

A REVIEW OF CARBON QUANTUM DOTS: SYNTHESIS, CHARACTERISTICS, ADVANCES, APPLICATIONS AND FUTURE PERSPECTIVES

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ABSTRACT

Recent developments in nanotechnology have opened new possibilities for improving drug design, delivery, and therapeutic performance. Among the various nanomaterials, carbon quantum dots (CQDs) have attracted considerable attention because of their small particle size, excellent photoluminescence, good water solubility, and low toxicity. In recent years, the concept of quantum drugs (Q-drugs) has emerged as an innovative strategy in which drug molecules themselves function as precursors for the formation of carbon quantum dots. This approach allows the direct conversion of pharmaceutical molecules into nanoscale quantum structures, eliminating the need for additional carbon sources or post-synthetic drug loading. As a result, the drug potentially improves solubility, bioavailability, and biological activity. This review highlights the fundamental concepts of quantum drugs and carbon quantum dots, including their structural characteristics, physicochemical properties, and synthesis methods. Both top-down and bottom-up approaches are employed in CQD synthesis, alongside emerging green and electrochemical techniques. Continued research is expected to expand the potential of CQDs and drug-derived quantum nanomaterials in pharmaceutical and biomedical applications.

KEYWORDS: Carbon quantum dots, nanoparticles, quantum yield, carbon dots, photoluminescence, fluorescence.

INTRODUCTION

Carbon quantum dots (CQDs), also known as carbon dots or C-dots, are a class of zero- dimensional carbon-based nanomaterials with particle sizes typically less than 10 nm.^[1] These nanomaterials have attracted significant attention in recent years due to their unique optical, electronic, and physicochemical properties.^[2] Carbon quantum dots (CQDs)

can be synthesized using two main strategies: top-down and bottom-up methods.^[3] The top-down approach breaks larger carbon materials such as graphite, carbon nanotubes, or graphene into nanoscale particles through techniques like laser ablation, electrochemical oxidation, and arc discharge.^[4] In contrast, the bottom-up method forms CQDs by carbonizing small molecular precursors such as citric acid, glucose, urea, or biomass using processes like hydrothermal treatment, microwave irradiation, and thermal decomposition.^[5] Because it is simple, low-cost, and suitable for large-scale production, the bottom-up approach is widely preferred,^[6] and recent green synthesis methods using plant extracts or biomass have further improved its environmental sustainability.^[7] Continued research in this field is expected to further expand the potential applications of carbon quantum dots in nanotechnology, medicine, environmental science, and energy systems.^[8]

QUANTUM DRUGS (Q-DRUGS)

Quantum drugs (Q-Drugs) refer to drug-derived carbon quantum dots (CQDs) that are synthesised directly from drug molecules.^[9] Unlike conventional drug delivery systems, in which drugs are loaded onto pre-synthesised CQDs, this approach converts drug molecules into CQDs during synthesis.^[10] In this process, the drug can function as a carbon source or as a heteroatom dopant depending on its chemical structure and elemental composition. This method eliminates the need for additional carbon precursors or dopants and enables the formation of pharmacologically active CQDs with drug molecules present on their surface. The Q-Drug approach offers a promising strategy for developing more active therapeutic agents with improved efficiency, potentially enabling faster drug action and reduced dosage.^[11] As a result, Q-Drugs may represent a new generation of therapeutics with innovative treatment possibilities.

CARBON QUANTUM DOTS

Carbon dots (CDs), also known as carbon quantum dots (CQDs), are a class of zero-dimensional fluorescent carbon nanomaterials with sizes typically below 10 nm.^[12] The term “carbon quantum dots” was introduced by Sun and co-workers,^[13] and since then, CQDs have gained significant attention due to their unique structure and remarkable physicochemical properties. These nanoparticles exhibit strong photoluminescence, high quantum yield, tunable excitation and emission behaviour, high thermal and optical stability, easy surface functionalization, and low toxicity with good biocompatibility.^[14] They can also be synthesised easily and cost-effectively from bio-based precursors. Because of these advantages, CQDs have found applications in various fields, including energy conversion and storage, photocatalysis, electrocatalysis, biosensing, bioimaging, drug and gene delivery, electrochemical sensing, and corrosion inhibition.^[15] The study of CQDs focuses on their fundamental properties and synthesis through top-down and bottom-up approaches, which contribute to their wide applicability compared to conventional semiconductor materials.

