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# Trends in Pharmacology and Drug Delivery



## Review article

## Carbon dots, synthesis and applications in cancer therapy

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**Abstract:** Carbon dots (CDs) are carbon-based nanomaterials (<10 nm) that have gained attention for cancer diagnosis and therapy due to their biocompatibility, eco-friendliness, facile synthesis, low toxicity, and chemical stability. Their versatile properties make them promising nanocarriers for drug delivery and effective agents for bioimaging, biosensing, gene delivery, photodynamic therapy, and diagnostics. Growing research efforts worldwide have advanced the understanding of their physicochemical properties, diagnostic potential, and therapeutic functions, positioning CDs as key candidates for next-generation nanotheranostics. This review highlights the synthesis of CDs and recent progress in their application as nanocarriers for cancer imaging and targeted therapy.

## 1. Introduction

Viral Cancer has become a predominant global health issue, marked by its significant incidence and mortality rates [1]. This disease is defined by the uncontrolled proliferation of cells, which can metastasize from an initial site to various parts of the body, ultimately leading to fatal outcomes. Consequently, the early detection and intervention of cancer are vital for minimizing its spread and associated mortality. There is a pressing need to develop novel therapies and strategies that enable precise and effective treatment of cancer [2]. Nanotheranostics, which integrate both diagnostic and therapeutic capabilities into a single nanopatform, are becoming increasingly significant in cancer therapy. This integration facilitates the collection of targeted data, allowing for low-interference, high-sensitivity, and precise

treatment of cancer. Additionally, such a combined approach can effectively monitor tumor metastasis and recurrence, thereby enhancing therapeutic efficacy [3].

Over the past decade, CDs have garnered significant attention across various fields, including light-emitting diodes, bioimaging, photocatalysis, and plant growth enhancement. This interest is largely attributed to their advantageous electrical, mechanical, optical, thermal, and biocompatible properties. CDs, also referred to as carbon quantum dots (CQDs), were discovered serendipitously by Xu and colleagues in 2004 [4]. They were named for their spectral characteristics, which are comparable to those of the widely studied silicon quantum dots. CDs have since been recognized as promising candidates for cancer diagnosis [5]. They have been explored for cancer diagnosis using

photoacoustic (PA) imaging, magnetic resonance imaging (MRI), and fluorescence imaging techniques [6].

The properties of CDs are largely influenced by quantum confinement and surface states, which can be tuned through different synthesis methods and precursors. CDs often contain functional groups such as amine, carboxyl, carbonyl, hydroxyl, ether, epoxy, and heteroatoms, which enable conjugation with organic molecules, polymers, and biomolecules [7]. Such surface modifications significantly influence their physicochemical behavior, particularly their photoluminescence (PL), which spans a broad range of emission wavelengths. This tunability is influenced by factors such as particle size (reflecting quantum effects), surface states, and the presence of diverse functional groups. The design flexibility enables precise control over size and surface functionalities, further expanding the range of possible emission wavelengths [8]. CDs have attracted significant attention in cancer research owing to their versatility, serving as bioimaging probes, nanocarriers for targeted drug delivery, and promising agents for photodynamic therapy (PDT) and photothermal therapy (PTT) [9]. Certain CDs inherently exhibit anticancer properties, contributing to their effectiveness in PDT and PTT. In PDT, photosensitizers generate reactive oxygen species (ROS) under light irradiation, inducing oxidative damage to cellular macromolecules and triggering cancer cell death [10]. In contrast, PTT employs photothermal agents that convert absorbed photon energy into localized heat, causing irreversible tumor cell damage [11]. Both PDT and PTT allow precise light targeting of tumor cells, thereby sparing healthy cells and reducing systemic toxicity compared to conventional chemotherapy or radiotherapy. Owing to their intrinsic phototheranostic properties, CDs present a promising platform for advanced tumor therapy applications [12].

This review highlights the synthesis strategies of CDs and their emerging role as nanotheranostic agents in cancer treatment. Particular emphasis is placed on their application as nanoscale drug delivery systems and their broader contributions to the advancement of cancer therapy.

