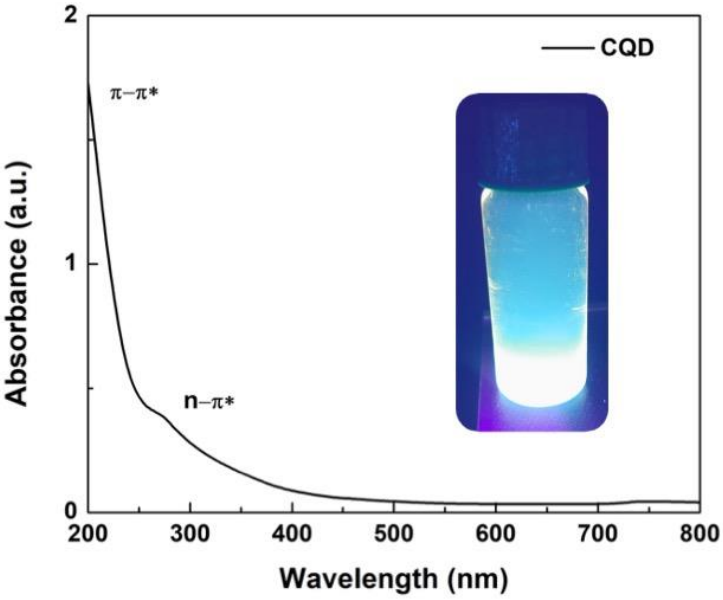


Figure 4.1: UV-Vis Spectra of CQDs (inset the image of CQDs showed a bright blue PL under a UV lamp at 365 nm)

4.2 PHOTOLUMINESCENCE (PL) SPECTROSCOPY

The photoluminescence (PL) spectra were recorded with an excitation wavelength of 340 nm. The synthesized CQDs showed fluorescence emission peaks in the blue region, ranging to 435 nm. (Jagannathan et al., 2021).This result indicated the maximum wavelength at which the emitted fluorescence was observed for CQDs. (**Figure 4.2).**

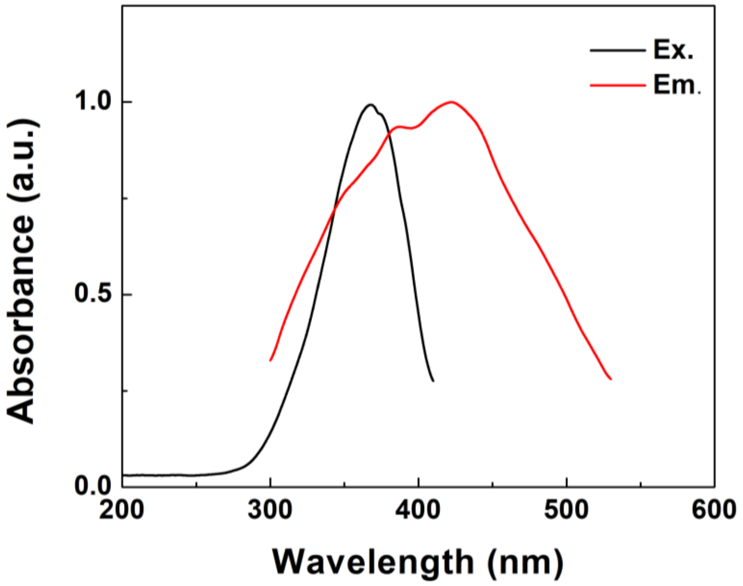


Figure 4.2: Excitation and Emission peak of CQDs.

4.3 FOURIER TRANSFORM INFRARED (FTIR) SPECTROSCOPY

The surface functional groups of CQDs was investigated using Fourier Transform Infrared (FTIR) spectroscopy, as presented in **Figure 4.3**. The CQDs exhibited identical C=C stretching and C-H bending peaks at around 1600 and 1027 cm^{-1}, respectively, attributed to the alkyl hydrocarbons from the teak leaf. broad signature band peak of -OH stretching at 3200 cm^{-1}, confirming the adsorption of water molecules onto sample surfaces, along with an -OH bending peak at around 1390 cm^{-1}. Additionally, a distinguished C=O stretching peak was detected at around 1740 cm^{-1} confirming the successful incorporation of a considerable amount of oxygen functional groups into the carbon moieties after treatment with H_2O_2. a superimposed C-H stretching peak was also observed in the region 2950 cm^{-1}. (Howell et al., 1999)