FUNDAMENTAL PRINCIPLE OF CARBON QUANTUM DOTS

Carbon quantum dots (CQDs) are photoluminescent nanoparticles with sizes typically below 10 nm and structures that vary depending on the synthesis method used. They typically have a quasi-spherical shape, low molecular weight, and exhibit quantum confinement.^[16] CQDs possess various surface functional groups such as –OH, –NH₂, and –COOH, which provide excellent water solubility, biocompatibility, and enable easy chemical modification.^[17] These functional groups also allow CQDs to interact with different organic, inorganic, and biological materials, while surface passivation and heteroatom doping can further enhance their optical and fluorescence properties. The chemical structure of CQDs strongly influences their luminescence behaviour, and techniques such as FTIR, UV–visible spectroscopy, and X-ray photoelectron spectroscopy (XPS) are commonly used for their characterisation.^[18] Due to these unique features, CQDs

offer advantages over other carbon nanomaterials, and research in this field focuses on several types of carbon dots, including CQDs, carbon nanodots (CNDs), polymer dots (PDs), carbonised polymer dots (CPDs), and graphene quantum dots (GQDs).

PROPERTIES OF CQDs

➤ OPTICAL PROPERTIES

Carbon quantum dots exhibit unique optical properties, particularly strong fluorescence, which arises when they absorb electromagnetic radiation and move to an excited state before emitting light.^[19] The fluorescence behaviour of CQDs can be adjusted by changing factors such as particle size, surface functional groups, and the synthesis method used during their preparation.^[20] Studies have also shown that the thickness of the quantum dots can influence their fluorescence characteristics. For example, Yang and co-workers prepared graphene quantum dots through the electrochemical exfoliation of graphite and observed that variations in surface defects and surface states resulted in different fluorescence behaviours. In many cases, CQDs show two distinct emission peaks at different excitation wavelengths. However, fluorescence in CQDs may originate from several mechanisms, including quantum confinement effects, surface defect states, molecular fluorophore states, and cross-link enhanced emission. Another important feature of CQDs is the stability of their fluorescence, as they can maintain strong emission intensity and high quantum yield even under harsh environmental conditions.

➤ CHEMICAL INERTNESS

Carbon quantum dots exhibit good chemical inertness, which means they remain stable and show limited reactivity with other chemical substances.^[19] This stability is determined by the functional groups present on their surface. These surface groups help maintain the structural integrity of CQDs and protect them from unwanted chemical changes. Studies have reported that CQDs can maintain strong fluorescence intensity and high quantum yield even when exposed to harsh conditions such as elevated temperatures, strong acidic or basic environments, and high concentrations. Because of this strong chemical stability, carbon quantum dots can perform reliably in various practical applications.

➤ BIOLOGICAL INERTNESS

CQDs are especially safe, where they show minimal toxicity to human cells and may even support cell growth. However, their cytotoxicity can increase when the concentration becomes too high. Compared with conventional semiconductor quantum dots, CQDs are considered safer because of their high biocompatibility and low toxicity. Their excellent water solubility and stability make them suitable for combining with biomolecules or drugs, which allows their use in applications such as bioimaging, drug delivery, and photo diagnostics. The strong fluorescence of CQDs also enables them to act as sensitive fluorescent probes for detection and analysis. In addition, their good compatibility with biological systems allows them to enter cells easily, making them useful for cellular imaging and therapeutic delivery. Biological studies showed that these CQDs were non-toxic to WRL-68 cells and only slightly toxic to HT1080 cancer cells, suggesting possible selective effects on cancer cells. They were also found to be non-toxic to plant seedlings and did not inhibit microbial growth. These findings highlight the potential of CQDs for biomedical uses such as biomolecular sensing, controlled drug release, drug delivery, and fluorescent tracing.