## **2. Carbon dots (CDs) and carbon quantum dots (CQDs)**

Carbon dots (CDs) and carbon quantum dots (CQDs) represent two classes of carbon-based nanomaterials, both typically measuring less than 10 nanometers in diameter. Despite

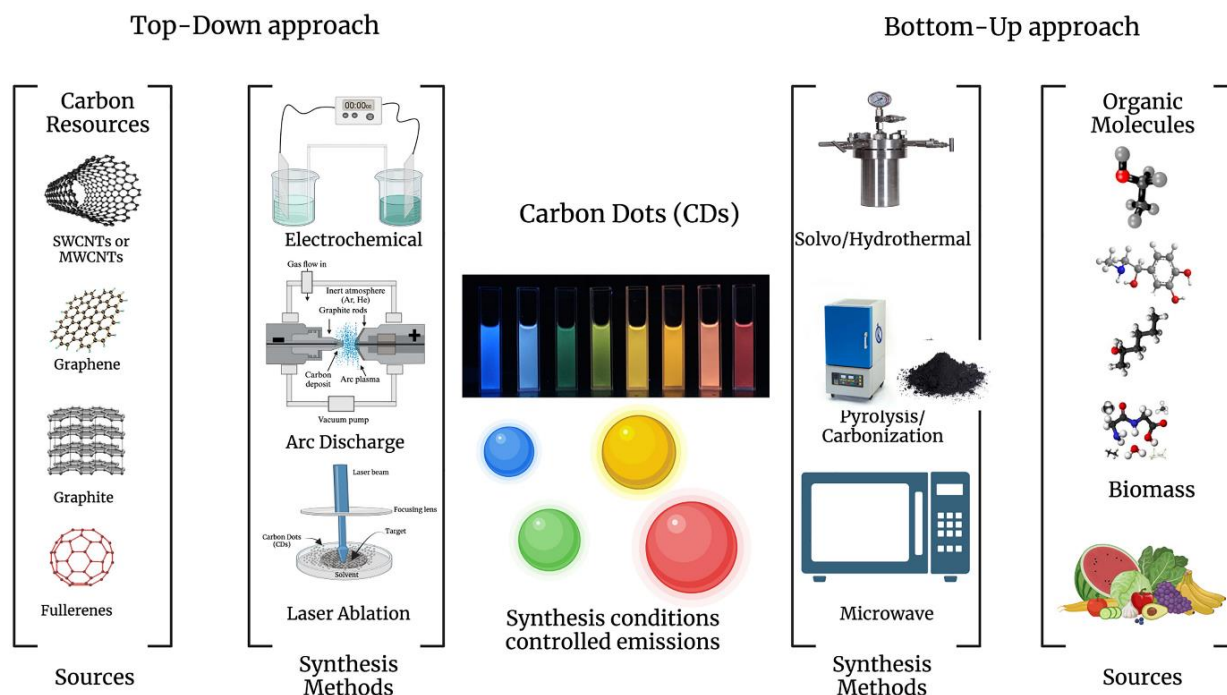
their similar sizes, they exhibit distinct structural characteristics and optical behaviors. CDs are predominantly amorphous or exhibit partial crystallinity, with their PL largely attributed to surface defects, chemical functional groups, or embedded molecular fluorophores. Conversely, CQDs possess a higher degree of crystallinity, featuring well-defined graphitic cores, and their optical properties are strongly governed by quantum confinement effects. This distinction enables CQDs to exhibit more tunable and size-dependent fluorescence compared to CDs. From a practical standpoint, CDs are often preferred in bioimaging and sensing applications due to their straightforward synthesis, low toxicity, and robust photostability. In contrast, CQDs are particularly advantageous for optoelectronic and photovoltaic applications, owing to their enhanced charge transport capabilities and higher quantum yield (QY). This nuanced differentiation underscores the importance of selecting the appropriate nanomaterial based on the specific demands of the intended application [13].

## **3. Synthesis of CDs**

Synthesis is crucial in determining the properties and functions of CDs. Typically, CD synthesis methods are categorized into two main types: "top-down" and "bottom-up" approaches (Figure 1) [14]. The top-down approach is limited by its tendency to produce CDs with non-uniform morphology and a wider size distribution. Additionally, this method may introduce contaminants that can negatively affect the fluorescence properties of the CDs. In contrast, the bottom-up technique utilizes carbon precursors, such as carbon hydrates, which react with solvents under specific synthesis conditions [15].

### **3.1. Top-down approach**

The top-down method for making CDs involves breaking down larger carbon sources, such as graphene, fullerenes, or nanotubes, into smaller particles. Different top-down techniques include arc discharge, oxidative cracking, laser ablation, and electrochemical oxidation processes [16]. The arc discharge method for CD synthesis is limited by the production of CDs with non-uniform sizes and the need for purification. Other techniques, such as oxidative cracking and laser ablation, often involve harmful reagents for passivation, making them less desirable. In contrast, the electrochemical oxidation method utilizes electrolytic graphite rods to produce crystalline CDs with excellent photocatalytic activity.



**Figure 1.** Overview of commonly employed top-down and bottom-up strategies for the synthesis of carbon dots, highlighting both green and chemical precursor sources [20].

