

Quantum Dots in Nanotechnology: Advances in Therapeutics, Drugs Delivery and Imaging

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ABSTRACT

Quantum Dots (QDs), semiconductor nanoparticles, exhibit unique optical properties like excellent photostability, high brightness, and size-tuneable emission wavelengths due to quantum confinement. Their broad absorption and narrow emission spectra make them ideal for high-resolution, multicoloured imaging in biological and medical applications. QDs are increasingly used in cellular, molecular, and *in vivo* imaging, as well as diagnostic techniques for cancer and pathogen detection. Additionally, they hold promise for targeted drug delivery, where surface functionalization with biomolecules allows precise targeting. However, concerns about QD toxicity, influenced by surface coatings and size, remain. Research into biocompatible coatings is essential to address safety concerns. Future advancements in QD synthesis, functionalization, and integration with nanotechnologies will further enhance their potential in personalized medicine. Overcoming regulatory and safety challenges is critical for their clinical adoption.

Keywords: Biocompatible coatings, Drug delivery, Multicoloured imaging, Nanomedicine, Quantum dots.

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Received: 16-11-2024;

Revised: 09-01-2025;

Accepted: 24-03-2025.

INTRODUCTION

Quantum dots, or QDS, are defined as follows

Semiconductor nanoparticles known as Quantum Dots (QDs) have special optical and electrical characteristics because often falling between 2 and 10 nm in size nano meters (Al-Douri *et al.*, 2023). At this scale, QDs exhibit quantum mechanical effects, particularly quantum confinement, where the motion of electrons is restricted to discrete energy levels. This quantum confinement leads to size-dependent optical properties, meaning QDs' light can have a variety of colours. precisely managed by changing the magnitude of (Sarkar, 2023). Light is emitted at shorter wavelengths by smaller QDs. (blue), bigger QDs, however, release light at longer wavelengths (red). These properties make QDs highly valuable in various applications (Huang *et al.*, 2020). In optical and electronic devices, their tuneable emission spectra and high brightness are leveraged for displays, solar cells, and LEDs. In biomedical fields, QDs are prized for their stability and superior fluorescence compared to traditional dyes, enabling

advanced imaging techniques (Jiao *et al.*, 2022). They allow for multicolour imaging and can be functionalized with biological molecules for targeted imaging and 1. Optimised Permeability and Retention Impact through Passive Targeting efficiency and versatility, providing significant advantages over conventional materials (Augustine *et al.*, 2021). Despite their potential, ongoing research is crucial to address their cytotoxicity and ensure safe implementation in medical and environmental applications (Ramburrun *et al.*, 2022).

Historical background and revelation

While the idea of Quantum Dots (QDs) emerged in the 1980s when researchers began to explore the effects of quantum confinement on semiconductor materials (Kambhampati *et al.*, 2021). "Quantum dot" was the phrase used to first created by physicist Mark Rees in 1982, who along with his colleagues, demonstrated the quantum confinement effect in nanostructures (Wang *et al.*, 2020). This effect occurs when the dimensions of the semiconductor are lowered to a size similar to the Bohr radius of an exciton, leading to discrete energy levels similar to those in atoms (Böer *et al.*, 2023). One of the pioneering discoveries in the field was made by Louis Brus in 1983 at Bell Laboratories, where colloidal synthesis methods were developed to produce Cadmium Selenide (Cd Se) quantum dots (Hao, 2020). Brus's



DOI: 10.5530/ijpi.20250248

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work highlighted the dimensions and optical characteristics of these nanoparticles, marking a significant advancement in nanotechnology (Khan *et al.*, 2022). In the 1990s, further development was spurred by creating superior-grade quantum dots using better control over the dimensions and topography properties, notably by the group of Paul Alivisatos and Mounqi Bawendi (Reddy *et al.*, 2024). Their contributions enabled the QDs' practical use in a variety of sectors, including biology as well as optoelectronics (Yoon *et al.*, 2021). As the commercial and scientific interest in quantum dots has since grown exponentially, driven by their potential in creating more efficient solar cells, displays, and biomedical imaging technologies. Today, quantum dots continue to be a vibrant area of research, promising innovations in multiple technological domains (García *et al.*, 2021).