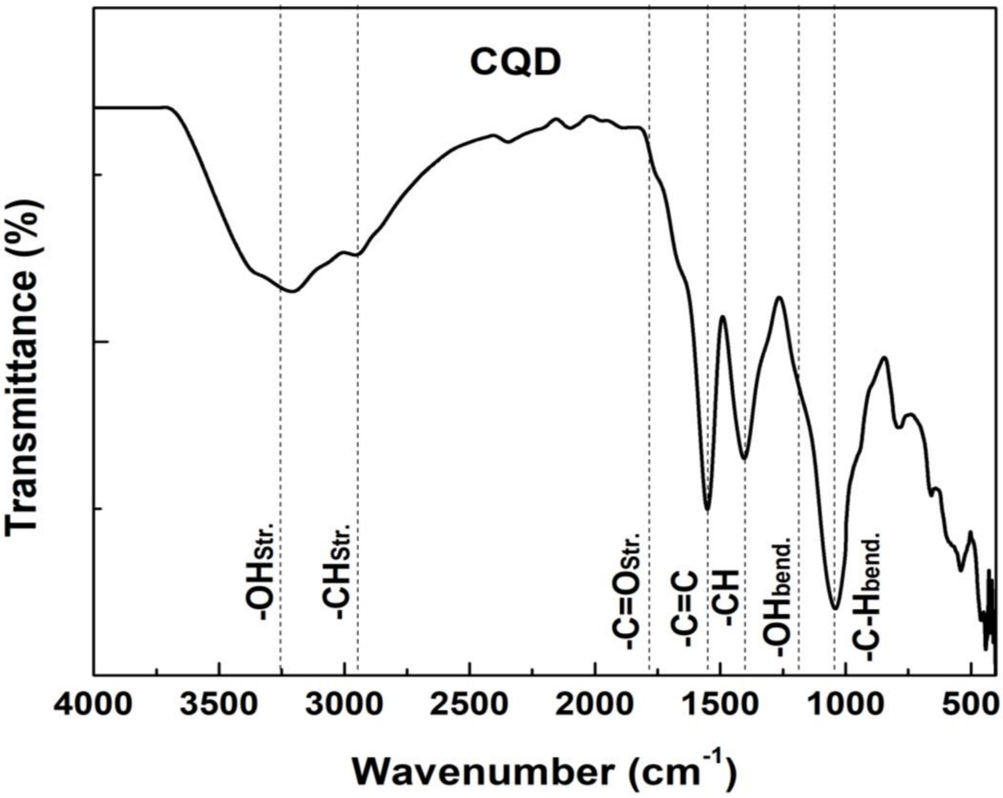


Figure 4.3: FT-IR Spectra of CQDs.

4.4 ZETA POTENTIAL

The zeta potential, which quantifies the surface charge of colloidal particles in a solution, was measured and presented in **Figure 4.4**. The zeta potential value was assessed using electrophoretic light scattering in an aqueous solution. The negative zeta potential value confirmed the negative surface charge encapsulated on the synthesized CQDs. This negative charge is attributed to the presence of oxygenated functional groups such as, -COOH, C=O, -OH, on the particle surfaces, which dissociate into the solution and generate negatively charged ions. Our synthesized CQDs displayed the negative zeta potential value of -27.7 mV which demonstrated the higher surface negative charge density. The formation of a greater number of functional groups on the particle surface can be attributed because of H_2O_2 treatment. The H_2O_2 treatment likely facilitated the introduction of more oxygen functionalities, leading to an increased negative charge on the surface. (Liu et al., 2021)

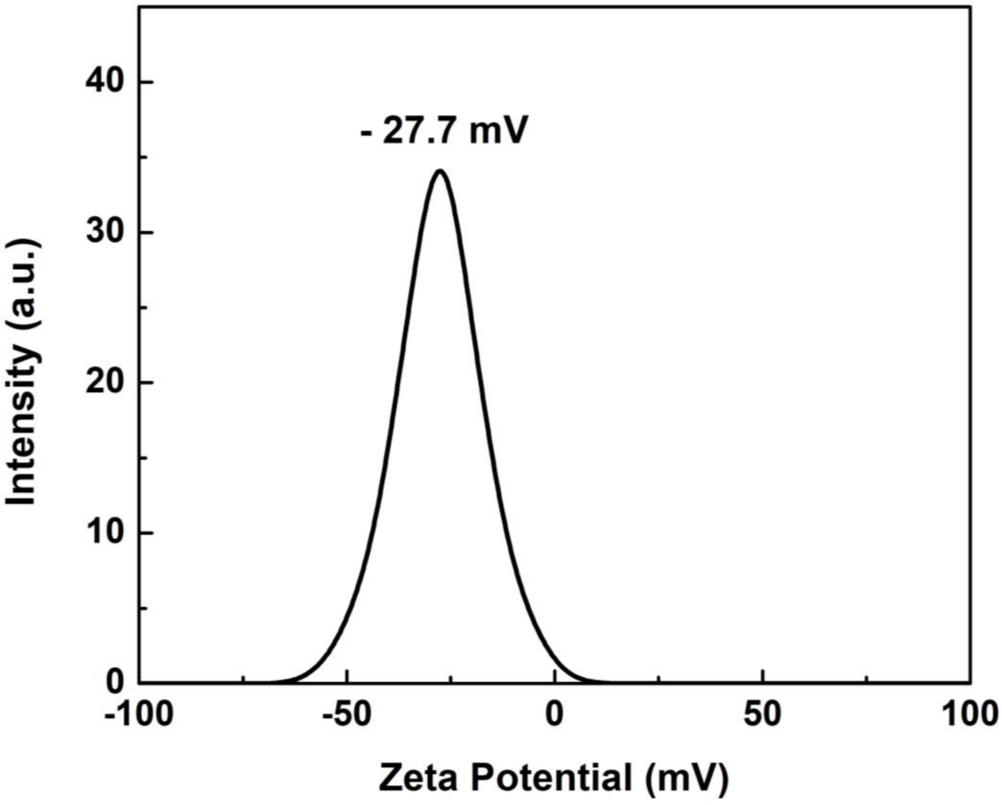


Figure 4.4: Zeta Potential measurement of CQDs

4.5 ENERGY DISPERSIVE X-RAY ANALYSIS (EDX)

The observed percentages in energy dispersive X-ray analysis (EDX) (**Figure 4.5**) reflect the relative abundance of carbon (C) and oxygen (O) atoms within each sample. CQDs exhibited a composition of 79.56% C and 20.47% O atoms, indicating a relatively higher oxygen content. (**Table 4.1**) The treatment with H_2O_2 mainly introduced oxygen-containing functional groups onto the surface of the carbon dots through oxidation reactions.

