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Theranostic Potential of Quantum Dots: From Imaging to Therapy

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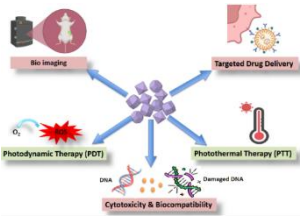
Abstract: The combination of nano-biotechnology advances the biomedical field, opening up groundbreaking opportunities for disease diagnosis, monitoring and treatment. Quantum dots (QDs) are at the leading edge of this innovation, known for their exceptional physicochemical qualities and customizable optoelectronic features. These luminous nanoparticles have become invaluable in theranostics by offering a unique combination of diagnostic and therapeutic capabilities. This review offers a comprehensive analysis of QDs, emphasizing their cytotoxicity, imaging potential, and applications in targeted drug delivery, photothermal therapy (PTT), and photodynamic therapy (PDT). By assessing their potential and limitations, we aim to harness QDs to reshape precision medicine and drive advancements in healthcare.



Keywords: *QDs, theranostic, toxicity*

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1. Introduction

Semiconductor quantum dots (QDs) have continued to captivate the scientific community in recent decades, with their unique optoelectronic properties and versatility making them a prime candidate for a wide range of applications, including theranostics.[1,2] Theranostics, derived from the words "therapeutics" and "diagnostics," is an innovative field that combines diagnostic and therapeutic functionalities into a single nanoplatform, ushering in a new era of personalized medicine[3]. In oncology, QDs have shown immense promise as theranostic agents. Their tunable emission spectra, high photostability, and ability to be functionalized with targeting moieties have made them valuable tools for cancer detection, imaging, and treatment.[3] For instance, QDs have been utilized for the simultaneous diagnosis and monitoring of tumour response to chemotherapy, allowing for timely adjustments to the treatment regimen.[4] Furthermore, the development of multifunctional quantum dot-based nanocomposites has paved the way for the integration of both imaging and therapeutic capabilities. By combining QDs with drug-delivery systems or photosensitizers, these nanoplatforms can provide a comprehensive approach to cancer management, enabling early detection, targeted drug delivery, and photo-induced tumour ablation.[5] QDs have various applications (fig.1) in fields like photothermal therapy (PTT),[6] chemotherapy,[7] and photodynamic therapy (PDT),[8] along with techniques such as photoacoustic imaging (PAI),[9] fluorescence imaging,[10] biosensing,[11] and magnetic resonance imaging (MRI).[12]

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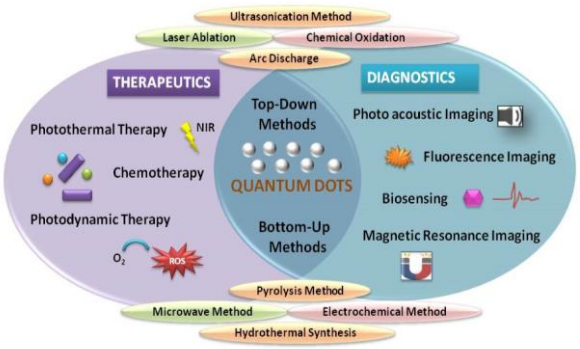

Figure 1: *Theranostic applications of QDs along with various synthetic methods*

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Table 1: *QDs with their sizes, synthetic methods, capping agents and theranostic applications*

