INTERNATIONAL JOURNAL OF LATEST TECHNOLOGY IN ENGINEERING, MANAGEMENT & APPLIED SCIENCE (IJLTEMAS)

ISSN 2278-2540 | DOI: 10.51583/IJLTEMAS | Volume XIV, Issue X, October 2025

Quantum Dots for Cancer Diagnosis: A Comprehensive Review

M.T Padmaja, Jayashree P, Srikanta A S

Dept. of Biochemistry and Chemistry, Vijaya College, R.V. Road, Bangalore 560004

DOI: https://doi.org/10.51583/IJLTEMAS.2025.1410000021

Abstract—Quantum dots (QDs) are semiconductor nanocrystals with exceptional optical and electronic properties, making them highly attractive in biomedical research [1], [6]. Their tunable fluorescence, broad excitation, and high photostability have positioned them as promising tools for cancer diagnostics [3], [7]. This review explores QD applications in in vitro diagnostics (IVD), point-of-care testing (POCT), bioimaging, and signal amplification strategies. Furthermore, emerging trends, safety considerations, and translational challenges are discussed, providing a roadmap toward clinical application [12].

Key words—Quantum dots, cancer diagnostics, bioimaging, multiplex detection, point-of-care, signal amplification, imag- ing, biosensors, nanotechnology.

I. Introduction

Cancer remains a leading cause of morbidity and mortality worldwide [11]. Early and precise diagno- sis is critical to improving survival outcomes, es- pecially given the rising incidence of hard-to-treat and rapidly spreading forms. Traditional diagnostic platforms—including histopathology, medical imaging, and immunoassays—often suffer from limited sensi- tivity, slow turnaround times, and inability to per- form true multiplexed analysis [12]. The emergence of nanotechnology-based medical platforms, particularly quantum dots (QDs), has begun to revolutionize health- care by enabling early, accurate, and in-depth disease detection [6].

QDs are remarkable for their size-tunable fluores- cence, high quantum yield, strong resistance to photo- bleaching, and surface modification versatility [1], [2]. These characteristics allow them to outperform conven- tional fluorophores and nanoparticles in sensitivity, mul- tiplexing, and imaging longevity. In cancer diagnostics, QDs offer uniquely powerful solutions for biomarker detection, bioimaging, and real-time monitoring, all of which support improved patient outcomes [4].

Quantum Dots: Structure, Types, and Synthesis

Structure and Optical Properties

Quantum dots are nanoscale semiconductor crystals, typically between 2 and 10 nm in diameter, exhibiting quantum confinement effects not seen in bulk ma- terials [1]. This quantum confinement leads to size- dependent emission wavelengths: smaller QDs fluoresce with higher energy (shorter wavelength), while larger ones emit lower energy light. QDs also display pro- longed photostability, crucial for applications requiring long-term observation or repeated measurements [2].

The crystal structure most commonly used for biomedical QDs is zinc blende (cubic) or wurtzite (hexagonal) [8]. Their cores often consist of elements such as CdSe, CdTe, ZnS, InP, or GaN, whose compo- sition and structure determine fundamental properties. Typically, a passivation layer or shell—such as ZnS or silica—is added to improve water solubility, biocom- patibility, and functionalization for targeting.

Types of Quantum Dots

There are several distinct classes of QDs [1], [6]:

II–VI QDs (CdSe, CdTe, ZnS): The most estab- lished, offering high quantum yield and narrow emission spectra, making them ideal for multi- plexing. However, their use is restricted in clinical settings due to cadmium toxicity concerns [7].

III–V QDs (InP, GaN): These alternative ma- terials offer similar optical properties with lower toxicity, improving their suitability for in vivo applications [3].

Carbon-based QDs (CQDs, GQDs): Derived from organic matter, carbon and graphene dots are highly biocompatible, display diverse emission behaviors, and are increasingly studied for their eco-friendly and safe nature [8].

Other emerging forms: Silicon QDs and Ag_2S NIR QDs have been explored for advanced imag- ing due to deeper tissue penetration and further reduced toxicity [1].

There is also significant interest in developing" hy- brid QDs," which combine organic and inorganic ele- ments to further tune properties such as emission band- width, photoluminescence quantum yield, or chemical robustness [6]. These innovations allow scientists to customize QDs for specific imaging, biosensing, or therapeutic requirements.