Additionally, CDs synthesized via electrochemical oxidation demonstrate protective effects against immune-mediated hepatitis by interfering with the activation of T cells and macrophages and accumulating in the liver. However, CDs generated through this method typically possess fewer surface functional groups, which can lead to reduced water dispersibility [17].

### 3.2. Bottom-up approach

The bottom-up approach to synthesizing CDs utilizes carbon-rich precursors such as small organic molecules or polymers bearing functional groups like  $-OH$ ,  $-COOH$ , and  $-NH_2$ . This process typically involves dehydration followed by carbonization, yielding CDs with uniform morphology, narrow size distribution, and reproducible properties. Different techniques are used in the bottom-up synthesis of CDs, including microwave synthesis, hydrothermal processes, template-assisted methods, and cage-opening techniques.

Among bottom-up synthesis techniques, microwave and hydrothermal methods have recently gained considerable attention [13]. The microwave method offers rapid heating and favorable reaction kinetics, enabling the efficient production of CDs with uniform sizes that can be tuned by adjusting microwave power and exposure time. However, a key

limitation is the possible generation of unwanted byproducts, which often necessitate additional purification steps [18]. The hydrothermal method is one of the most widely used techniques for CD synthesis owing to its eco-friendly, cost-effective, and scalable nature. In some cases, it has been shown to outperform microwave-based approaches. CDs generated through hydrothermal treatment typically display abundant hydrophilic surface groups ( $-OH$ ,  $-COOH$ ,  $-NH_2$ ), which enhance their water dispersibility [19]. Owing to their biocompatibility and low toxicity, hydrothermally synthesized CDs hold strong promise for bioimaging, theranostics, and as nanocarriers in anticancer drug delivery systems.

## 4. Properties of CDs

### 4.1. Optical properties

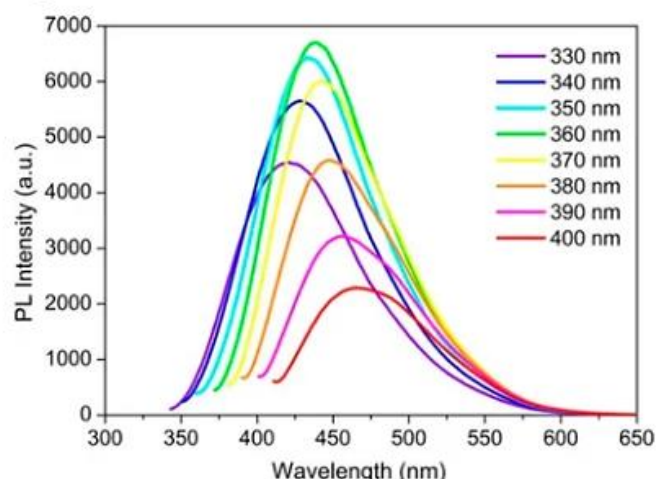
#### 4.1.1. Absorbance

Generally, CQDs absorb light from the ultraviolet (UV) range (260-320 nm) to the visible spectrum (400-700 nm). As efficient photon-harvesting agents, CQDs show distinct absorption peaks at shorter wavelengths. The most prominent peak, around 230 nm, results from the  $\pi-\pi^*$  transition in  $sp^2$ -conjugated carbon domains. Additionally, a shoulder near 300 nm is typically attributed to the  $\pi-\pi^*$  transition influenced by

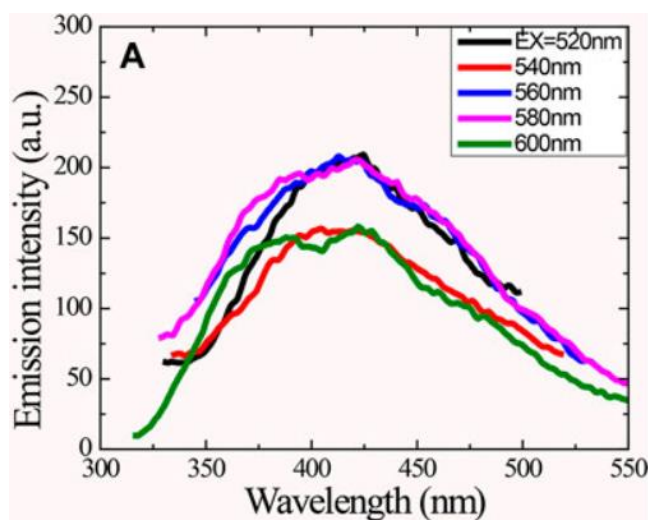
hybridization with heteroatoms such as nitrogen (N), sulfur (S), magnesium (Mg), phosphorus (P), or oxygen (O) [21]. The absorption properties of CQDs can be effectively tuned through surface passivation or chemical modification processes. Jiang *et al.* successfully synthesized red, green, and blue luminescent CQDs via a hydrothermal approach employing three different isomers of phenylenediamine [22]. A gradual red-shift in absorption was observed in all three CQDs. Additionally, heteroatom doping is an effective technique for modifying the absorption of CQDs. Qu and collaborators reported that doping CQDs with S and N heteroatoms shifted the absorption band into the visible range, from 550 to 595 nm [21, 23].