QD Type	Size (nm)	Synthetic Method	Capping Agent	Theranostic Applications
CdSe QDs	3.5–5.8	Wet chemical method	Trioctylphosphine (TOP) and oleic acid (OA)	ROS-mediated apoptosis, fluorescence imaging, gastric cancer therapy
CdZnSe QDs	21 ± 7	Hot injection	Gallic acid/Alginate	Drug delivery (BA, C2), enhanced fluorescence imaging
CQDs (Orange Juice)	~12	Hydrothermal	—	ROS-induced apoptosis in HCT-116 cells, bioimaging
CQDs (Hibiscus)	~ 12	Microwave-assisted	Hibiscus *rosa-sinensis* leaf extract	Wound healing, anti-inflammatory, antimicrobial
CQDs (Gandha Prasarini)	2-3.5	Hydrothermal	*Gandha Prasarini* leaves	Fluorescent tartrazine sensing, antibacterial activity
CQDs	~2–10	Hydrothermal	Intrinsic N-containing functional groups	NIR-triggered PTT in HeLa and MCF7 cells
GQDs	~1–10	Green/microwave/top-down	Poly-L-lysine, Au nanostars	Brain cancer therapy, immune modulation, PDT, PTT, radiotracer imaging
AIS QDs	< 8	One-step aqueous	2MPA, PEI/2MPA	ALA-based PDT, colon cancer therapy, fluorescence imaging
SiQDs@DMSNs	140–300	One-pot synthesis	DMSNs	Bioimaging, anti-counterfeiting, fluorescence stability
Chiral SiQDs	~2–10 (core) ~10–20 (hydrodynamic size)	Hydrothermal	KYF peptide	$ONOO^-$ detection in inflammation and cancer diagnostics
$CuInSe_2$@ZnS:Mn QDs	~71 (DLS), ~5–10 (core)	Hot injection	ZnS shell	NIR-II/MRI imaging, PTT, immune activation, anti-tumor therapy

Recent advancements in the field of quantum dot-based theranostics have also extended beyond oncology, with potential applications in other disease areas, such as neurological disorders and cardiovascular diseases.[13] Mazahir *et al.*[14] reviewed the theranostic potential of bioinspired QDs (BQDs) in cancer treatment, highlighting their superior solubility, low toxicity, biocompatibility, and targeted action. They emphasized BQDs' unique features like photoluminescence, photothermal effect, singlet oxygen and H_2S generation, while also addressing existing challenges in their clinical application. Ho *et al.*[15] summarized the theranostic potential of QDs as multifunctional platforms for imaging and drug delivery while noting existing challenges.

The synthesis of QDs is generally categorized into two primary strategies: the top-down[16] and bottom-up[17] approaches. In the top-down method,[18] breaks down larger bulk materials into nanoscale QDs using techniques like laser ablation, chemical oxidation, arc discharge or ultra-sonic method. Though effective, this method often involves high costs and complex setups. The bottom-up method,[19] on the other hand, builds QDs from smaller precursors using simpler, cost-effective methods like, hydrothermal synthesis, electrochemical method, combustion or microwave irradiation. This method is not only cost-effective and scalable but also offers the flexibility needed for various real-world applications, from advanced drug delivery systems to cutting-edge diagnostic tools, contributing to its increasing popularity in both research and industry. The theranostic applications of the QDs depend upon its material, particle size, capping agents used and the method of synthesis (see table-1).

After synthesis, QDs are characterized using techniques such as high-resolution transmission electron microscopy (HRTEM) for morphology, selected area electron diffraction (SAED) and X-ray diffraction (XRD) for crystallinity, UV-Vis and photoluminescence (PL) spectroscopy for optical properties, and Fourier-transform infrared spectroscopy (FTIR) for surface functional group, ensuring their quality and functionality for biomedical applications[20]. When comparing the toxicity levels of semiconductor QDs, binary QDs stand out as the most hazardous. This stems from their composition, which often includes toxic heavy metals like Lead (Pb), Cadmium (Cd), and Mercury (Hg). The harmful effects of these elements on both health and the environment restrict the use of binary QDs, particularly in biomedicine and consumer products.[21,22] In contrast, ternary QDs, often made from less harmful elements like Copper (Cu), Indium (In), and Sulfur (S) or Selenium (Se), for example, $CuInS_2$[23] and CdZnSe[24] show much lower toxicity. Their advantageous properties make them viable alternatives to traditional binary QDs, enabling use in various fields without the risks associated with heavy metals[10] and have piqued interest for their adjustable optical characteristics and reduced toxicity, which makes them highly compatible with biological applications like drug delivery and imaging.[25] The toxicity of quaternary QDs can fluctuate based on their elemental composition. While some may exhibit low toxicity, akin to ternary QDs, the incorporation of specific metals could raise potential health risks. Nonetheless, many quaternary QDs are crafted to boost performance while keeping toxicity at a minimum.[26] Because of their safer profile, ternary QDs are frequently chosen for sensitive applications, highlighting a movement towards more sustainable materials in nanotechnology.