Synthesis and Surface Engineering

Numerous methods exist for synthesizing QDs [6]. Hydrothermal, solvothermal, atomic layer deposition, drop-casting, spin-coating, and ultrasonication all pro- duce high-quality quantum dots. Electrochemical and layer-by-layer assembly are used for

ISSN 2278-2540 | DOI: 10.51583/IJLTEMAS | Volume XIV, Issue X, October 2025

scalable medical device manufacturing. Surface modification via PEGy- lation, silica coating, and ligand exchange enhances stability and solubility [8]. Bioconjugation with antibodies or aptamers provides disease-specific targeting [7].

Quantum Dots in In Vitro Cancer Diagnostics

Immunoassays

Quantum dot-based immunoassays represent a new horizon in cancer diagnostics [7], [11]. Traditional enzyme-linked immunosorbent assays (ELISAs) can only detect biomarkers down to relatively high concen- trations, limiting early disease detection [7]. QDs, with their intense and stable fluorescence, enable detection of cancer-related proteins (e.g., PSA, AFP, CEA) even at femtomolar concentrations—well below the reach of conventional methods [11].

Quantum dot immunoassays also offer superior re- sistance to photobleaching, making them highly re- producible and suitable for high-throughput, automated platforms [6]. Multiplexed immunoassays—with each QD color assigned to a specific target—allow simulta- neous analysis of many biomarkers from a single patient sample, cutting costs and improving efficiency [11].

Recent developments include integrating QD im- munoassays into microfluidic chips and portable point- of-care devices [11]. These approaches lower the bar- rier for early cancer screening in both developed and resource-limited regions [2].

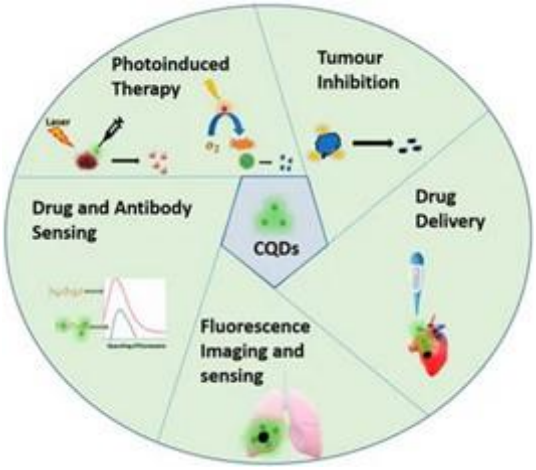

Fig. 1. Schematic representation of biomolecule-derived quantum dots in cancer diagnostics and treatment. QDs can be engineered for multiplexed detection and advanced imaging applications [8].

Multiplex Biomarker Detection

Managing cancer often involves identifying and quantifying multiple biomarkers, an approach critical for subtyping malignancies and predicting therapeutic responses [11]. QDs excel in multiplexing due to their well-defined, sharp emission peaks and the possibility to excite many different QDs using a single light source [2], [6].

In clinical applications, multiplexed QD assays us- ing encoded microbeads or multi-color labels are now widely adopted for rapid, high-throughput protein, miRNA, or genomic marker profiling [2], [11]. The

evolution of immuno-PCR and quantum dot-based next- generation sequencing platforms further amplifies their multiplexing edge [11].

Expanding on this, QDs are now being adapted to mi- croarray formats, enabling an integrated ”lab-on-a-chip” capable of analyzing entire cancer panels in minutes [3]. Such advancements enable large-scale population screening, personalized therapies, and dynamic disease monitoring.

After exploring these benefits, a visual summary is shown below.

Liquid Biopsy Interfaces

Liquid biopsy platforms are at the cutting edge of non-invasive cancer diagnostics [12]. By harnessing quantum dots in biosensors, highly sensitive and selec- tive detection of circulating tumor cells (CTCs), ctDNA, and exosomes is possible from a routine blood sample [1], [6].

Recent studies show that QD-enabled biosensors can be functionalized with antibodies or aptamers to specifically capture rare CTCs or exosomes tagged with key markers (e.g., EpCAM, CD63) [1], [8]. Because of this, QD-based liquid biopsy platforms can track cancer evolution, monitor progression or recurrence, and guide therapy choices in real time—a crucial step for personalized medicine [3].