➤ UPCONVERSION PHOTOLUMINESCENCE

- Carbon quantum dots exhibit several types of photoluminescence behaviours, among which down-conversion and up-conversion luminescence are important. Down-conversion photoluminescence is the more commonly observed phenomenon, where the emitted light has a longer wavelength than the excitation light.
- In contrast, up-conversion photoluminescence occurs less frequently and involves the absorption of two or more photons at the same time, leading to the emission of light with a shorter wavelength than the excitation source, also known as anti-Stokes emission.
- Researchers have also demonstrated that by modifying the structure and surface functional groups of CQDs, it is possible to tune their optical properties so that they can be excited by visible light and emit red or near-infrared radiation.
- For instance, Jia and co-workers prepared CQDs with up-conversion fluorescence through a simple one-step synthesis method, where excitation in the near-infrared region produced a stable emission peak around 540 nm, indicating that the emission originated from the lowest excited state regardless of the excitation wavelength.

➤ ADSORPTION PROPERTIES

- Carbon quantum dots possess remarkable adsorption ability because of their high specific surface area, porous nature, reactive surface sites, and the presence of numerous functional groups. These characteristics allow them to effectively capture several types of substances such as organic molecules, metal ions, toxic compounds, and gases. Owing to these properties, carbon quantum dots have been widely explored in applications including environmental remediation, drug delivery, and photocatalysis.
- In water treatment, they are particularly useful for removing organic contaminants like dyes, antibiotics, and pesticides. As reported by Wang et al., the adsorption efficiency of carbon quantum dots depends on several factors, including the synthesis technique, structural features, chemical composition, and surface modifications.
- Environmental conditions such as pH, temperature, ionic strength, and the amount of organic matter present in water also play a significant role. The adsorption process occurs through interactions such as electrostatic attraction, hydrogen bonding, π - π stacking, and van der Waals forces, although the dominant interaction may vary depending on the type of organic pollutant involved.

TYPES OF CARBON QUANTUM DOTS

Carbon quantum dots can be broadly classified into different types based on their structure, composition, and method of preparation. The main types include carbon quantum dots (CQDs), graphene quantum dots (GQDs), carbonized polymer dots (CPDs), and carbon nanodots (CNDs).

- **Carbon quantum dots (CQDs)** are small spherical carbon nanoparticles that contain both crystalline and amorphous carbon cores. Their surfaces usually have various functional groups such as hydroxyl, carboxyl, and carbonyl groups, which improve their solubility and chemical reactivity. These dots are widely used in sensing, bioimaging, and environmental applications because of their good optical and chemical properties.

These are small spherical carbon nanoparticles containing both crystalline and amorphous carbon structures. They are commonly synthesized by hydrothermal or solvothermal methods, where organic precursors such as glucose or citric acid are heated in a sealed reactor to form nanosized carbon particles.

- **Graphene quantum dots (GQDs)** are nanoscale fragments of graphene sheets with a layered structure. They possess excellent electronic and optical properties due to the presence of graphene-like sp^2 carbon networks. Because of their strong fluorescence and high stability, graphene quantum dots are commonly applied in optoelectronics, biosensing, and energy-related fields.

They are usually prepared by top-down methods, such as chemical oxidation, hydrothermal cutting, or electrochemical exfoliation of graphene or graphite.

- **Carbon nanodots (CNDs)** are quasi-spherical nanoparticles composed of amorphous carbon. They typically show strong photoluminescence and good water solubility. Their surfaces often contain oxygen-containing functional groups, which make them suitable for biomedical imaging, drug delivery, and environmental monitoring.

They are often synthesized through microwave-assisted synthesis, laser ablation, or pyrolysis of small organic molecules.

- **Carbonized polymer dots (CPDs)** are formed from the partial carbonization of polymer precursors. In these dots, polymer chains and carbon cores coexist, which contributes to their unique optical properties. CPDs often show strong fluorescence and are frequently used in bioimaging, sensing, and photocatalytic application.

These dots are produced from the partial carbonization of polymer or organic precursors. The common synthesis methods include thermal treatment or hydrothermal carbonization of polymers such as polyethylene glycol or other organic compounds.