2. Toxicity of Semiconductor QDs

The possible cytotoxicity of semiconductor QDs remains a significant issue, and understanding the underlying mechanisms is essential for their safe and effective application in theranostic. One of the primary mechanisms of QD-induced cytotoxicity is

generating reactive oxygen species (ROS).[27] Semiconductor QDs, particularly those composed of heavy metal elements, can undergo photocatalytic reactions, producing superoxide radicals, hydroxyl radicals and hydrogen peroxide. These ROS can generate oxidative stress within cells, causing damage to cellular macromolecules (fig. 2), such as DNA, proteins, and lipids, ultimately leading to cell death. The interaction of QDs with cell membranes plays a role in their toxicity. Smaller QDs can enter cells more readily, accumulate in organelles, and interfere with regular cellular functions. Additionally, QD exposure can induce inflammatory reactions in tissues, worsening tissue damage and increasing overall toxicity. Carbon-based,[28] silicon-based,[29,30] and biomolecule-based ternary I-III-VI QDs have emerged as promising alternatives with reduced toxicity profiles. These novel designs aim to preserve the desirable optical and semiconductor properties of QDs while mitigating their inherent toxicity. Some strategies are used to control the toxicity of QDs including core/shell structure,[31] surface modification,[32] biomolecule,[33] and green synthesis methods.[34]

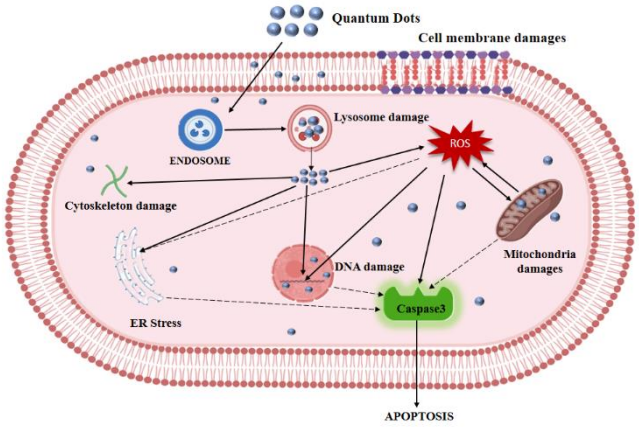

Figure 2: *The mechanism of cytotoxicity of Quantum Dots*

3. Cadmium-based QDs

Cadmium-based QDs are recognized for their excellent photoluminescence and therapeutic properties, making them useful in nanotheranostic applications. Nonetheless, their application is frequently constrained by safety issues, mainly stemming from the release of (Cd^{2+}).[35] Multimodal nanoparticles combining GZCIS/ZnS QDs, mesoporous silica, and gold nanoparticles are designed as targeted therapeutic carriers for colorectal cancer (CRC). These nanoparticles, which carry the chemotherapy drug epirubicin and are engineered to specifically target CRC cells, exhibit selective cytotoxicity towards cancer cells and enhanced anti-tumour effects in animal studies. This approach offers the potential for more effective cancer treatment and imaging with reduced side effects.[7] Bimodal nanoprobes were developed by combining CdTe QDs with thiolated GdDOTA complexes for optical and MRI imaging. These nanoprobes showed enhanced fluorescence and improved MRI contrast, with r1 values 69% higher than clinical GdDOTA, making them promising for imaging applications.[36] Huong *et al.*[37] synthesized CdSe QDs, sized 3.5-5.8 nm with strong emission peaks from 585-630 nm using the wet chemical method. Cytotoxicity tests on HepG2 liver cancer cells revealed cell cycle arrest in S and G0/G1 phases and apoptosis induced by ROS generation. Among three QDs sizes, CdSe2 (4.7nm) showed the strongest anti-cancer activity against AGS stomach cancer cells as compared to CdSe1 (3.5nm) and CdSe3 (5.4nm), with effective concentrations between 5 and 20 µg/mL, offering potential for gastric cancer therapy.