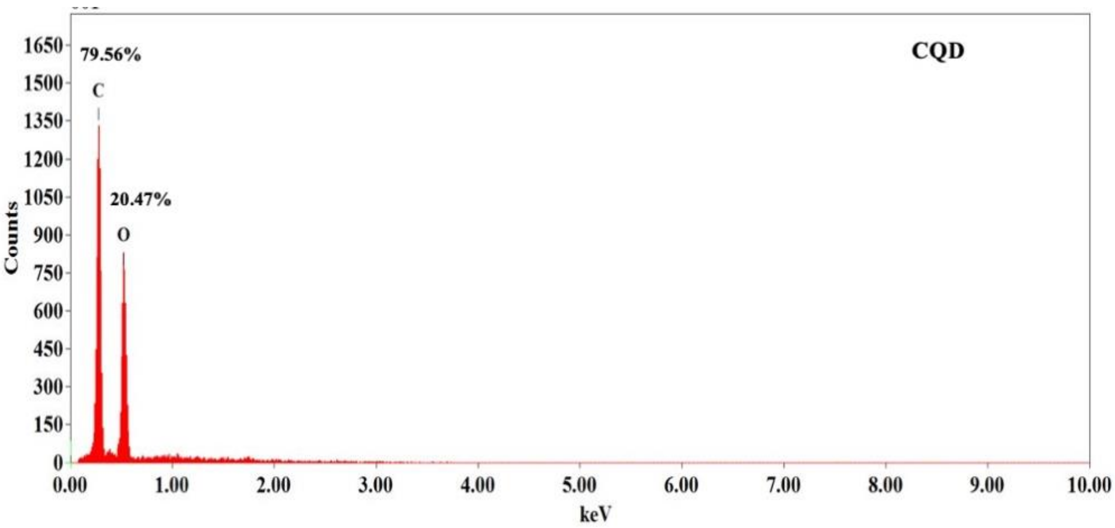


Figure 4.5: EDX data of CQDs.

Table 4.1: Composition data of CQDs analysed by EDX

EDX data		
Samples	Mass %C	Mass %O
CQDs	79.56	20.47

4.6 FIELD-EMISSION SCANNING ELECTRON MICROSCOPY (FE-SEM)

In this study, we also investigated the surface morphology of CQDs using field-emission scanning electron microscopy (FE-SEM). The acquired FE-SEM images provided insights revealing that CQDs exhibited notably smaller particle sizes ranging between 30 to 40 nm, in comparison to teak leaves powder (**Figure 4.6 and 4.7**).

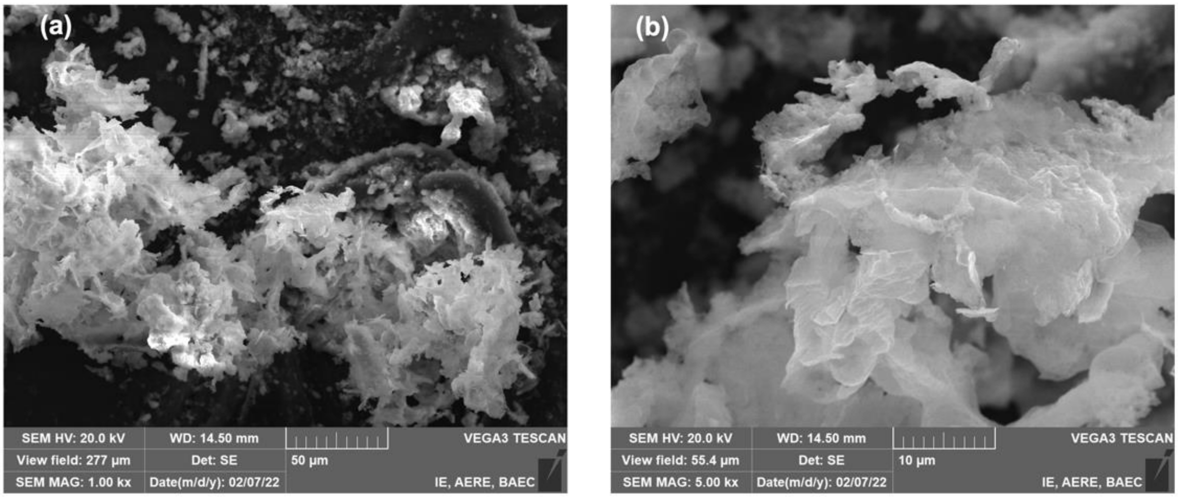


Figure 4.6: FESEM images of Teak leaves powder.

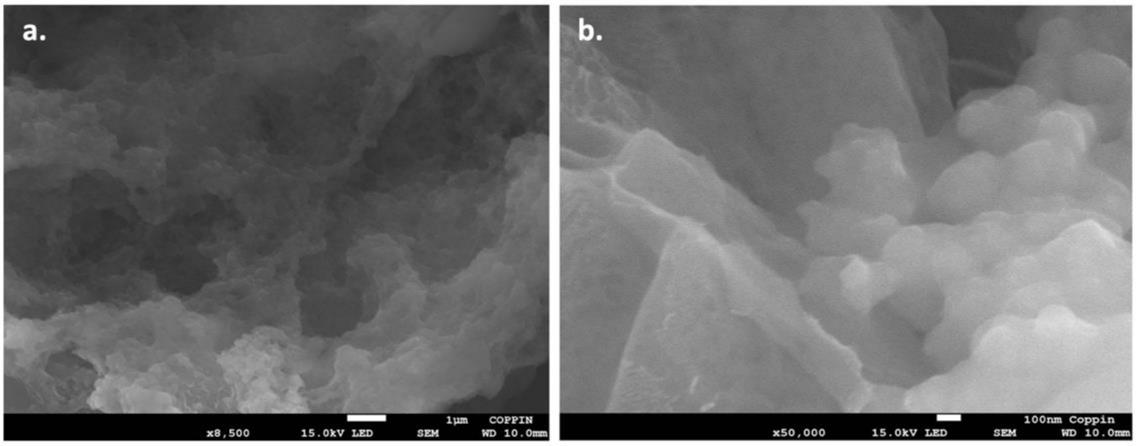


Figure 4.7: FESEM images of CQDs.

