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A REVIEW ON SYNTHESIS AND APPLICATION OF CARBON QUANTUM DOTS

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Abstract—

The term "carbon quantum dots" refers to a surface passivation process used to carbon nanoparticles. These cutting-edge luminescent nanomaterials hold immense promise in numerous domains including catalysis, drug delivery, bioimaging, biosensing, energy conservation, and storage. Their minute size, outstanding water solubility, minimal toxicity, customizable light-emitting properties, and remarkable biocompatibility collectively make them highly advantageous. The production of carbon dots can be achieved through top-down or bottom-up methods. Top-down techniques involve cutting macroscale materials into carbon nanoparticles, with graphene sheets, carbon nanotubes, and even candle soot being used as precursors. This paper briefly discusses some of the preparation methods for carbon dots.

This review provides an overview of recent research on CQDs, including their synthesis methods, properties, and potential applications. Green synthesis methods have been developed using sustainable and low-cost materials, and CQDs can be tuned to exhibit photoluminescence and electrochemical properties. Applications for CQDs include sensing, bioimaging, drug delivery, and energy storage and conversion. As new synthesis methods are developed and their properties are better understood, CQDs are expected to find even more exciting applications in a range of fields. The research on CQDs is an active and ongoing area of investigation, and further advances in this field will continue to contribute to the development of new and innovative technologies.

Keywords: *Carbon Quantum Dots, luminescent, nanomaterial, carbon nanoparticle, Precursors*

1. Introduction

Due to its distinct optical and electrical characteristics, carbon quantum dots (CQDs) are a form of nanoscale carbon material that have attracted growing attention in recent years. They typically have a carbon atom core that is surrounded by functional groups like hydroxyl, carboxyl, or amino groups. They are fewer than 10 nm in size.

CQDs are characterized by strong fluorescence[1], high biocompatibility[2], low toxicity, and excellent photostability[3], making them promising candidates for a variety of applications, such as bioimaging[4], drug delivery, sensing, and optoelectronics. In addition, CQDs can be synthesized through simple and environmentally friendly methods, such as hydrothermal treatment, microwave irradiation, or electrochemical oxidation, using readily available precursors such as glucose, citric acid, or carbon black.

The unique properties and facile synthesis of CQDs make them an attractive research area for the creation of novel materials and uses.

Nanomaterials with a diameter of less than 10 nm, such as carbon quantum dots (CQDs) and graphene quantum dots (GQDs), are a novel type of carbon-based material. They were initially discovered in 2004 while purifying unidirectional carbon nanotubes through electrophoresis, and again in 2006 during the laser ablation of graphite powder and cement. Carbon quantum dots have gradually gained popularity because of their abundant, inexpensive, and environmentally friendly attributes, and have now become an important member of the nanocarbon family with fascinating characteristics. In general, carbon has been known to have poor solubility in water and low fluorescence[5], and it is commonly found in black form. However, carbon-based quantum dots, also known as carbon nanotubes, have gained significant attention due to their high solubility and strong luminosity. Carbon-based quantum dots, have become a subject of significant interest due to their remarkable luminosity and superior solubility. Carbon quantum dots (CQDs), a new type of nanocarbon, are currently semiconductor quantum dots (QDs) are preferred due to their favorable characteristics for instance solubility, little toxicity, easy manufacturability, and desired optical properties. Moreover, their synthesis pathway allows for control of their physiochemical features. For instance, they exhibit exceptional aqueous solubility, chemical inertness, and making them easier to modify**.** Furthermore, they possess advanced biology characteristics such as presence of small hazardous level and high biocompatibility, which make them promising candidates for applications in biosensors, bioimaging, and drug delivery**.** Various uses are available in figure 1.