#### 4.1.2. Photoluminescence

One of the defining features of CQDs is their tunable PL, which allows emission across a broad spectrum ranging from ultraviolet (UV) to near-infrared (NIR) wavelengths. This is often referred to as excitation-dependent luminescence, where the emission color of CQDs can be adjusted by changing the excitation wavelength. This tunability is a result of the quantum confinement effect (QCE) and variations in nanoparticle size. Figure 2 shows the excitation-dependent luminescence spectra of a typical CQD sample, along with their corresponding emission colors [8]. The PL properties of CQDs stem from energy states related to surface defects, which are heavily influenced by surface passivation strategies aimed at improving QY [21].



**Figure 2.** Excitation-dependent luminescence spectra of CQDs. Adapted from Wang *et al.* (2019c) [24].



**Figure 3.** Up-conversion photoluminescence emission of CQDs excited at different wavelengths. Adapted from Gude (2014) [25].

#### 4.1.3. Up-conversion photoluminescence

CQDs are characterized by up-conversion photoluminescence (UCPL), a process in which two or more low-energy (long-wavelength) photons are absorbed and subsequently emitted as a higher-energy (short-wavelength) photon. This distinctive optical property underpins advanced applications, including two-photon luminescence microscopy and photocatalysis, which span the visible to NIR spectrum. The initial observation of UCPL was reported by Cao *et al.*, who demonstrated that CQDs could emit visible light (approximately 5 nm) under NIR excitation (800 nm) via femtosecond pulsed laser ablation. Despite ongoing debate, UCPL remains an intriguing property of CQDs, offering substantial potential for advanced optical and biomedical applications. Figure 3 illustrates the UCPL emission of CQDs excited at different wavelengths.

#### 4.2. Biological properties

Substantial advancements have been made in the synthesis of CQDs that exhibit strong and stable PL for use as bio-probes; however, concerns regarding their biocompatibility and cytotoxicity continue to impede broader implementation in living systems. In recent years, numerous studies have systematically evaluated the cytotoxic effects of CQDs synthesized through various techniques and functionalized with a range of surface groups. For example, CQDs produced via electrochemical treatment of graphite exhibited no adverse effects on human kidney cells, as confirmed by MTT assays [21]. Surface functionalization plays a pivotal role in modulating biocompatibility. *In vivo* studies have shown that PEG1500N-passivated CQDs administered to mice over 28 days caused no significant toxic effects, further confirming their biocompatibility for use in biological systems [26]. Conversely, polyacrylic acid (PAA) coatings were found to induce cytotoxicity; both free PAA and PAA-conjugated CQDs caused notable cell death after 24 h, although toxicity was less pronounced at shorter exposure intervals [27]. More recently, nitrogen-doped CQDs (N-CQDs) have garnered attention due to their enhanced biocompatibility. When evaluated on HepG2 cells, N-CQDs exhibited lower toxicity than undoped CQDs and maintained high cell viability even at elevated concentrations, indicating their potential for use in cellular imaging and other biomedical applications [28]. These findings underscore the need for

careful selection of synthesis methods and surface passivation strategies to ensure the safe and effective application of CQDs in bioimaging, drug delivery, and diagnostics.

### 5. Carbon dots in cancer theranostics

#### 5.1. Cancer cell detection

CDs surpass organic dyes in several key aspects, including hydrophilicity, biocompatibility, ease of synthesis, and low toxicity. In addition, different colors of QDs can be concurrently activated with a single light source, resulting in minimal spectral overlap, which provides a considerable advantage for the combinatorial detection of target molecules. These advantages enhance their utility as effective tools for cancer detection. Quantum dots (QDs) enable reduced background interference and strong tissue penetration, reaching depths of up to 1 cm, which makes them highly suitable for diagnosing lymph node metastases. Similarly, fluorescent CDs can be engineered as imaging probes, either alone or in combination with magnetic probes. When doped or hybridized with metals such as gadolinium, fluorescent CDs not only enhance imaging performance but also help minimize organ toxicity and control probe leakage [29].