Our investigation showed that the introduction of H_2O_2 during the synthesis process exerted a pronounced impact on the particle size of CQDs which leads to a more substantial reduction compared to the raw materials.

4.7 TRANSMISSION ELECTRON MICROSCOPY (TEM)

The TEM images also displayed individual particles within a size range of 30-40 nm, as depicted in **Figure 4.8**.

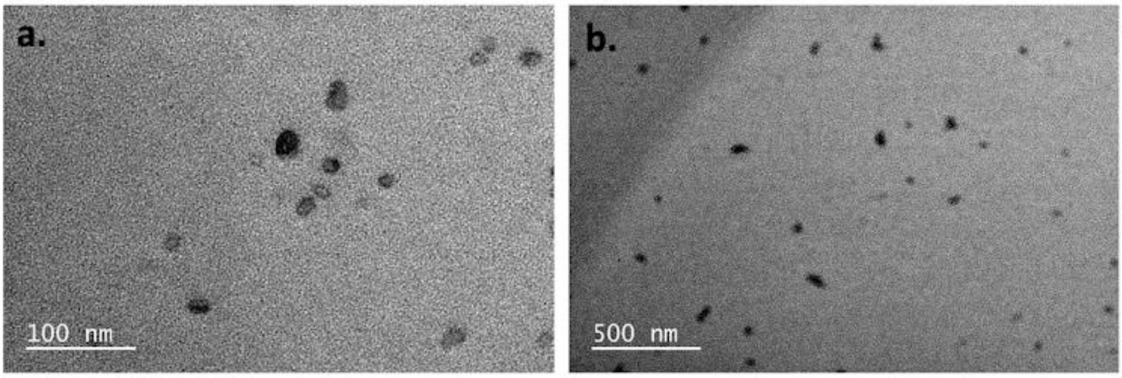


Figure 4.8: TEM images of CQDs.

4.8 PARTICLE SIZE DISTRIBUTION HISTOGRAM (PSDH)

The particle size of CQDs was also estimated by particle size distribution histogram (**Figure 4.9**). The average particle sizes of CQDs showed around 32-40 nm. This obtained result is consistent with the FESEM and TEM images.

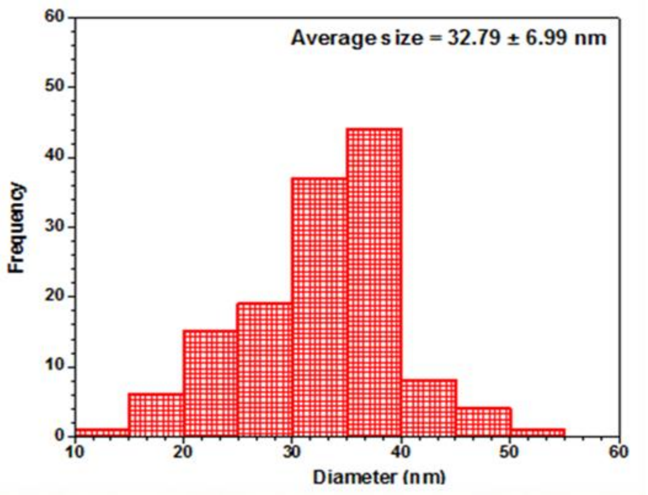


Figure 4.9: Particle size distribution histogram of CQDs.

4.9 PHOTOLUMINESCENCE (PL) LIFETIME

The photoluminescence (PL) lifetime values were measured for CQDs (**Figure 4.10**). In this figure, the PL lifetime values were 2.20 ns and 8.69 ns, indicating two distinct decay processes.

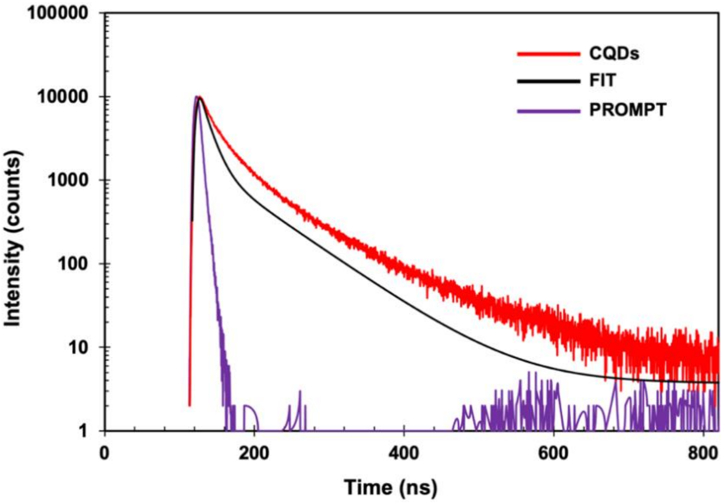


Figure 4.10: Photoluminescence decay curves at 420 nm emission wavelength of the CQDs.