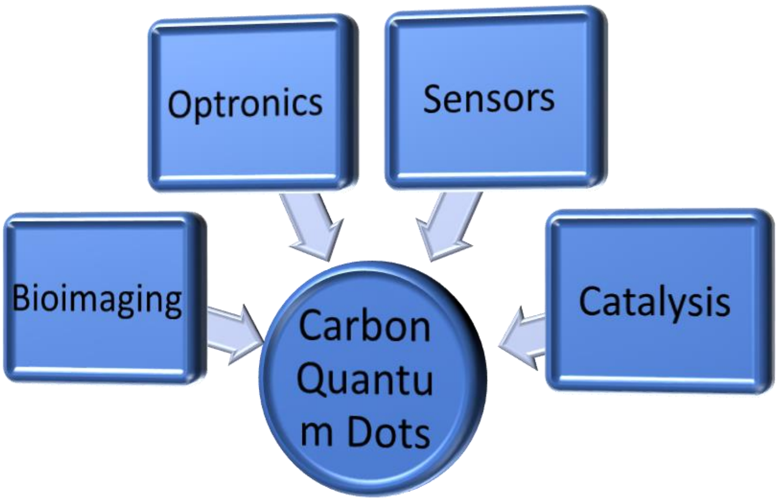


Figure 1: Various Uses of Carbon Quantum Dots (CQDs).

2. Synthesis, Size Control

In the past ten years, a variety of approaches to CQD preparation have been put forth. There are two main strategies for addressing a problem: “Top-down” and “Bottom-up.” These strategies can be modified before or after treatment, and there are three key concerns to consider. It's important to note how CQDs preparation: When carbonization occurs, there is a risk of (i) Carbonaceous aggregation can be avoided using particular procedures from solution chemistry, concurrent pyrolysis, or electrochemical synthesis[6]. (ii) control over size and homogeneity is essential for standardized attributes and mechanistic research, and (iii)techniques used after treatment, such as gel electro-phoresis, as well as surface qualities, can be used to improve a product., that are necessary for certain applications and solubility, can be adjusted before or after therapy. We shall outline the primary CQD synthesis[7] techniques and size control via coordinated pyrolysis and the as well as functionalization, doping, and nanohybridization of CQDs.

Several techniques, including microwave-assisted synthesis[8], hydrothermal synthesis[9], and electrochemical synthesis[10], can be used to create CQDs.[11]The Carbon quantum dots (CQDs) are frequently produced using this method. involves the use of stabilizing agents during the carbonization process of organic precursors like citric acid, glucose, and starch. The CQDs produced through this method usually possess a size spectrum between 2-10 nm and can be subjected to surface modifications[12] to tailor their characteristics.

2.1. Chemical Eradication

- **Carbonization by electrochemistry**

A potent technique for creating CQDs that uses different bulk carbon-based compounds as starters is electrochemical soaking. Only a few studies have been made, nevertheless, about electrochemically carbonising tiny compounds to form CQDs. When electrochemical carbonization took place under fundamental circumstances, the alcohols underwent conversion into CQDs. With greater possibility for application, these CQDs grow in size and degree of graphitization[13]. Carbonization by electrochemistry refers to the technique of creating carbon quantum dots from carbon precursors using an electrochemical method. This method involves the use of an electrochemical cell and appropriate electrodes to initiate and control the carbonization reaction.

Here’s a general overview of the process:

1. **Carbon Precursor Selection:** The first step is to choose a suitable carbon precursor. Common carbon precursors for CQDs synthesis include small organic molecules, biomass, polymers, or even waste materials rich in carbon content.
2. **Electrochemical Cell Setup**: An electrochemical cell is prepared with appropriate electrodes. Typically, a working electrode (anode) and a counter electrode (cathode) are used, with a suitable electrolyte solution
3. **Carbonization Reaction**: The carbon precursor is dissolved or dispersed in the electrolyte solution, and the electrochemical cell is energized. The electrochemical potential applied to the electrodes initiates the carbonization process.
4. **Electrolyte and Reaction Conditions:** The choice of electrolyte solution and reaction conditions (temperature, pH, voltage, etc.) depends on the specific carbon precursor and desired properties of the CQDs. The electrolyte can act as a reaction medium, influencing the size, morphology, and surface functionalization of the resulting CQDs.
5. **Carbon Dot Formation:** Under the influence of the electrochemical potential, carbon atoms from the precursor material are released and reorganize into small clusters or quantum dots. The precise mechanism of carbon dot formation is still an area of active research, and various pathways have been proposed.
6. **Post-Treatment**: Once the carbon dots are formed, they are usually separated from the electrolyte solution and subjected to post-treatment processes. These processes may involve purification steps, such as filtration or

dialysis, to remove impurities or unreacted precursors.