Additionally, it is well established that abnormal levels of  $\text{Fe}^{3+}$  can contribute to the development of cancer. Current research is focused on developing fluorescence sensors for the detection of  $\text{Fe}^{3+}$  using CDs. In these studies, glutathione (GSH) was combined with CDs to evaluate fluorescence efficacy, as GSH levels are associated with cancer progression, thereby suggesting a novel approach for cancer cell detection. Elevated GSH levels help reduce oxidative stress in cancer cells, while a deficiency in GSH promotes cancer growth and progression. Furthermore, it has been demonstrated that GSH can enhance the fluorescence of a CDs and  $\text{Fe}^{3+}$  mixed solution (CDs/ $\text{Fe}^{3+}$ ), enabling the effective distinction of malignant cells from normal cells based on the differing GSH content in the two cell types [30].

#### 5.2. Cancer diagnosis via targeted bioimaging

CDs have garnered considerable interest as contrast agents for *in vivo* optical imaging due to their unique photophysical characteristics, including tunable PL, high stability, and biocompatibility. The most common approach remains direct PL imaging, which uses down-conversion or multiphoton up-conversion fluorescence to visualize biological structures. Nonetheless, the diffraction limit of

conventional fluorescence microscopy has led to the adoption of super-resolution techniques such as stochastic optical reconstruction microscopy (STORM), photo-activated localization microscopy (PALM), stimulated emission depletion (STED) microscopy, and structured illumination microscopy (SIM). Additionally, alternative imaging methods, such as afterglow imaging (utilizing phosphorescence and thermally activated delayed fluorescence (TADF) and cathodoluminescence (CL)), have gained prominence, offering high sensitivity with minimal background autofluorescence [31]. For the *in vivo* optical imaging studies, a nude mouse was inoculated with tumor cells and subsequently administered CQDs via intravenous injection through the tail vein. Figure 4 presents the sequential imaging results obtained over a 0–24 h period. Following euthanasia, *ex vivo* imaging of the major organs was performed. Consistent with the *in vitro* findings, the *in vivo* experiments demonstrated the low toxicity, intrinsic antioxidant activity, and excellent bioimaging performance of the CQDs [32].

To improve tumor-targeted imaging, CDs are functionalized to increase their accumulation in cancer tissues by leveraging mechanisms like the enhanced permeability and retention (EPR) effect, responsiveness to the tumor microenvironment, and specific biomolecular interactions. Examples include charge and pH-sensitive CDs, zwitterionic surface modifications, and conjugation with aptamers (e.g., AS1411), folic acid, or other cancer biomarkers [32]. Recent developments include creating CDs that can cross the BBB via transporter-mediated (GLUT-1) and receptor-mediated (ASCT2) pathways, enabling glioma targeting without the need for external ligands [33]. Self-targeting CDs, such as those made from glucose and L-aspartic acid (CD-Asp), or LAAM TC-CDs functionalized with amino and carboxyl groups, demonstrated selective tumor accumulation by interacting with human L-type amino acid transporter 1 (LAT1) transporters [34]. Additionally, aromatic drug-loaded CDs have enabled NIR fluorescence and PA imaging, broadening their application in cancer diagnostics and therapy [35].