ISSN 2278-2540 | DOI: 10.51583/IJLTEMAS | Volume XIV, Issue X, October 2025

Innovations such as microfluidic devices exploit- ing QD signal amplification, and integration with smartphone-based readers, are transforming cancer management by making precision diagnostics accessible to broader populations [2].

POINT-OF-CARE TESTING (POCT) AND LATERAL FLOW ASSAYS (LFAS)

POCT for Rapid Diagnosis

Quantum dots are revolutionizing point-of-care test- ing by imparting robust, multiplexed fluorescent read- outs to portable devices [5], [7]. These technologies allow real-time detection of cancer biomarkers directly at the bedside, critical for early intervention and moni- toring [6].

QD-powered POCT devices are often embedded in microfluidic chips or hand-held sensors, delivering re- sults within minutes [2]. Innovations such as AI-based image recognition and wireless data transmission are being integrated into POCT platforms, enabling auto- matic analysis and telemedicine applications [2], [3].

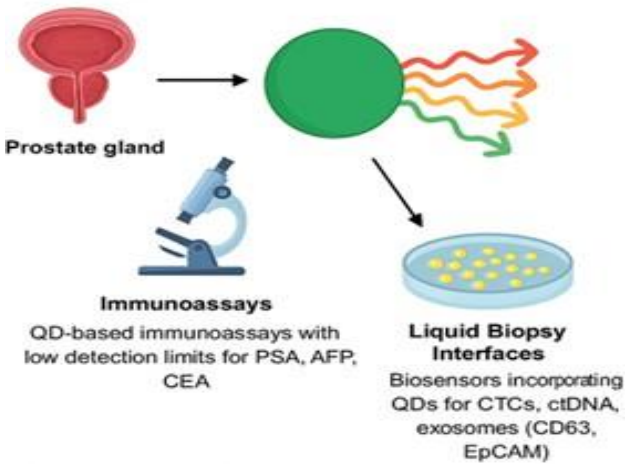

Fig. 2. Quantum dots in multiplexed biomarker detection platforms. Multiplexed QD assays support simultaneous quantification of proteins, miRNAs, and exosomal markers [7].

QD-enabled POCT is especially impactful in resource-limited settings, where centralized laboratories may be unavailable or overburdened [5].

QD-Based Lateral Flow Assays

Quantum dot-enhanced lateral flow immunoassays (LFAs) offer far greater sensitivity and quantitative capability than gold nanoparticle-based LFAs [5]. Re- cent clinical studies show QDs can reduce false nega- tives and enable quantification using simple smartphone readers [4].

Through multiplexed labeling, several cancer biomarkers (e.g., CYFRA 21-1, AFP) can be detected simultaneously in a single device. The result: cheaper, faster, and more reliable cancer screening at the point-of-need [5].

The technology continues to evolve, with QDs now being integrated into flexible, wearable biosensors for real-time health monitoring and dynamic responses to therapy [3].

This is summarized in the following figure.

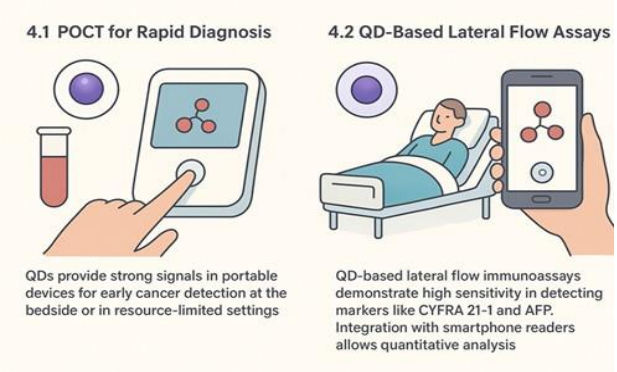

Fig. 3. Illustration of quantum dot-based POCT and lateral flow assays for rapid, sensitive cancer detection [5]. These devices offer transformational benefits in healthcare accessibility.