7. **Characterization and Applications:** The resulting carbon quantum dots can be characterized using various analytical techniques, including spectroscopy, microscopy, and elemental analysis.

It's worth noting that the specific details and parameters of the carbonization process can vary depending on the research or manufacturing methods employed. Researchers continue to explore different strategies to enhance the production and characteristics of carbon quantum dots, aiming to unlock their full potential for diverse applications.

- **Laser ablation**

Laser ablation has developed into a promising method for the synthesis of CQDs due to its ability to produce highly crystalline and well-defined carbon nanoparticles. Here's a short note on laser ablation for carbon quantum dots:

Laser ablation for carbon quantum dots synthesis involves the following key steps:

1. **Laser Setup**: A high-energy laser, such as a pulsed Nd: YAG or femtosecond laser, is employed to ablate a carbon-containing target material. The laser parameters, such as pulse duration, fluence, and repetition rate, are carefully controlled to achieve the desired outcomes.
2. **Target Material Selection**: Carbon-rich materials, such as graphite, carbon nanotubes, or carbonaceous precursors, are chosen as the intended content. These materials serve as the source of carbon atoms for the formation of CQDs.
3. **Laser Ablation Process**: On the desired substance, a laser beam is focused, resulting in the rapid heating and vaporization of the carbon-rich material. The intense laser energy creates a plasma plume containing carbon vapor, which subsequently undergoes nucleation and condensation processes to form CQDs.
4. **Cooling and Collection**: The plasma plume rapidly expands and cools down, allowing the CQDs to solidify. Depending on the specific setup, the CQDs can be collected on a substrate or in a collection chamber.
5. **Post-Treatment**: The collected CQDs often require post-treatment processes to remove impurities and improve their properties. Purification techniques such as filtration, centrifugation, or dialysis may be employed.
6. **Characterization and Applications**: The synthesized CQDs are characterized using various techniques, including spectroscopy, microscopy, and elemental analysis, to determine their size, structure, surface chemistry, and photoluminescent properties. They can be further functionalized or integrated into various Platforms, such as optoelectronics, and energy storage.

Laser ablation offers several advantages in order to create carbon quantum dots. Additionally, it is a relatively fast and scalable technique that enables the production of high-quality CQDs with excellent photoluminescence. However, optimization of laser parameters, target material selection, and post-treatment processes are crucial to achieving the desired CQD properties.

- **Microwave irradiation**

A quick and inexpensive way to make CQDs is by irradiating organic molecules with microwave energy.

Microwave irradiation has gained attention as a rapid and efficient method for the formation of (CQDs). Here's a short note on the use of microwave irradiation for carbon quantum dots synthesis:

Microwave Irradiation for Carbon Quantum Dots Synthesis:

1. **Precursor Selection**: Carbon-rich precursors, such as organic molecules, sugars, biomass, or polymers, are chosen as the starting materials for CQDs synthesis. The choice of precursor influences the properties and characteristics of the resulting CQDs.
2. **Microwave Reaction Setup**: The precursor solution or mixture is prepared, typically in a suitable solvent. The solution is then placed in a microwave reactor vessel that can withstand microwave irradiation.
3. **Microwave Irradiation**: The reactor vessel is subjected to microwave irradiation, which generates an intense electromagnetic field. The microwave energy rapidly and uniformly heats the precursor solution, promoting the carbonization process.
4. **Carbonization and CQD Formation**: The applied microwave energy causes the precursor molecules to undergo carbonization, CQDs, or carbon-rich clusters, are created as a result. The specific mechanism of CQD formation under microwave irradiation is still an area of ongoing research.
5. **Reaction Control**: The power level, irradiation time, and reaction conditions (temperature, pressure, atmosphere) can be altered to regulate the dimensions, composition, and characteristics of the synthesized CQDs. The reaction progress can be monitored by periodic sampling and characterization.
6. **Post-Treatment**: When the reaction is finished, the CQDs are typically separated from the reaction mixture and subjected to post-treatment processes. This may involve purification steps, such as filtration or dialysis, to remove impurities or unreacted precursors.
7. **Characterization and Applications**: The synthesized CQDs are characterized using various techniques, including spectroscopy, microscopy, and elemental analysis, to determine their size, structure, surface chemistry, and optical properties. They can be used in many different fields such as bioimaging, sensing, energy storage, and catalysis.

The application of microwave irradiation for carbon quantum dots synthesis offers several advantages, including rapid reaction times, energy efficiency, and precise control over reaction parameters. It enables the synthesis of CQDs with desirable properties, such as uniform size distribution, enhanced photoluminescence, and surface functionalization. However, optimization of precursor selection, microwave power, and reaction conditions is crucial to achieve the desired CQD characteristics. In summary, microwave irradiation is a promising method in order to create carbon quantum dots, providing a convenient and efficient approach to produce well-defined nanoparticles with potential applications in various fields

- **Hydrothermal/solvothermal treatment**

Solventothermal carbonization, or carbonization caused by hydrothermal processes (HTC)[14], is a cost-effective and eco-friendly technique for creating new carbon-based substances from diverse source materials, while also being a secure and harmless procedure. Typically, a water-based reactor is used to seal off and heat an organic precursor solution. From a range of precursors, including protein, $C_6H_{12}O_6$, citrus acid, and banana juice, CQDs were produced via HTC.

By hydrothermally treating orange juice and then centrifuging it, Mohapatra et al. created CQDs with a QY of 26% and strong photoluminescence[49]. Fluorescent[24] CQDs with amino functionalization, having sizes between 1.5 to 4.5 nm, were produced by Liu et al. Keep in mind that the fluorescent[44] CQDs with amino functionalization can be used right away as cutting-edge bioimaging tools . A common method for producing CQDs is through solvothermal carbonization, which involves using an organic solvent for extraction after the process. Some instances, high-boiling organic solvents are heated with carbon-yielding compounds prior to extraction and concentration. This procedure has been reported in various studies .

Using the carbonization of carbohydrates, **Bhunia et al.**[6] created two varieties of CQDs with sizes less than 10 nm: hydrophobic and hydrophilic. To create hydrophobic ones, different concentrations of carbohydrate were mixed with octadecyl amine and octadecene. This process was used as a method in their production. These were then heated for 10 to 30 minutes at 70 to 300 °C. By heating a carbohydrate solution a broad pH range in water, the hydrophilic ones can be produced. A process for creating hydrophilic CQDs with yellow and red emissions involves the addition of concentrated phosphoric acid to a carbohydrate-containing aqueous solution and heating the mixture for 1 hrs.

2.2. Size Controlled, Restricted Pyrolysis

Achieving uniform properties in CQD (colloidal quantum dots) through size control is vital for targeted applications and in-depth understanding of their mechanisms.

Several approaches have been suggested for obtaining homogeneous colloidal quantum dots (CQDs) either during or post-therapy. Most of the research papers utilized various techniques used after therapy such as filtering, dialysis, centrifuging, column chromatography for the purification of the generated CQDs fragments. Throughout the preparation phase, it is crucial to keep the size under control. By utilizing nanoreactors, discrete carbon quantum dots (CQDs) can be synthesized with precise control over their sizes. This is achieved through enclosed pyrolysis of an organic precursor. The release of CQDs in their original form involves three essential processes, wherein capillary force plays a crucial role. These processes include: (i) absorption of permeable nanoreactors with the organic precursor (ii) conversion of the carbonaceous matter trapped in the nanoreactors into CQDs, and (iii) removal of the nanoreactors. The textural parameters of the nanoreactors are responsible for governing the Measurement and size dispersion of the CQDs generated through this approach.