4. Carbon QDs

Carbon QDs (CQDs), known for their outstanding optical properties, high quantum yield, strong absorption, low toxicity, and excellent biocompatibility, hold great potential for cancer treatment in various applications, including targeted drug delivery to cancer cells, tumour imaging, and therapies like PTT and PDT.[38] Recent developments in green synthesis have attracted considerable attention for producing low-cost and environmentally friendly CQDs, addressing issues of toxicity and avoiding the use of harmful chemicals.[39,40] Natural resources such as waste biomass,[41,42] bamboo leaves,[43,44] orange juice,[45] lemon juice,[46] microorganism,[47] milk,[48] tulsi leaves,[49] red lentils,[50] aloe vera,[51] almond resin,[52] egg,[53] turmeric[54] and neem leaves[55] etc. have been explored for eco-friendly synthesis of CQDs. CQDs were prepared from orange juice through a hydrothermal synthesis approach and combined with silver nanoparticles to form CQD/Ag heterostructures, which exhibit strong photoluminescence, low toxicity to healthy cells, effective cellular uptake, bioimaging capability, and significant anticancer effects in human colorectal cancer (HCT 116) cells at 6 µg/mL through a ROS-mediated mitochondrial apoptosis pathway involving Akt (RAC-α serine/threonine-protein kinase).[56] Additionally, the bio-fabricated CQDs from Mesosphaerum suaveolens using microwave-assisted approach extracts demonstrated anticancer activity against MDA-MB-231 breast cancer cells at a concentration of 6 µg/mL, showcasing their potential for cancer treatment and as a theranostic agent for cancer diagnosis and therapy.[57] Using the microwave-assisted method, CQDs extracted from *Hibiscus rosa-sinensis* leaves showed strong fluorescence, wound healing, anti-inflammatory properties, and effectiveness against *K. pneumoniae* and *B. Cereus* bacteria. They inhibited COX-2 and regulated inflammatory cytokines, with excellent biocompatibility, making them promising for therapeutic applications in wound healing and infection treatment.[58] Activated carbon nanoparticles (ANs) from coconut shells, loaded with gadodiamide (Gd@PANs), efficiently generate hydroxyl radicals for chemodynamic therapy (CDT) in cancer cells and

exhibit 45.20% photothermal conversion efficiency for PTT. They also enable T1-MRI imaging, combining diagnosis and treatment.[12] N,S-doped CDs derived from Gandha Prasarini leaves exhibited green fluorescence and detected tartrazine with a 0.18 µM detection limit and 92–110.2% recovery in honey and soft drinks. They also showed strong antibacterial effects against harmful bacteria by damaging their membranes, without harming human red blood cells, highlighting their dual role in both diagnostics and therapy, making them promising for biomedical applications such as bacterial infection treatment and targeted detection.[59] CQDs synthesized from citric acid with urea and ammonium fluoride showed strong NIR emission at 808 nm. The ammonium fluoride-based CDs (MF) had better NIR absorption and photothermal efficiency, effectively killing HeLa and MCF7 cancer cells under NIR irradiation, while both types displayed excellent biocompatibility and caused no toxicity or tissue damage in mice, indicating their potential for NIR-triggered cancer treatment.[60] However, high-purity CDs were synthesized from graphite via pulse electrolysis, with a concentration of 500 µg/mL showed a photothermal conversion efficiency of 64.3% under NIR irradiation, raising the temperature to 82.2°C. The CDs were absorbed by HepG2 cells, decomposed H_2O_2, and induced apoptosis. In vivo studies indicated their potential in PAI and guiding tumour treatment, making them a promising tool for cancer diagnosis and therapy.[9] Curcumin-based carbon nanodots as discussed by Rai *et al.*[61] are small, water-soluble, biocompatible, and effective against pathogenic microbes. They can be used for early diagnosis, bioimaging, and as carriers for antimicrobial drugs. Wu *et al.*[62] developed curcumin-quaternized CQDs (Q-CQDs) with stronger antibacterial properties than natural curcumin. The Q-CQDs damage bacterial membranes, generate ROS, and lead to bacterial death. In mouse wound infection models, they reduced bacterial growth, decreased inflammation, and enhanced healing. These findings suggest that Q-CQDs could be an effective antibacterial agent for treating infections and promoting wound healing. C_5N_5 QDs with piezoelectric effects demonstrated efficient H_2O_2 production at a rate of 918.4 µM/h, with a 2.6% efficiency in converting solar energy into chemical energy under low light conditions (0.1 sun). It enabled effective sono-photochemodynamic cancer therapy by producing reactive intermediates essential for tumour treatment and supporting diagnostic imaging[63]. Broccoli-based carbon QDs (BCQDs), synthesized using a simple hydrothermal process, demonstrate significant promise as a PDT agent. These BCQDs effectively produce singlet oxygen ($^1O_2$) when exposed to 660 nm light and trigger germline apoptosis in *C. elegans* via the cep-1/p53 pathway. This research positions BCQDs as an effective PDT agent and presents *C. elegans* as a useful model for rapid PDT assessment.[8] Liu *et al.*[6] derived CDs from osmanthus fragrans fruits demonstrated great biocompatibility, 46.7% photothermal conversion efficiency under 808 nm light, and effective cell killing in HeLa cells, indicating their potential for PTT. Rutin-loaded CDs (R-CDs) effectively killed *methicillin-resistant Staphylococcus aureus* (MRSA) at a MIC of 32 µg/mL, causing membrane damage and exhibiting strong antibacterial effects in a mouse model. They also showed good biocompatibility, indicating their potential as an alternative to traditional antibiotics.[64] Khan *et al.*[65] developed blue-emitting CDs (Du-CDs) from *Diaporthe unshiuensis* YSP3 extract, which displayed strong antimicrobial activity against bacteria and fungi at low MICs. Du-CDs also prevented biofilm formation, damage cell membranes, and supported wound healing in a mouse model, highlighting their potential as an effective and biocompatible antimicrobial agent. Mg/N-doped CQDs were synthesized with an impressive quantum yield of 89.44%, and modified with hyaluronic acid and folic acid to specifically target cancer cell delivery of epirubicin (CQD-FA-HA-EPI). In vitro studies demonstrated enhanced toxicity and cellular uptake in 4T1 and MCF-7 cell lines. Additionally, in vivo experiments with breast cancer mouse models showed a significant reduction in tumour size and minimal organ damage, indicating the potential of CQD-FA-HA as an effective multifunctional drug delivery system.[66]