METHODS OF SYNTHESIS

The synthesis of carbon quantum dots (CQDs) can be classified into two major approaches: top-down and bottom-up methods. In the top-down approach, larger carbon materials such as graphite, graphene, or carbon nanotubes are broken down into nanoscale particles. In contrast, bottom-up approaches involve the carbonization of small molecular precursors such as organic molecules, polymers, or biomass to form nanoscale carbon structures. Each method has its own advantages, limitations, and applications depending on the desired properties of the carbon dots.

1) TOP-DOWN SYNTHESIS METHOD

Top-down synthesis methods involve the breaking down of bulk carbon materials into nanoscale carbon dots through physical, chemical, or electrochemical processes. In this approach, large carbon frameworks such as graphite, carbon fibres, carbon black, graphene, or carbon nanotubes are cleaved into smaller fluorescent carbon domains. These methods are particularly effective for producing graphene quantum dots and highly oxidized carbon dots.

- **Chemical Oxidation Method**

Chemical oxidation is one of the earliest and most widely used methods for synthesizing carbon quantum dots. In this process, bulk carbon materials are treated with strong oxidizing agents such as nitric acid, sulfuric acid, potassium permanganate, or their combinations. These oxidizing agents break down the large carbon structures into nanoscale fragments while simultaneously introducing oxygen-containing functional groups on the surface of the carbon dots. The process involves several stages. Initially, the oxidizing agents attack the carbon framework, leading to the cleavage of carbon layers and the formation of smaller fragments. These fragments then undergo further oxidation and

functionalization, resulting in nanosized carbon particles with abundant surface functional groups such as hydroxyl, carbonyl, and carboxyl groups. Finally, purification techniques such as dialysis or centrifugation are used to isolate the carbon dots.

➤ **Electrochemical Exfoliation**

Electrochemical exfoliation is a mild and controllable top-down technique used for producing carbon quantum dots. In this method, graphite rods or carbon electrodes are used as working electrodes and subjected to an applied potential in an electrolyte solution. During the process, anodic oxidation causes the carbon layers to gradually exfoliate and break down into nanoscale carbon dots. The electrochemical reactions occurring at the electrode– electrolyte interface generate oxidative stress that cleaves the carbon framework into smaller fragments. Parameters such as applied voltage, electrolyte composition, reaction time, and pH play a crucial role in determining the size and properties of the resulting carbon dots. This technique offers several advantages including mild reaction conditions, minimal chemical waste, and narrow size distribution. However, the method may still face challenges related to large-scale production and precise control over surface functionalization.

➤ **Laser Ablation Method**

Laser ablation is another top-down approach used for synthesising carbon quantum dots. In this technique, high- energy laser pulses are directed at bulk carbon targets such as graphite or carbon powders. The intense laser energy causes rapid vaporisation and fragmentation of the carbon material. The vaporised carbon species then cool and condense to form nanoscale carbon dots. The properties of the resulting carbon dots depend on a range of factors such as the type of carbon target, laser power, pulse duration, and surrounding medium. This method produces carbon dots with high purity and minimal chemical contamination, making it suitable for optical and biomedical studies.

➤ **Arc Discharge Method**

The arc discharge technique is a high- temperature method originally developed for carbon nanotube synthesis but later adapted for the preparation of carbon dots. In this method, two carbon electrodes are placed in an inert atmosphere and subjected to a high-current electric arc. The intense heat generated by the arc vaporises the carbon electrodes, and the evaporated carbon species condense to form nanoscale carbon structures, including carbon dots. Although this method can produce highly crystalline carbon structures, it has several drawbacks, such as poor size control, complex purification steps, and high energy consumption. As a result, it is less commonly used for the synthesis of carbon dots compared with other techniques.

2) BOTTOM-UP SYNTHESIS METHOD

Bottom-up synthesis involves the formation of carbon quantum dots from small organic molecules through chemical reactions such as dehydration, polymerisation, and carbonisation. This approach is widely preferred because it is simple, cost- effective, and allows better control over the chemical composition and surface functionality of carbon dots.