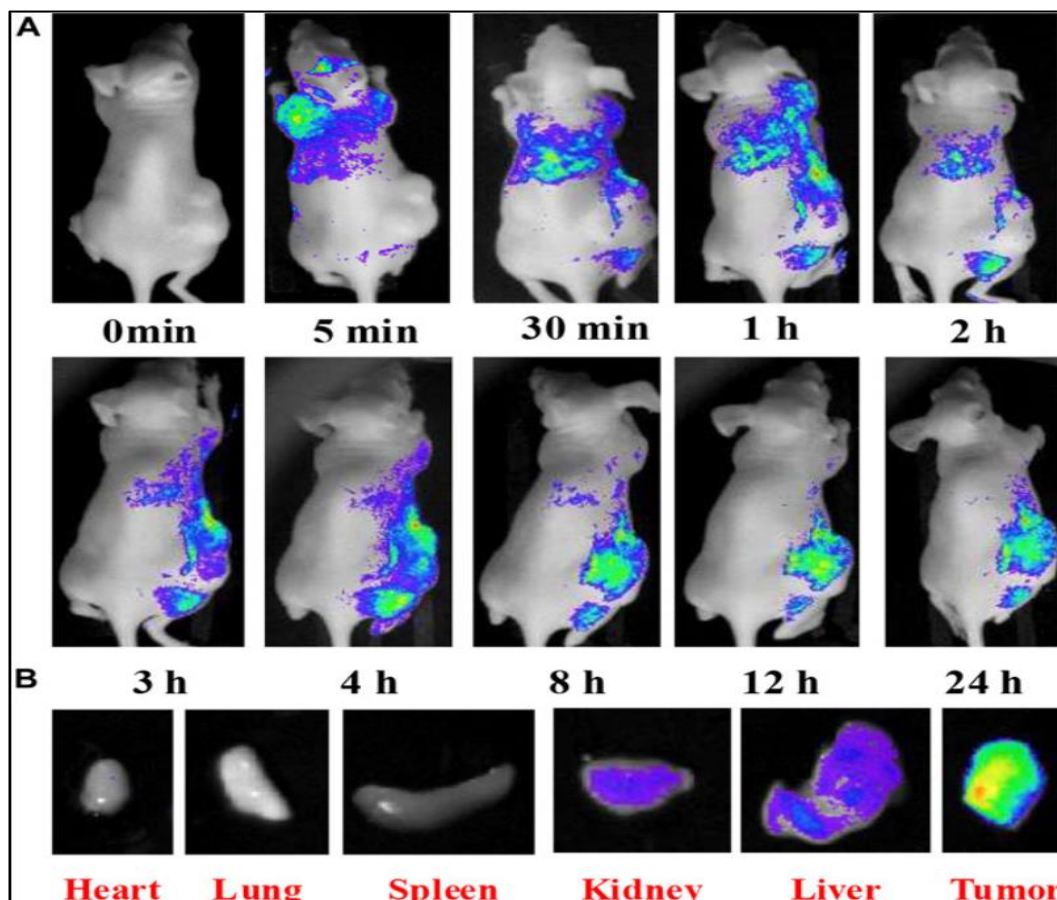
Furthermore, CDs have been widely employed in biosensing and imaging of intracellular targets such as glutathione, hyaluronidase, and folate receptors. Their sensing mechanisms

typically rely on fluorescence “turn-on/off” responses, disruption of Förster resonance energy transfer (FRET), or ratiometric signal changes. These functionalized CDs exhibit high selectivity and sensitivity, enabling precise detection and imaging of cancer cells [35]. Their clinical potential has also been highlighted. For instance, in thyroid cancer surgery, CDs have been successfully employed as lymphatic tracers to facilitate lymph node identification and reduce surgical complications, thereby underscoring their promise in precision oncology [35]. Overall, the versatility, biocompatibility, and tunable optical properties of CDs position them as powerful tools for targeted bioimaging, with significant potential for clinical translation in cancer diagnosis and image-guided therapy.

### 5.3. CDs as nanomedicines

Due to their excellent biocompatibility, efficient cellular uptake, intrinsic luminescence, and versatile surface chemistry, CDs are particularly promising for drug delivery applications. Nanoparticle formulations can enhance the solubility, bioavailability, and half-life of therapeutic agents. Numerous CD-based nanocarriers have been engineered to address the limitations of conventional chemotherapeutics, which often suffer from poor aqueous solubility, limited biocompatibility, and severe side effects. A key function of CD-based drug delivery systems in oncology is to encapsulate and solubilize anticancer drugs. Nevertheless, achieving adequate solubility remains challenging for many chemotherapeutics owing to their inherently hydrophobic nature [36].

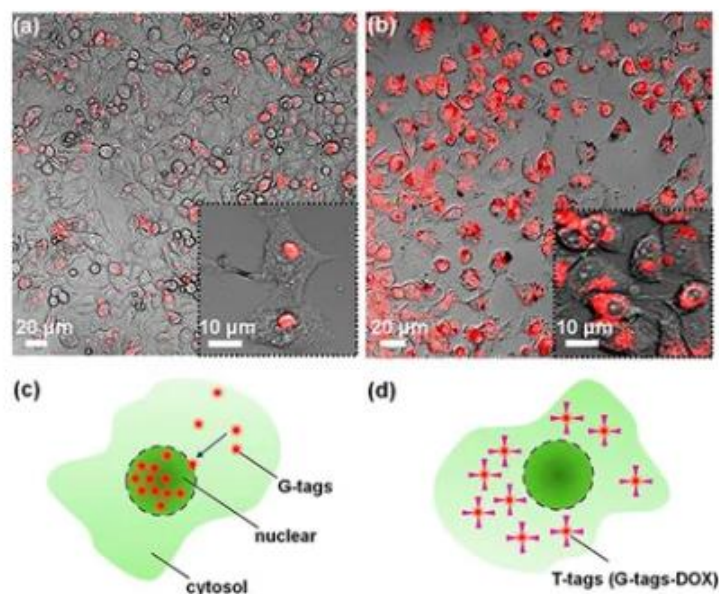
CDs can form stable inclusion complexes with specific drugs, thereby markedly enhancing their solubility, bioavailability, and stability. Following administration, these CD–drug complexes facilitate efficient delivery of therapeutic agents to the tumor site. Moreover, CD-based systems can be tailored for targeted drug delivery through surface functionalization with ligands or antibodies that recognize receptors or antigens overexpressed on cancer cells. Such modifications enable selective binding to malignant cells while sparing normal tissues. This targeted approach enhances drug accumulation at the tumor site while minimizing systemic exposure and associated adverse effects [37].