5. Graphene QDs

Graphene QDs represent a distinctive type of carbon nanomaterial, defined by their quasi-zero-dimensional structure and derived from graphene, which preserves its planar configuration. The quasi-zero-dimensional structure of GQDs means they are small graphene segments with an extensive surface area relative to their volume, offering excellent chemical reactivity and biocompatibility. Their strong photoluminescence and tunable emission make them highly appropriate for bioimaging, drug delivery, and biological molecule detection.[67] These biocompatible nanoparticles are capable of crossing the blood-brain barrier, offering promising potential for the treatment of brain diseases like glioblastoma,[68] Parkinson's disease,[69] and Alzheimer's disease.[70] Moreover, GQDs boosted the efficacy of chemotherapy even at subtherapeutic levels, including 1 µM doxorubicin and 100 µg/mL temozolomide, by enhancing drug delivery and reducing tumour growth in 3D glioblastoma models.[71] In contrast, CQDs are produced from a wide range of carbon sources, including organic substances and carbon soot, typically leading to a more amorphous structure. These differences in their origins and structural characteristics result in notable variations in their properties, with GQDs offering better electrical conductivity and stability compared to CQDs.[72] Deng *et al.*[73] studied the toxicity of four types of GQDs on zebrafish embryos. A-GQDs led to developmental problems, such as reduced survival, heartbeat rates, and more malformations at concentrations of 100 and