Chapter 5: APPLICATIONS

5.1 PHOTOCATALYTIC ACTIVITY TEST

The photocatalytic activity of the synthesised carbon quantum dots (CQDs) was analysed by degrading methylene blue (MB) dye solutions under visible light ($\lambda > 420$ nm). The photochemical reactor was lighted using a 300 W Xenon lamp (PLS-SXE300E, Beijing Perfect light Technology Co. Ltd., China) and 420 nm UV-cut filter. The visible light intensity was measured to be 130.0 mW cm^{-2}. In a typical experiment, 0.1 mg of photocatalysts were suspended in 10 mL of a 10 mg/L MB aqueous solution. Prior to light irradiation, the mixture was held in the dark for 30 minutes to ensure that the reactants and CQDs reached adsorption and desorption equilibrium. The mixture was then exposed to light for up to 90 minutes, while 10 mL of dye solution (10 ppm) free of CQDs was used as a control. During irradiation, 2 mL of the suspension was removed and filtered through a 0.2 PTFE filter before measurement. The concentration of MB was determined using a T80+ UV/Vis spectrophotometer (PG Instrument Limited, UK) at room temperature and its peak absorbance at 665 nm. To assess the concentration of degraded MB in aqueous solution, we created a concentration curve using three concentrations (10 mg/L). The R^2 of our build curve is 0.998, which is shown in **Figure 5.1.** To investigate the degradation efficiency, a photocatalytic degradation study was incorporated into this research and was determined using Equation (1) (Ahmed et al., 2016):

$$\textbf{Degradation (\%)} = [(C_0 - C_t) / C_0] \times 100\ \% \ldots\ldots\ldots(1)$$

Where C_0 is the initial concentration of MB, C_t is the resulting concentration of MB solution after treatment for time t (min).

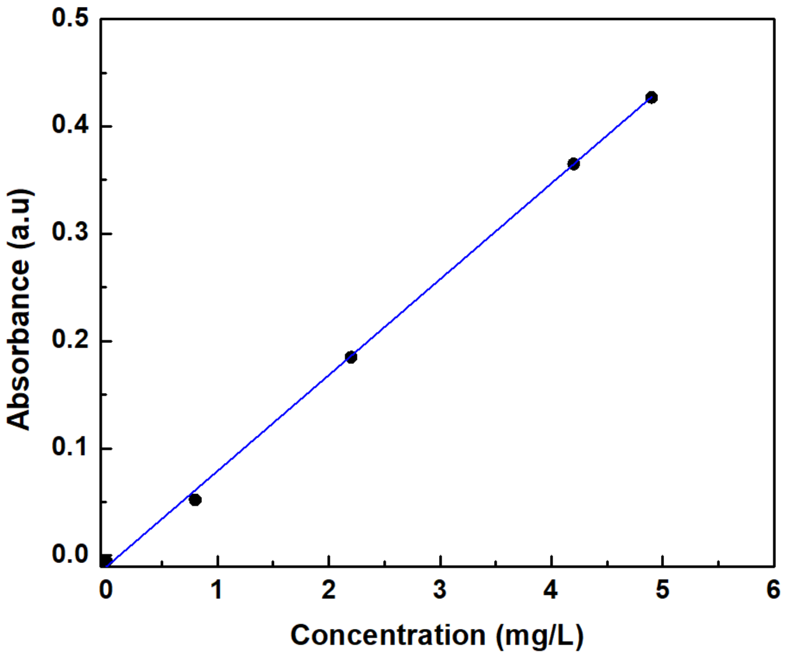


Figure 5.1: Calibration curve for determining the concentration of MB in an aqueous solution.

5.2 PHOTOCATALYTIC ACTIVITY OF METHYLENE BLUE DYE SOLUTION

The photocatalytic efficiency of CQDs was evaluated by the degradation of MB dye, a member of the thiazine dye family that finds widespread application in textile industries (Ahmed et al., 2016). The time-dependent UV-Vis absorption spectra were recorded for the removal of MB from aqueous solution during the photodegradation reaction for 0 min up to 90 min. **Figure 5.2** showed an apparent change in the UV-Vis spectra of the MB solution between the 420-750 nm range when CQDs was introduced. The degradation rate of MB dye was shown very lower in the presence of light only. Specifically, almost 73% of the MB dye was degraded when CQDs were absent within a 90-minute timeframe (**Figure 5.3**). The findings indicated that the MB dye solution might undergo slow degradation in the presence of light without catalyst. The presence of lone pairs on the nitrogen and sulphur atoms in the MB structure mostly contributed to this phenomenon. These locations contain an abundance of electrons, which became reactive upon being illuminated. The bond pair electrons displayed repulsive forces, resulting in instability. Consequently, they interacted with the adjacent water molecules to establish a stable bond (Rani et al., 2021).

The addition of CQDs significantly reduces the intensity of the two adsorption peaks, suggesting a significant alteration in the structure of the MB molecule in the presence of CQDs, leading to its efficient destruction. Based on the degradation results, 98% of MB had been degraded within 90 min in the presence of CQDs. This result suggested that CQDs significantly affected the activity of the photocatalyst. Upon exposure of MB dye solution to solar simulated light irradiation, CQDs particles absorbed the UV light that the simulated light provided. Following the transfer of electrons from the valence band to the conduction band, electron-hole pairs were generated. Free radical molecules would be generated when electrons and holes are attracted to the dissolved oxygen and hydroxide ions, causing the MB dye molecules to oxidize and decompose into non-toxic by-products like carbon dioxide and water (Cheng et al., 2019). The photocatalytic activity of MB was also evaluated under a xenon lamp for comparison. **Figure 5.3** illustrates that the degradation of MB exhibited lower efficiency compared to when CQDs were added.