CQDs of a consistent size ranging from 1.5-2.5 nm were successfully synthesized using pyrolysis at 300°C in the occurrence of air, followed by the removal of silica and dialysis. These CQDs exhibit excellent photostability, low toxicity, remarkable luminosity, and the ability to perform up-conversion.

Linear polymers with enediyne units were used to create single-chain polymeric nanoparticles through a process of chain collapse that is mediated by Bergman cyclization. We created well-dened CQDs with adjustable and uniform diameters. The polymeric nanoparticles that included polynaphthylene that were created underwent a bijective process to become One-to-one correspondence, or CQDs.

The luminescent properties of the generated CQDs were found to be size-dependent, with the peak emission color shifting to blue as the size increased.

3.CQDs Properties and Applications

Properties:

The distinctive characteristics of CQDs include robust fluorescence, biocompatibility, minimal toxicity, and exceptional photostability, which are attributed to both their quantum confinement effect and surface functional groups. CQDs also have a high surface area and can be easily they are functionalized with different groups, making them appropriate for a variety of applications.

Carbon quantum dots (CQDs) are a specific category of nanomaterials, possess unique properties that render them well-suited for various applications, including biomedical imaging, drug delivery, and solar cells.

Several essential characteristics of CQDs include:

1. **Size**: CQDs typically have a diameter of less than 10 nanometers, which makes them extremely small and allows them to penetrate cell membranes and tissues more easily than larger particles.
2. **Optical Properties:** CQDs exhibit unique optical[15] characteristics like high fluorescence, excellent photostability, adjustable emission and many more.
3. **Surface Chemistry:** CQDs' surface can be quickly functionalized, enabling the attachment of several biomolecules, medications, and other functional groups.
4. **Biocompatibility:** CQDs are generally biocompatible, meaning they do not elicit a significant immune response and are not toxic to cells.
5. **Chemical Stability:** CQDs are chemically stable, which means they can withstand harsh environments and are not prone to degradation over time.
6. **Electrical Properties:** CQDs also exhibit interesting electrical properties, such as high electron mobility and good conductivity, making them useful for applications in optoelectronics[6] and energy storage.

Applications:

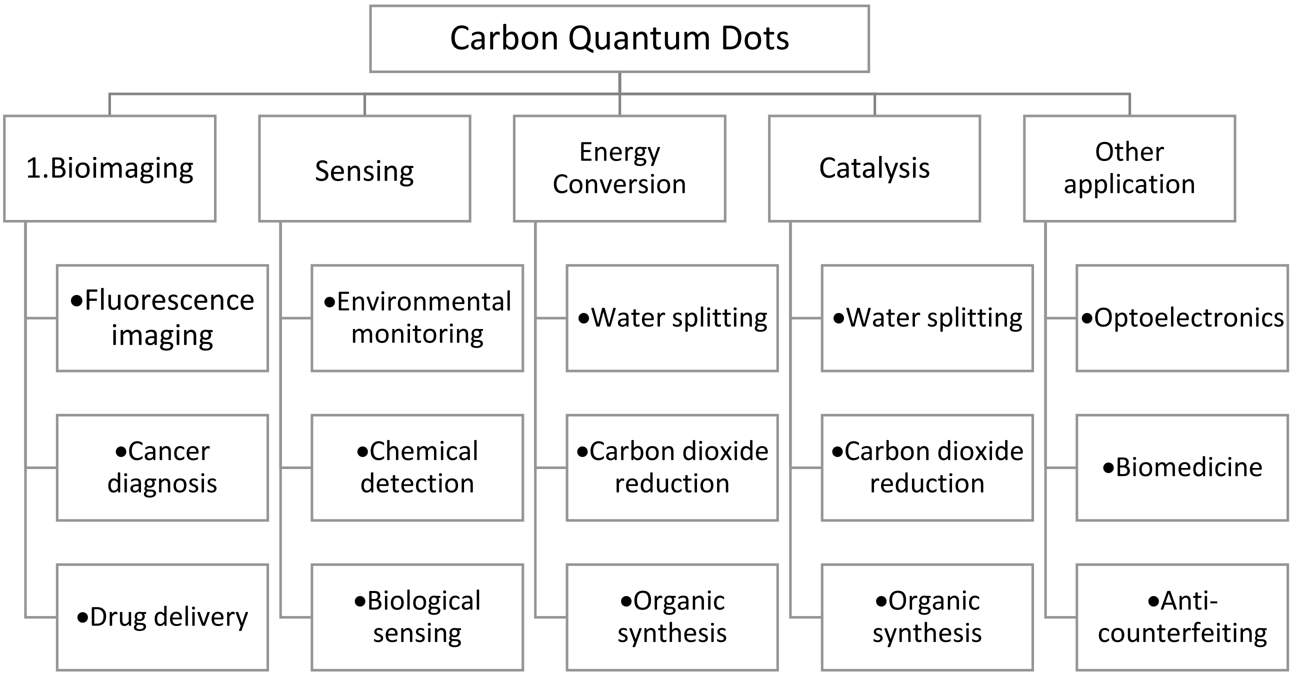
CQDs have the potential for utilization in a variety of industries, including bioimaging, optoelectronics[15], and energy storage. In bioimaging[4], CQDs able to serve as fluorescent[16] imaging probes of biological samples such as cells and tissues they are less hazardous and high biocompatibility. In optoelectronics, CQDs can act as a component in light-emitting diodes (LEDs) due to their strong fluorescence[17] and high photostability[18]. Due to their substantial surface area[19] and notable capacitance, carbon quantum dots (CQDs) have the potential to serve as a constituent in supercapacitors, particularly in the field of energy storage.

Recent studies on CQDs have primarily concentrated on enhancing their characteristics and facilitating their utilization in diverse applications through the exploration of novel synthesis approaches. One area of interest is the development of green synthesis methods that use sustainable and low-cost materials, such as waste biomass, to produce CQDs.

Additional studies have concentrated on investigating the characteristics of the photoluminescence[12] exhibited by CQDs. These traits can be adjusted by managing the conditions of synthesis, such as temperature, concentration of the precursor, and duration regarding the reaction.

Apart from their optical[20] characteristics, CQDs possess have also been investigated for their electrochemical[21] properties, which Form them attractive for use in Storage and conversion of energy devices such as supercapacitors and batteries. Here is a Table 1 of potential applications for CQDs.

Table 1: Potential Applications of Carbon Quantum Dots (CQDs).



Conclusion

To sum up, CQDs are a promising nanomaterial with special qualities and potential uses in a range of industries. To fully achieve the potential of CQDs and create cutting-edge synthesis techniques and applications, more study is required.

Carbon Quantum Dots, possess exceptional qualities like high surface area, photoluminescence, and low toxicity, which make them a versatile and promising material class. Their distinct attributes have made them a subject of extensive study for various purposes, including bioimaging, sensing, drug delivery, and energy storage and conversion.

Recent research has focused on developing green synthesis methods for CQDs using sustainable and low-cost materials, alongside exploring their photoluminescence and electrochemical properties. CQDs are attractive for use in a number of applications since they can obtain their properties through synthesis conditions.

As new synthesis methods are developed and their properties are better understood, CQDs are expected to find even more exciting applications in a range of fields. The research on CQDs is an active and ongoing area of investigation, and further advances in this field will continue to contribute to the creation of new and innovative technologies.

Conflict of Interest:

We, authors of this research article declare no conflict of interest.

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