200µg/mL. mRNA analysis revealed that all GQDs influenced ion channels, with A-GQDs particularly disrupting the coagulation pathway. Xia *et al.*[74] introduce a technique to enhance cancer treatment by using GQDs to deliver microRNA155 (miR) to monocytes. This strategy helps bypass the tumour's immune defences by reprogramming harmful immune cells into those that target the tumour, improving tumour eradication. A novel fluorescence-based method has been developed for detecting *Carcinoembryonic Antigen (CEA)* using poly-l-lysine-functionalized GQDs (PLL-GQDs) made from peanut shell waste. This eco-friendly technique offers a high sensitivity limit of detection 1.19pg/mL and 98.32% accuracy in real samples, with potential applications in bioimaging and therapy.[75] Tehrani *et al.*[76] created ^{99m}Tc-labeled GQDs for glioma tumour detection. The GQDs demonstrated stability with a radiochemical yield above 97% and efficiently targeted tumour sites in animal models. Scintigraphy imaging revealed notable accumulation in both glioma tumours and organs such as the kidneys, indicating their potential as a radiotracer for glioma diagnosis. Soleimany *et al.*[77] developed a nanohybrid combining riboflavin-conjugated GQDs (Rf-N,S-GQDs) and thiolated chitosan-coated gold nanostars (AuNS-TCS) for dual PDT and PTT. Utilizing a single low-power laser (200 mW·cm^{-2}, 760 nm), the system demonstrated increased singlet oxygen production, efficient thermal effects, and enhanced tumour destruction compared to standalone treatments. Its notable effectiveness in 3D tumour models emphasizes its potential for treating solid tumours and progressing toward clinical applications. Lung cancer, a leading cause of death, faces challenges in early detection and treatment. GQDs show promise in therapies like photolytic therapy, hyperthermia therapy, and drug delivery, offering the potential for improved lung cancer management.[78] Ku *et al.*[79] investigated three types of GQDs on breast cancer cells such as MCF-7, MDA-MB-231, T-47D, and BT-474, at concentrations ranging from 2.5 to 40 µg/L. All GQDs reduced cell viability, with ortho-GQDs specifically inducing arrest in the G2/M phase of cell division. Treatment also led to an increase in the apoptotic proteins p21 (1.41-fold) and p27 (4.75-fold). These GQDs show potential for treating estrogen receptor-positive breast cancer. Organotin (IV) complexes are effective in cancer therapy but are limited by their poor water solubility. To address this, nitrogen-doped GQDs were modified with organotin-based compounds and 4-formylbenzoic acid (FBA). The resulting NGQDs-FBA-Sn system demonstrated significant toxicity against breast cancer cells (MDA-MB-231), with IC_{50} value of 0.10 µM (Sn2) and 0.41 µM (Sn1), while showing minimal effect on non-cancerous HEK293T cells (IC_{50} of 0.27µM and 0.87 µM respectively). Additionally, the system allowed for fluorescence imaging, suggesting efficient cellular uptake and drug release.[80] Khose *et al.*[81] synthesized N-GQDs from discarded materials like arjuna bark and melamine sponge using microwave treatment and used for bio-imaging of MDA-MB-231 breast cancer cells, successfully staining them in blue fluorescence. The N-GQDs also showed fluorescence quenching in the presence of H_2O_2, allowing toxin detection. With 70% cell survival at a concentration of approximately 1.8 mg/ml, the N-GQDs showed high biocompatibility, highlighting their potential for imaging and sensing applications in cancer studies. The incorporation of GQDs into polycaprolactone (PCL) scaffolds significantly enhanced mechanical strength and bioactivity, with 3 wt% showing optimal performance, suggesting their potential for theranostic use in tissue regeneration[11]. Najafi *et al.*[82] developed a pH-responsive drug delivery system by combining Agarose, GQDs, and α-Fe_2O_3 in a hydrogel nanocomposite for the controlled release of the highly effective anti-cancer compound Quercetin. The nanoparticles measured an average size of 279.04 nm and had a zeta potential of 52.8 mV. Incorporating α-Fe_2O_3 improved the drug loading and encapsulation efficiencies to 47% and 86.25%, respectively. In vitro testing on HepG2 cells demonstrated enhanced anticancer activity, suggesting the system's promising potential for cancer therapy. Zhang *et al.*[10] introduced a new treatment for liposarcoma using graphene quantum dot-based nanoprobes. The nanoprobes, made of gadolinium (Gd^{3+}), IR820 dye, and a heat shock protein inhibitor (17-AAG), enhance mild photothermal therapy and enable effective T1-MRI and near-infrared fluorescence imaging. In vivo studies revealed that the nanoprobes had low toxicity, were efficiently excreted, and lowered heat shock protein expression in tumour cells, improving the therapeutic effect.