Excellent photochemical properties and high solar light-induced photocatalytic activity are characteristics of CQDs. Due to their capacity to absorb a significant fraction of the UV–Vis region of the solar spectrum and their positive valence band, which is conducive to accelerating the photocatalytic redox rate, they are capable of functioning as effective photocatalysts. Furthermore, charge recombination can be impeded, thereby enhancing charge separation *via* CQDs. Consequently, enhanced separation and recombination of electron-hole pairs result in increased photocatalytic degradation activity performance. This also suggests that CQDs have the potential to generate more photoinduced electrons and holes through more efficient utilization of sunlight (Qu et al., 2020).

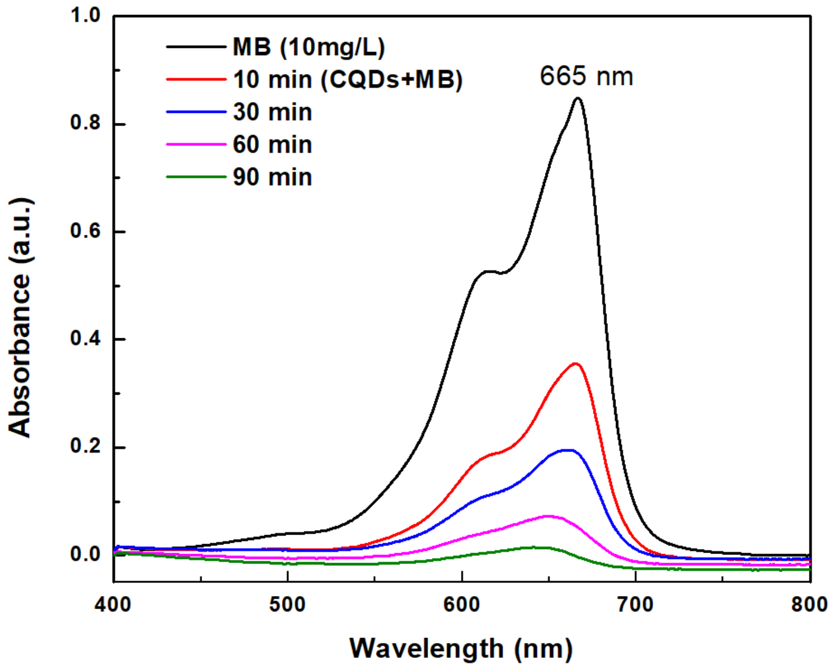


Figure 5.2: UV-Vis absorption spectra of degradation of MB with CQDs composite under a Xenon lamp.

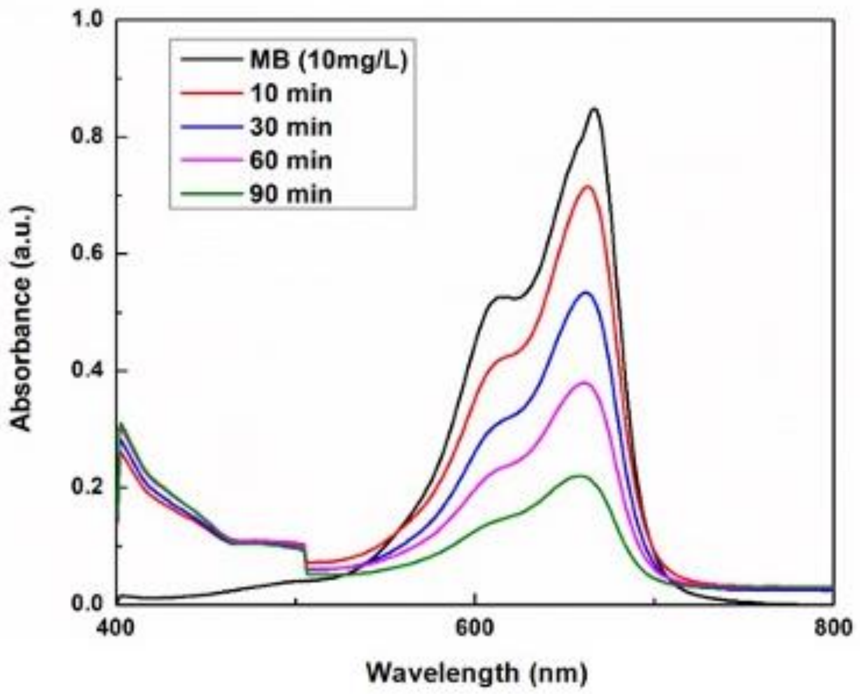


Figure 5.3: UV-Vis absorption spectra of degradation of MB under a Xenon lamp.

5.3 CHEMICAL OXYGEN DEMAND (COD)

An experiment in COD was conducted to verify that the decolorization of MB dye resulted from photocatalytic degradation rather than adsorption. (Venkatraman et al., 2020). In this experiment, the COD was assessed using the HI83399 Multiparameter Photometer from Hanna Instruments with their dedicated COD reagent kits (HI93754A-25).

Table 5.1: COD estimation of methylene blue for initial and final of CQDs.

CQD/MB	Time (min)	COD (mg/L)
0.1mg/10 mL	0	142
	90	12

The percentage of photodegradation was calculated using the formula:

$$\textbf{Photodegradation efficiency (\%)} = \frac{(COD_0 - COD_{90})}{COD_0} \times 100\% \quad \ldots\ldots\ldots\ldots(2)$$

$$= \frac{(142 - 12)}{142} \times 100\%$$

$$= 91.5\%$$

In this equation,

COD_0 is the value at the initial time (0 min).