ISSN 2278-2540 | DOI: 10.51583/IJLTEMAS | Volume XIV, Issue X, October 2025

Bioimaging Applications

Near-Infrared Imaging

Quantum dots emitting in the near-infrared II (NIR- II) window (1000–1700 nm) deliver unprecedented deep tissue imaging [1], [2]. This spectral range reduces absorption and scattering by biological tissues, allowing clear visualization of tumors and internal organs [4].

Modern NIR-II QDs (Ag_2S, InP, Si) also minimize autofluorescence, boosting signal-to-noise ratios [1]. These capabilities are game-changing for non-invasive tumor localization, sentinel lymph node mapping, and monitoring of metastasis in preclinical and potentially clinical settings [2].

Fluorescence-Guided Surgery

The integration of QDs into fluorescence-guided surgery (FGS) allows real-time margin visualization and distinction between malignant and healthy tissue [4]. By conjugating QDs with tumor-specific antibod- ies or peptides, surgeons can achieve complete tumor excision—significantly reducing recurrence rates and improving overall patient survival [3].

Current research focuses on developing biocompati- ble, non-toxic NIR QDs for intraoperative imaging, with clinical studies now underway to validate their utility in complex cancer resections [4].

Cellular Imaging

Quantum dots offer exceptional photostability and tunable emission spectra for continuous cellular imag- ing over extended periods [3], [12]. Targeted QDs enable the tracking of cancer cell migration, invasion, and interaction with the microenvironment, advancing both basic cancer biology and translational therapeutics [2].

Many groups are using quantum dots for in vivo fate mapping of circulating tumor cells and monitoring of therapeutic efficacy in animal and human models, supporting the design of biomarker-driven therapies throughout cancer care [3].

A graphical summary is shown below.

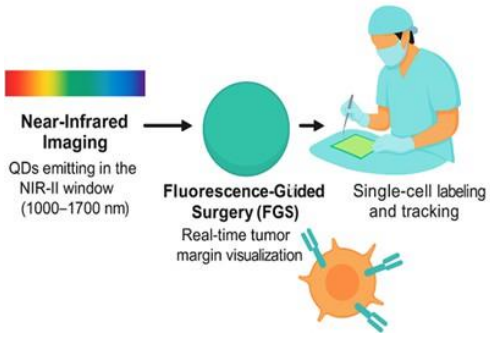

Fig. 4. Bioimaging: Near-infrared QDs enable superior deep tissue, single- cell, and intraoperative tumor imaging for research and clinical translation [1].

Signal Amplification Strategies

Fluorescence Resonance Energy Transfer (FRET)

Quantum dots are uniquely suited to serve as energy donors in FRET biosensors, enhancing sensitivity for the detection of DNA, RNA, and protein interactions at the nanoscale [9], [11]. These systems are widely adopted for real-time molecular diagnostics and cell biology studies [4].

Applications include early detection of genetic mu-

tations, diagnosis of viral infection in cancer patients, and monitoring of drug resistance by watching target- protein dynamics [7], [11]. Advances in QD surface chemistry have enabled the design of robust FRET systems for multiplexed cancer biomarker detection [11].

Electrochemiluminescence (ECL)

Electrochemiluminescence biosensors based on QDs provide extraordinary sensitivity, suitable for quantify- ing microRNAs, protein biomarkers, and even metabo- lites [9], [10]. Immobilizing QDs on electrode surfaces allows them to emit strong, consistent signals upon electrochemical stimulation.

QD-ECL platforms are advantageous for their low background, high-throughput operation, and compati- bility with multiplexing [9], making them ideal for clinical research, early cancer diagnosis, and assessment of treatment efficacy.

ISSN 2278-2540 | DOI: 10.51583/IJLTEMAS | Volume XIV, Issue X, October 2025

Photoelectrochemical (PEC) Biosensing

Photoelectrochemical biosensors leverage the pho- toactivity of QDs to advance sensitivity in liquid biopsy, early cancer detection, and monitoring therapy response [10]. By generating photocurrents upon illumination, these systems deliver fast and quantitative analysis even in complex sample matrices.

Emerging research is exploring integration of QD- PEC sensors with wearable monitoring devices and remote diagnostic systems, promising new paradigms in personalized medicine [3].

A summary figure appears below.