6. Silver QDs

Silver-based QDs, such as Ag_2S, Ag_2Se, Ag_2Te, have shown significant potential in theranostic applications due to their unique optical properties and biocompatibility. These QDs emit in the second near-infrared window (NIR-II, 900-1700nm), which allows for deeper tissue penetration and reduced background fluorescence, making them ideal for bioimaging and therapeutic applications.[83] Ag_2S QDs combined with ALA and Cetuximab achieved over 80% cell death in colorectal cancer cells using only 0.17 mM ALA. When paired with 5-fluorouracil (5FU), the treatment resulted in nearly complete cell death at 0.35 mM ALA and 15 µg/mL 5FU. The QDs also improved photothermal therapy and reduced the required dose of methotrexate from 10 µg/mL to 0.21 µg/mL for targeted killing of cancer cells. This approach is being studied for more effective treatments, including for breast cancer.[84] Silver–indium–sulfide QDs (AIS QDs) were produced using a simple method, achieving high quantum yields and long-lasting stability. Cationic (AIS-PEI/2MPA) and anionic (AIS-2MPA) QDs, when loaded with 5-aminolevulinic acid (ALA), enhanced PDT in colon

cancer cells by increasing ROS production, leading to significant cell death. The cationic AIS QDs notably reduced the IC50 for ALA to 0.01 mM, demonstrating AIS-2MPA's potential as a promising theranostic agent for drug delivery and imaging.[85]

7. Alloy QDs

Alloy QDs can be engineered to reduce the toxicity associated with heavy metals in traditional QDs. This is particularly significant for clinical applications where ensuring biocompatibility is a critical requirement. For example, CdZnSeS QDs were prepared using the hot injection method, with a quantum yield of 85% were stabilized in gallic acid/alginate matrices. These QD-based carriers, loaded with anticancer drugs such as ceranib-2 (C2) and betulinic acid (BA), demonstrated enhanced therapeutic efficiency. In vitro results revealed that BA-loaded carriers achieved an IC50 of 8.76μg/mL for HL-60 cells, a threefold improvement over free BA, while C2-loaded carriers displayed IC50 values of 2.24μg/mL for HL-60 and 7.37μg/mL for PC-3 cells, showcasing their potential for advanced cancer therapies.[86] $CuInSe_2$@ZnS:Mn QDs were developed with high near-infrared (NIR)-II fluorescence efficiency (31.2%) and MRI contrast, enabling accurate detection of small metastases in 4T1 breast cancer tumours. These QDs showed a tendency to accumulate in tumours, and upon exposure to NIR light, they produced heat and radicals that destroyed cancer cells and triggered an immune response. This method successfully prevented tumour regrowth in 80% of mice.[87]