COD_{90} is the value at 90 min.

In this study, CQDs were employed as photocatalysts in the photodegradation of Methylene Blue (MB), a commonly used dye pollutant. The initial Chemical Oxygen Demand (COD) of the MB solution was measured at 142 mg/L. After 90 minutes of exposure to CQDs under illumination, the COD value significantly decreased to 12 mg/L, resulting in a calculated photodegradation efficiency of approximately 92%. (**Table 5.1**) This high efficiency suggests that CQDs effectively facilitated the degradation of MB molecules under the influence of light. The observed photocatalytic activity can be attributed to CQDs acting as electron transfer mediators or photosensitizers, generating reactive species that degrade MB through processes like oxidation or direct photolysis. These findings underscore the potential of CQDs as promising materials for environmental remediation applications, particularly in the treatment of dye-contaminated wastewater. Further investigations into the mechanism and optimization of CQD-based photocatalysts could enhance their practical implementation in sustainable water treatment technologies.

Chapter 6: CONCLUSION

6.1 GENERAL

In this thesis report, we have demonstrated an easy and large-scale H_2O_2-based CQDs synthesis from an economical and available natural precursor teak leaf. H_2O_2 not only increases the degree of surface oxidation of the carbon framework, but also improves their stability in aqueous solution. The prepared CQDs showed blue emission fluorescence with high aqueous stability. Overall, the development of H_2O_2-assisted CQDs have opened new avenues for the application of carbon-based nanomaterials in various fields, and their potential uses are still being explored.

6.2 LIMITATIONS

Our synthesized CQDs have demonstrated considerable effectiveness as catalysts for the degradation of methylene blue. However, there are some limitations. One notable issue is the non-uniform size of the synthesized CQDs, which can influence both their performance and reproducibility. Additionally, the properties of biomass-based CQDs can influence various factors, including their interaction with the surrounding environment and their suitability for specific locations.

6.3 RECOMMENDATION FOR FURTHER STUDY

- Investigate the specific mechanisms underlying the exceptional photocatalytic activity of teak-derived CQDs.
- Conduct comparative studies with other carbon-based photocatalysts or conventional semiconductor photocatalysts to explain the distinct advantages of teak-derived CQDs.

- Examine the scalability and reproducibility of the synthesis method on a larger scale for practical applications.
- Further research in these areas has the potential to unlock the full capabilities of teak-derived CQDs and pave the way for their widespread use in environmental remediation

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Appendices

Appendix A:

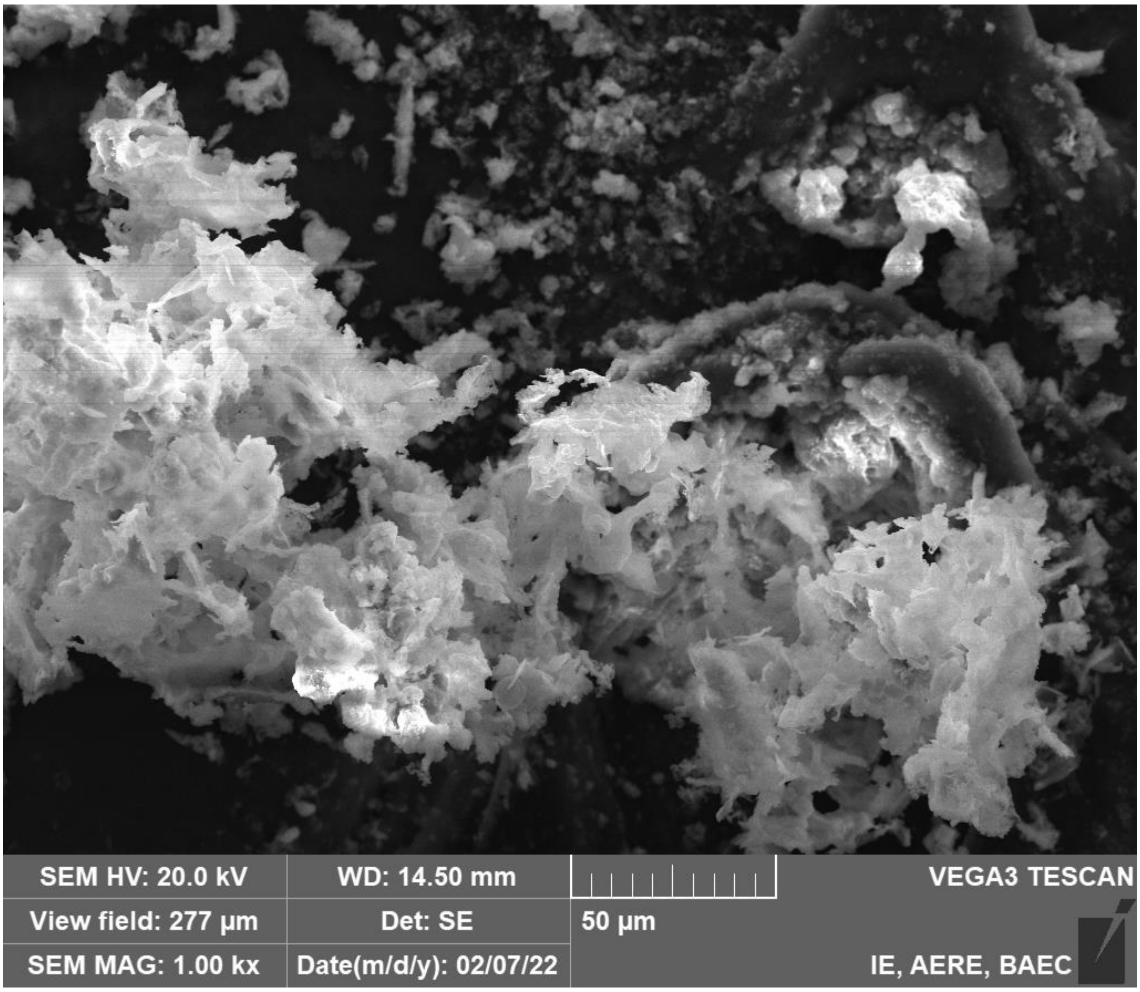

Figure A: FE-SEM image of dried teak leaf powder.