**Figure 4.** (A) In vivo fluorescence imaging of nude mice after injection of CQD solution; (B) fluorescence images of dissected organs of a mouse after intravenous injection of CQD solution for 24 h. Adapted from Huang *et al.* (2019) [32].

For instance, Arsalani *et al.* prepared polyethylene glycol-passivated fluorescent CDs (CDs-PEG) derived from gelatin and PEG, which serve as nanocarriers for tumor treatment using methotrexate (MTX) as the anticancer agent [38]. The synthesized CDs-PEG exhibited blue PL with a maximum QY of 34%. The effect of PEG on the PL intensity of the CDs was investigated, revealing that CDs-PEG demonstrated enhanced PL properties compared to pure gelatin-derived CDs. Furthermore, CDs-PEG showed superior antitumor efficacy *in vitro* compared to free MTX, attributed to improved nuclear delivery. These findings highlight the potential of CDs for targeted cancer therapy [38]. On the other hand, Zheng *et al.* developed a system utilizing luminous CDs in conjunction with Oxa (IV)-COOH (Oxa-CDs), an oxaliplatin derivative. They proposed that Oxa-CDs enter cells through endocytosis mediated by the CDs. Once inside the cells, Oxa (IV)-COOH is converted to oxaliplatin (II), thereby reducing its toxicity to normal cells [39].

Additionally, Su *et al.* discovered that red-emissive CQDs can be effectively targeted to the nuclei of cancer cells and cancer stem cells. When doxorubicin (DOX) was conjugated to the surface of CQDs, it reduced HeLa cell viability to 21%, in contrast to 50% viability observed with free DOX. The findings indicate that CDs exhibit a significant cytotoxic effect on tumor cells, and enhance therapeutic efficacy, thereby reducing the likelihood of recurrence [40]. In one study, hydrothermally synthesized CQDs were employed as a drug delivery system for targeted delivery of doxorubicin (DOX) [41]. Another investigation demonstrated that drug-loaded CQDs exhibited greater tumor localization compared to free DOX. To further evaluate their biological activity, DOX-conjugated CQDs were incubated with HepG2 and MCF-7 cells (Figure 5). The results revealed that DOX-CQDs exerted higher cytotoxicity in cancer cells relative to normal cells [42].



**Figure 5.** Confocal microscopy images of cancer cells after 24 h incubation. (A) G-tags (CQDs) showed no cytotoxic effects, whereas (B) DOX-conjugated CQDs (T-tags) induced evident cytotoxicity. (C) G-tags were predominantly localized in the nucleus, while (D) DOX-conjugated CQDs were mainly distributed in the cytosol. Adapted from Lee *et al.* (2014) [42].

It is essential to emphasize that implementing CD-based drug delivery systems can significantly reduce the side effects associated with chemotherapy. By improving drug solubility and allowing targeted delivery, CDs can significantly lower the exposure of healthy tissues to potent anticancer agents. This targeted method lessens common side effects associated with traditional chemotherapy, such as nausea, hair loss, and immunosuppression. Enhancing drug delivery directly to the tumor site while protecting healthy tissues is vital for improving the quality of life for cancer patients [43].

#### 5.4. Gene therapy

Recent advancements in nanotechnology have highlighted CQDs as promising non-viral gene delivery systems with intrinsic bioimaging capabilities. CQDs offer several advantages, including high biocompatibility, low cytotoxicity, tunable fluorescence, and efficient gene condensation properties, making them suitable for theranostic applications. For instance, Wu *et al.* developed theranostic and reducible nanoagents (fc-rPEI-CQDs) capable of delivering siRNAs to targeted lung cancer cells, where gene release was triggered in a reductive intracellular environment [44]. Similarly, cationic CQDs synthesized via one-step microwave pyrolysis have been employed for SOX9 gene delivery in

chondrogenesis, forming nanostructures of 10-30 nm with high transfection efficiency [45]. Overall, the multifunctional nature of CQDs positions them as next-generation nanocarriers for integrated gene therapy and diagnostic imaging in biomedical applications [21].