8. Silicon QDs

Silicon QDs (SiQDs) are becoming promising theranostic agents because of their unique features, such as biocompatibility, adjustable photoluminescence, and capability for multimodal imaging and therapy. Traditional SiQDs encounter issues such as complicated preparation, inconsistent quality, low water solubility, and aggregation-caused quenching (ACQ), which lowers their brightness. However, their key benefit is biocompatibility, as silicon is less toxic than QDs made from heavy metals, reducing potential in vivo risks.[88] SiQDs are being increasingly used to develop high-performance fluorescent biosensors for detecting chemical and biological substances. These biosensors leverage the unique photoluminescent properties of SiQDs, which offer excellent optical stability and biocompatibility. Recent developments include the creation of water-soluble SiQDs and the development of biosensors that display photoluminescence variations in response to analytes.[89] Huang *et al.*[90] introduced SiQDs@DMSNs, a novel fluorescent material consisting of SiQDs encapsulated within dendritic mesoporous silica (DMSNs), with particle sizes ranging from 140 to 300 nm. These particles emitted blue light under UV exposure, with sodium salicylate (NaSAL) playing a key role in their formation. SiQDs@DMSNs exhibited strong fluorescence, high water solubility, stability, and successfully avoided ACQ. They are suitable for applications in biosensors, nanomedicine, imaging, fingerprint identification, and anti-counterfeiting. Chiral SiQDs-(K/P) ox were developed for the precise detection of $ONOO^-$, a molecule involved in inflammation and cancer. These SiQDs, created through a one-step hydrothermal method with KYF as a precursor, have a broad emission range (380–700 nm) and peak at 490 nm. SiQDs-(K/D-P)ox demonstrates a high quantum yield (47.66%), while SiQDs-(K/L-P)ox offers a long fluorescence lifetime (27.219 μs) and strong biocompatibility. SiQDs-(K/L-P)ox can effectively detect ONOO– in cells via fluorescence quenching, making it a valuable tool for detecting inflammation in cancer cells.[91] Moreover, Pei *et al.*[92] developed SiQDs that emit blue fluorescence and have antibacterial activity. The SiQDs inhibited the growth of *E. coli* (0.45 mg/mL) and *S. aureus* (0.25 mg/mL) by damaging their cell walls. A fluorescence sensor for tetracycline (TC) detection had a limit of 0.0006μmol/L and a range of 0.001 to 0.010 μmol/L. The sensor successfully detected TC in honey with nearly 100% recovery. A fluorescent probe, SiQDs@PDA, was created by attaching dopamine to silicon QDs, emitting at 530 nm with a quantum yield of 44.7%. This probe can interact with various molecules and was employed to selectively label and image gram-positive and gram-negative bacteria, along with their biofilms. Due to the distinctive properties of the SiQDs@PDA is highly resistant to photobleaching, making it a valuable tool for studying microbial research.[93] Liang *et al.*[94] focused on enhancing the optical properties of SiQDs and CQDs by encapsulating them in polyhedral oligomeric silsesquioxanes (POSS). The resulting green-emitting POSS-G-CNDs, red-emitting POSS-R-CNDs, and blue-emitting POSS-SiQDs showed excellent luminescence, biocompatibility, and the ability to penetrate cell membranes. This makes them highly suitable for multicolour intracellular imaging and offers potential applications in clinical diagnostics and bioimaging. Researchers have made significant progress in synthesizing multi-emissive SiQDs, which can emit multiple colours depending on the excitation wavelength. This property is particularly useful for biological and analytical applications, as it allows for more precise and versatile detection methods. These SiQDs exhibit low toxicity to cells, high luminous efficiency, and strong resistance to photobleaching.[95]

9. Conclusion

This review provides information on the emerging theranostic potential of QDs, emphasizing their unique optical tunability, diverse synthesis strategies, biomedical applications, and the critical challenges associated with toxicity. While Cd-based QDs have demonstrated considerable promise, their clinical translation is hindered by toxicity concerns

related to their composition, surface coatings, and administration routes. Studies with other QDs like CQDs, GQDs, and silicon QDs are actively focusing on developing biocompatible surface coatings and using naturally sourced, less toxic materials to reduce toxicity. Another limitation is the lack of robust clinical data on the long-term safety and efficacy of theranostic systems. Extensive preclinical and clinical trials are necessary to establish the safety and clinical utility of these nanomaterials before they can be widely adopted in the clinic. Ongoing research efforts are focused on enhancing biocompatibility and reducing the toxicity of QD systems, improving tumour targeting strategies, and establishing robust clinical data on their safety and efficacy. The future looks bright for multifunctional QDs that can both diagnose and treat diseases simultaneously, with artificial intelligence (AI) playing an important role in their development. AI enhances QDs by optimizing their synthesis, predicting toxicity, improving imaging accuracy, and enabling targeted drug delivery. This combination of AI and QDs is expected to change personalized medicine, making treatments safer, more effective, and specially designed for each patient. As these advancements continue, the theranostic applications of semiconductor QDs are poised to have a transformative impact on managing cancer and other diseases. As we advance these technologies and accumulate clinical data, the theranostic capabilities of semiconductor QDs are set to revolutionize the field of medicine. The combination of AI with eco-friendly, biocompatible QDs will pave the way for groundbreaking healthcare solutions, tackling both disease management challenges and promoting environmental sustainability.

Author Contribution Declaration

Miss Pratibha Chahal has conducted the literature survey, designed the images and written the manuscript. Dr. Ajit Kumar has given suggestion regarding the theranostic applications and has done the proofreading and editing. Dr. Avinash Singh has prepared the manuscript draft, designed the images and performed the proof reading.
Attention! The authors have no financial conflict of interest to declare.

Data Availability Declaration

In this review, no new data was created or analyzed, and no primary research findings or software were used.

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