Figure B: Polypropylene (PPL) lined Hydrothermal Autoclave

Figure C: LyoQuest laboratory freeze dryers (Telstar)

Figure D: Muffle Furnace (Carbolite, ELF 11/14B)

Figure E: Laboratoy Drying Oven (Lenton Thermal Designs WF60)

Figure F: Vacuum Filtration

Figure G: High Power Xenon Light Source (PLS-SXE300E, China)

Figure H: Digital Balance Machine

Figure I : Hot Plate Magnetic Stirrer (MS-H380-Pro, USA)

Figure J: Centrifuge Machine (CTF-TH16, China)

Figure K: Bath Sonicator (Powersonic 405, South Korea)

Figure L: Deionized Water Filter

Figure M: Multiparameter Photometer (HI83399)

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Jackson Barua

ID: **18MCHEM008P**

Department of Chemistry

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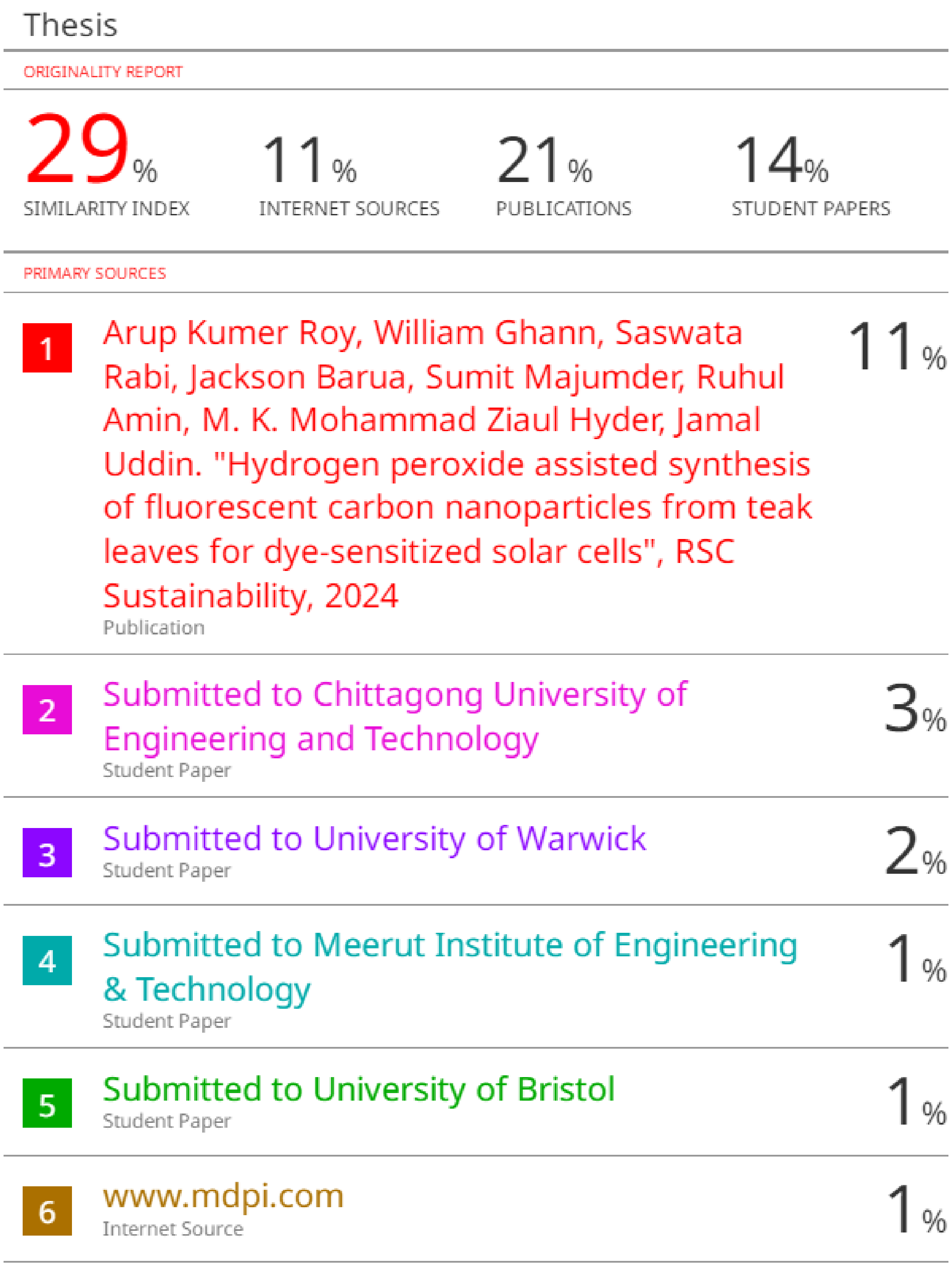
Chattogram-4349, Bangladesh



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