#### 5.5. Photodynamic therapy/photothermal therapy

Photodynamic therapy (PDT) has emerged as a minimally invasive and highly targeted approach for the treatment of diverse cancers, as well as certain non-neoplastic conditions, offering reduced adverse effects compared to conventional therapies. The therapeutic efficacy of PDT primarily depends on the use of photodynamic or photothermal agents capable of converting light energy into cytotoxic effects [21]. Recent advancements in nanotechnology have introduced multifunctional CQD-based nanocomposites that enhance the therapeutic efficacy of PDT. One such system involves DOX-loaded, sgc8c aptamer-conjugated SWCNTs-PEG-Fe<sub>3</sub>O<sub>4</sub>@CQDs, which demonstrated potent anticancer activity through both photothermal and photodynamic mechanisms [46]. These nanocomposites effectively absorb NIR light (808 nm), generate ROS, and induce localized hyperthermia, leading to selective cancer cell destruction. Their biocompatibility, magnetic properties, hydrophilicity, and

stability further enable applications in drug delivery and magnetic resonance imaging, making them particularly suitable for treating cervical cancer.

Another strategy has involved the hydrothermal synthesis of folic acid-functionalized CQDs conjugated with a riboflavin photosensitizer and subsequently embedded within chitosan-based polymer nanospheres [47]. These FeN@CQD nanocomposites exhibit high photothermal conversion efficiency and controlled DOX release upon NIR stimulation, enhancing drug accumulation in cancer cells and improving therapeutic outcomes. Additionally, CQDs and C60 fullerenes have shown potential as photosensitizers by inducing autophagic responses in target cells upon photoexcitation, contributing to the photodynamic cytotoxicity mechanism [48]. Together, these findings highlight the increasing potential of CQD-based nanoplatforms in enhancing phototherapy for cancer treatment.

## **6. Challenges and opportunities of CDs: safety issues**

Despite their numerous advantages and broad applications in environmental and biomedical sciences, the practical translation of CQDs remains hindered by several critical challenges that must be addressed. These challenges encompass difficulties in achieving precise size control, low QY, limited reproducibility in synthesis, and inadequate standardization of fabrication methodologies. Given that the optical and biological properties of CQDs are highly dependent on size, meticulous control over their morphology and surface defects is imperative for ensuring consistent bioactivity. Advanced synthesis strategies, particularly those involving surface functionalization and bandgap engineering, are being investigated to enhance PL and address limitations in QY. Furthermore, the intrinsic ability of CQDs to absorb light and generate heat or reactive oxygen species ROS without reliance on complex theranostic platforms highlights their potential as dual-purpose agents for both diagnostic and therapeutic applications. Nevertheless, significant efforts are still needed to improve their selectivity and sensitivity, particularly in biosensing, while ensuring optimal performance through the use of biocompatible and sustainable carbon sources, which remains a substantial challenge.

The transition from conventional to green synthesis approaches has increased the accessibility of CQD production;

however, a gap persists in their direct use as labeling or tagging agents. Although CQDs are presently employed more frequently as carriers for labels and therapeutic agents, they are increasingly recognized as safer alternatives to traditional semiconductor quantum dots, owing to their low toxicity, high biocompatibility, and tunable PL. Innovative applications are emerging, such as the development of long-lasting, photostable CQD-based microneedle patches for recording vaccination status or allergy information—an approach particularly valuable in regions with limited healthcare infrastructure or in emergency medical contexts. CQD-based tags can be detected using portable NIR imaging devices or even adapted smartphone cameras. Additionally, the integration of CQDs into next-generation radiological imaging films, radiation dosimeters, and contamination sensors opens promising avenues for environmental monitoring and public safety. With ongoing advances in synthesis techniques and functional modifications, CQDs are positioned to become pivotal components in the evolution of biomedical and environmental nanotechnologies.

## **7. Conclusion**

The integration of imaging modalities within CDs enables simultaneous diagnosis and therapy, advancing the field of cancer theranostics. Their intrinsic biodegradability and biocompatibility contribute to reduced long-term toxicity, addressing one of the key challenges in oncological treatment. Growing evidence highlights the remarkable potential of CDs in the formulation of anticancer nanodrug conjugates, enabling highly tailored and targeted therapeutic strategies. In this context, CDs play multifaceted roles, acting as drug delivery vehicles, bioimaging probes, and agents for photothermal and photodynamic therapy, thereby enhancing therapeutic efficacy while minimizing systemic toxicity.

## **Author contribution**

The authors equally contributed to this work.

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## **Declaration of interest statement**

The authors declare that this work has not been done or published before and has no competing interests of any type.

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## Data Availability

Data will be made available on request.

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