➤ **Hydrothermal Synthesis**

Hydrothermal synthesis is one of the most widely used bottom-up methods for preparing carbon quantum dots due to its simplicity and environmental compatibility. In this method, organic precursors such as citric acid, glucose, polymers, or pharmaceutical molecules are dissolved in water and heated in a sealed autoclave at elevated temperatures, typically between 150 °C and 250 °C. Under these conditions, several chemical transformations occur sequentially. Initially, the

precursor molecules undergo decomposition and dehydration reactions. This is followed by polymerization and condensation processes that form carbon-rich molecular clusters. These clusters then undergo aromatization and carbonization to produce sp^2 -rich carbon nuclei. Finally, nucleation and growth processes lead to the formation of nanoscale carbon cores, while residual functional groups remain on the surface, providing natural surface passivation. Hydrothermal synthesis produces carbon dots with good water solubility, excellent photoluminescence, and tunable surface functionality. The method is also suitable for large-scale production and for the synthesis of drug-derived carbon dots.

➤ **Solvothermal Synthesis**

Solvothermal synthesis is like hydrothermal synthesis but uses organic solvents instead of water as the reaction medium. In this method, molecular precursors are dissolved in solvents such as ethanol, dimethylformamide, or ethylene glycol and heated in a sealed reactor at temperatures typically ranging from 180 °C to 300 °C. During the solvothermal process, precursor molecules undergo solvent- assisted decomposition followed by polymerisation and carbonisation reactions. These reactions lead to the formation of sp^2 - hybridized carbon domains that eventually grow into nanoscale carbon dots. The choice of solvent plays a crucial role in determining the reaction kinetics, degree of carbonisation, and surface chemistry of the resulting carbon dots. Solvothermal methods often produce carbon dots with improved fluorescence properties and enhanced surface functionality, making them suitable for bioimaging and sensing applications.

➤ **Microwave-Assisted Synthesis**

Microwave-assisted synthesis is a rapid and energy-efficient method for producing carbon quantum dots. In this approach, microwave irradiation is used as the heating source to induce carbonisation of molecular precursors. Unlike conventional heating, microwave irradiation generates uniform volumetric heating through dipolar polarization and ionic conduction. This leads to significantly faster reaction rates and shorter synthesis times, often producing carbon dots within a few minutes. Microwave synthesis is advantageous because it reduces energy consumption, provides uniform heating, and improves reaction efficiency. Additionally, it allows rapid screening of different precursor materials for the preparation of carbon dots with tailored properties.

➤ **Pyrolysis or Carbonisation Method**

Pyrolysis is a thermal decomposition process in which organic precursors are heated at elevated temperatures to form carbon-rich nanostructures. During pyrolysis, the precursor molecules undergo dehydration, decomposition, and condensation reactions that eventually produce a carbonaceous core with surface functional groups. The temperature required for carbon dot synthesis through pyrolysis typically ranges from 150 °C to 350 °C. This process results in partial carbonisation rather than complete graphitisation, which helps preserve surface functional groups that contribute to photoluminescence and solubility.

➤ **Chemical Vapor Decomposition (CVD)**

Chemical vapor decomposition is a vapor- phase method in which volatile carbon- containing precursors are thermally decomposed at elevated temperatures in a controlled atmosphere. The decomposition of the precursor molecules leads to the formation of nanoscale carbon structures, including carbon dots. CVD typically produces carbon dots with highly crystalline structures and narrow size distributions. However, the high- temperature conditions limit surface functionalization and require additional post-synthesis treatments to improve dispersibility and optical properties.

Therefore, this method is used for structural studies rather than pharmaceutical applications.

APPLICATIONS OF CARBON QUANTUM DOTS

Carbon quantum dots are emerging nanomaterials that are widely used in a variety of fields due to their unique optical, electrical, thermal, and biocompatible properties. The fields of application of carbon quantum dots.^[20]

➤ Drug Delivery

Carbon dots are widely used in drug delivery because of their photoluminescence, low toxicity, and good biocompatibility. Many anticancer drugs have poor water solubility and may damage healthy cells, which limits their clinical use. Carbon dots can act as nanocarriers that help deliver these drugs directly to cancer cells. For example, researchers have combined carbon dots with the anticancer drug doxorubicin (DOX). Carbon dots synthesized from citric acid and ethylenediamine using the hydrothermal method were conjugated with DOX to form a CDs-DOX complex, improving drug delivery efficiency.