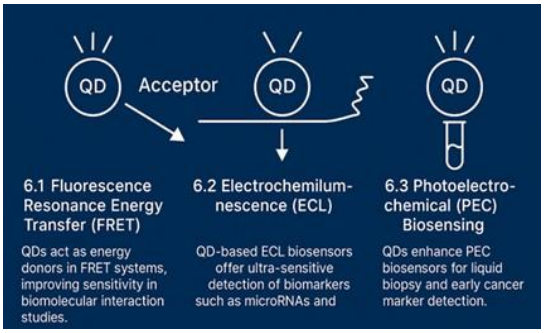

Fig. 5. Signal amplification: QDs in FRET, ECL, and PEC systems enable ultrasensitive biomarker detection and next-generation biosensing [9].

Safety, Challenges, and Future Perspectives

Safety Concerns of Quantum Dots

Heavy-metal-based QDs pose potential toxicity risks,

Challenges in Clinical Translation

Key hurdles for quantum dots include ensuring re- producibility and consistency in synthesis, overcoming regulatory and intellectual property barriers, and eluci- dating long-term fate in the human body [8], [12].

Regulatory agencies demand exhaustive toxicological studies, pharmacokinetics, and immune response data, and the lack of standardized protocols complicates the approval process [12]. Further, scaling up QD produc- tion while maintaining quality and affordability requires interdisciplinary collaboration and new manufacturing approaches [12].

Future Perspectives

The future of QDs in cancer medicine is bright [3]. Advances in non-toxic QDs—such as carbon dots, sil- icon QDs, and biomimetic versions—are being rapidly pursued [3], [8]. The fusion of quantum dot diagnostics with artificial intelligence and big data will enable automated clinical analysis and personalized therapy [12].

Large clinical validation studies, FDA regulatory progress for silica QDs, and enhanced targeting by next- gen ligands suggest that QDs will soon be mainstream diagnostic and therapeutic tools [4]. Multifunctional QDs are also under intense investigation for use in photothermal therapy, gene delivery, and multimodal imaging, broadening the impact of these versatile ma- terials [3].

II. Conclusion

Quantum dots are transforming cancer diagnostics with their sensitivity, multiplexing ability, and imaging capabilities [2], [3], [7]. Ongoing advances in bio- compatibility, clinical validation, and regulatory frame- works promise rapid adoption of QD-based platforms in routine care [3]. The future may see personalized, real-time cancer management driven by quantum dot biosensors, imaging agents, and integrated theranostics. As more studies confirm their efficacy and safety, QDs are positioned to become a new standard in molecular diagnostics and targeted therapy [12].

References

1. Chen, L.-L. et al., “Near-Infrared-II Quantum Dots for In Vivo Imaging and Cancer Therapy,” Small, 18(8), 2022.
2. NIR-II Fluorescent Probes for Fluorescence-Imaging-Guided Tumor Surgery, Bioengineering, 11(2), 2024.
3. Zhu, Q. et al., “Recent advances in NIR-II small molecule fluo- rophores for cancer theranostics,” J. Mater. Chem. B, 2025.
4. Wang, P. et al., “RBC-Based Multimodal Theranostic Probes,” Theranostics, 9, 369–380, 2019.
5. Chen, X. et al., “CYFRA 21-1 Quantum Dot Fluorescent Lateral Flow Immunoassay,” Biosensors, 14(1), 2024.

ISSN 2278-2540 | DOI: 10.51583/IJLTEMAS | Volume XIV, Issue X, October 2025

6. Versatile Approaches of Quantum Dots in Biosensing and Imaging, Wiley Interdiscip. Rev. Nanomed. Nanobiotechnol., 16(5), 2024.
7. Quantum Dot-Enabled Biosensing for Prostate Cancer Diagnostics, Nanomaterials, 15(15), 2025.
8. Quantum Dots as Multifunctional Materials for Diagnosis and Ther- apy, Nanomaterials, 14(13), 2024.
9. Electrochemiluminescence of Semiconductor QDs in Biosensing, Biosensors, 13(7), 2023.
10. Low-Dimensional Nanomaterials for Biosensing, Biosensors, 15(7), 2025.
11. Quantum Dot-Based Multiplexed Detection for Cancer Biomarkers, Nanomaterials, 14(13), 2024.
12. Quantum Dots for Theranostic Biosensing, Wiley Interdis- cip. Rev. Nanomed. Nanobiotechnol., 16(5), 2024.