➤ Bioimaging

Carbon dots have attracted attention as fluorescent probes for bioimaging due to their strong and stable fluorescence, small size, and low toxicity. Traditional dyes used in cell imaging can be toxic and often require cell fixation. Carbon dots overcome these limitations and enable imaging in living cells. For instance, carbon dots prepared from *Plectranthus amboinicus* leaves have been successfully used for cell imaging and as fluorescent staining agents for *Candida albicans* with minimal toxicity.

➤ Sensing Application

Carbon dots are also used as sensors for detecting metal ions, anions, bacteria, and small molecules. Their sensing ability arises from functional groups such as hydroxyl, carboxyl, and amine groups on their surface. These groups interact with analytes and can cause fluorescence quenching through electron transfer processes. Carbon dots have been reported for the detection of metal ions including Fe^{3+} , Hg^{2+} , Ag^+ , Pb^{2+} , Cu^{2+} , Au^{3+} , and Cr^{6+} .

➤ Water Purification

Carbon dots have promising applications in water treatment due to their photocatalytic properties. They can degrade organic pollutants when exposed to light. For example, carbon dots synthesized from pear juice have been used to degrade methylene blue dye. Their photocatalytic activity can be further enhanced by metal ion doping, heteroatom doping, or forming composites with metal oxides such as TiO_2 , ZnO , and SiO_2 . These combinations improve charge separation and generate reactive oxygen species that break down pollutants. Studies have shown that TiO_2 /nitrogen-doped carbon dot composites can achieve about 90% degradation of methylene blue within 40 minutes.

➤ Solar Cells

Carbon dots are being explored in solar cell technology because of their intense light absorption, photoluminescence, and efficient electron transfer properties. They can function as electron-accepting materials or sensitizers in dye-sensitized solar cells. Recent research shows that incorporating carbon dots into perovskite solar cells can improve their efficiency and performance.

➤ Cancer Therapy

Carbon nanomaterials such as carbon dots, carbon nanotubes, and fullerenes have gained significant attention in cancer research. Their stability, biocompatibility, and ability to be functionalized make them useful for targeted drug delivery and therapy. Carbon dots can help overcome challenges such as poor drug stability, limited penetration, and non-specific targeting, thereby improving the effectiveness of anticancer treatments.

CURRENT CHALLENGES

One of the main challenges in the application of carbon quantum dots (CQDs) is the lack of uniformity in their size, surface chemistry, and structural properties caused by current synthesis methods. Techniques such as laser ablation, chemical vapor deposition, and hydrothermal synthesis often involve expensive materials and high energy consumption, making large-scale production difficult. In addition, CQDs produced by these methods may show variations in optical properties, which can affect their performance in biological systems. Maintaining stability in physiological conditions is another concern, as CQDs may degrade or lose their fluorescence over time. Although surface modification methods are used to improve stability and reduce toxicity, further research is needed to enhance targeting ability, photostability, and overall compatibility for long-term biomedical applications.

FUTURE PERSPECTIVES

Future research on CQDs is expected to focus on improving targeted drug delivery and advanced bioimaging techniques. By modifying their surface with specific ligands, CQDs can potentially deliver drugs directly to diseased tissues or cancer cells, reducing side effects on healthy cells. Their tunable fluorescence and low toxicity also make them suitable for multimodal imaging platforms that combine fluorescence with techniques such as MRI or CT. Enhancing photostability and extending fluorescence into the near-infrared region could improve tissue penetration and enable longer imaging periods. Continued development of stable, scalable, and cost-effective synthesis methods will be essential for translating CQD technology from laboratory research to clinical applications.

CONCLUSION

Carbon quantum dots (CQDs) have gained significant attention due to their unique optical properties, good biocompatibility, and versatile surface chemistry. Their size-dependent electronic structure and strong photoluminescence allow tunable emission across the visible spectrum, making them useful in many scientific and technological fields. Because they are water-soluble and contain functional surface groups, CQDs have shown immense potential in biomedical applications such as fluorescence imaging, drug delivery, and biosensing. With ongoing research to overcome current limitations, CQDs are expected to play a significant role in future developments in nanotechnology and biomedical science.

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