Significance in Nanotechnology and Medicine

Emerging role in various fields

The role of Quantum Dots (QDs) increasingly pivotal part of the nanotechnology and medical fields because of their distinct optical and electrical characteristics (Shao *et al.*, 2020). In which realm that of the nanotechnology, QDs are revolutionizing display technologies with their use in QLED (Quantum Dot Light-Emitting Diode) televisions, offering superior colour accuracy, brightness, as well as energy conservation compared as well traditional LCD in addition to OLED displays (Abbas *et al.*, 2024). Their highly quantifiable emission frequencies and yield manufacture them ideal for creating vivid, lifelike visuals (Zhao *et al.*, 2020). In solar energy, QDs are improving solar energy cells' efficiency (AlGhamdi *et al.*, 2020). By tailoring that absorption properties of QDs, researchers are developing solar cells that can harness a broader spectrum of sunlight, potentially surpassing the efficiency of conventional silicon-based solar cells (Gong, 2024). In medicine, QDs are transforming imaging and diagnostic techniques (Devi *et al.*, 2022). Their high brightness, photostability, and size-tuneable fluorescence enable precise cellular and molecular imaging, aiding in early disease detection and monitoring (Abdel-Salam *et al.*, 2020). QDs are utilised in multiplexed imaging, in which numerous biological targets are visualized simultaneously, enhancing diagnostic accuracy (Díaz-González *et al.*, 2020). Furthermore, QDs are being explored for precise administration of medication. Their surfaces allows for the exact delivery of medicines to sick cells while limiting negative effects when functionalised with particular ligands or antibodies (Díez-Pascual, 2022). This targeted approach promises significant advancements in therapy for illnesses such as cancer, showcasing that vast potential that of quantum dots in improving healthcare outcomes (Murar *et al.*, 2022).

Overview of applications in imaging and drug delivery

Quantum Dots (QDs) have transformative uses for imaging and drug delivery, leveraging its distinct visual characteristics and functional versatility (Biswas *et al.*, 2024). In imaging, QDs are used extensively for their exceptional brightness and photostability, which surpass those of traditional fluorescent dyes (Table 1) (Li *et al.*, 2022). Their size-tuneable fluorescence allows for multicolour visualising, allowing scientists to label and track multiple biochemical molecules simultaneously (Tessitore *et al.*, 2021). This capability is especially beneficial in cellular and molecular visualising, where QDs provide high-resolution and long-term imaging of cellular processes, aiding in the study of disease mechanisms and early diagnosis (Guo *et al.*, 2021). For example, QDs conjugated using targeted compounds, cancer cells can be selectively bound, facilitating the particular visualization that of tumours and metastases (Jin *et al.*, 2020). This specificity improves the accuracy of diagnostic imaging and the effectiveness of treatments (Pellico *et al.*, 2021).

In drug delivery, QDs offer precise targeting capabilities. Their surfaces ligands, antibodies, or peptides that bind can be used to functionalise specifically as well target cells, such as cancer cells (Dhas *et al.*, 2022). This targeted delivery system ensures that therapeutic agents are delivered directly to ill cells, reducing adverse effects across the body, and enhancing treatment efficacy (Majumder and Minko, 2021). Additionally, QDs enable real-time medication tracking distribution additionally release inside the body, providing valuable feedback on the therapeutic process and enhancing personalized medicine approaches (Chen *et al.*, 2012). The integration of QDs in imaging and drug delivery exemplifies their significant potential in advancing healthcare technologies (Alharbi *et al.*, 2024).

UNIQUE OPTICAL PROPERTIES OF QUANTUM DOTS

Quantum Confinement Effect

Explanation of size dependent properties

The quantum confinement effect happens when the dimensions of a semiconductor nanoparticle, such as a Quantum Dot (QD), is diminished to a size that is similar to the exciton Bohr radius, usually between 1 and 10 nm (Osypiw *et al.*, 2022). At this nanoscale, in all three spatial dimensions, the motion of electrons and holes is constrained, resulting in discrete energy levels rather than the unceasing power bands observed while working with large quantities (Erkaboiev *et al.*, 2023). This confinement significantly alters both the optical and electrical properties from the content (William *et al.*, 2023). A single of that most notable consequences of quantum confinement is the adjustment of the QD's emission according to size wavelength (Wang *et al.*, 2020). The energy difference between the valence and conduction bands

Table 1: Comparative Analysis of Quantum Dots (QDs) and Traditional Fluorescent Dyes.

Parameter	Quantum Dots (QDs)	Traditional Fluorescent Dyes
Emission Spectrum	<ul style="list-style-type: none"> -Narrow and Size-Tunable: QDs exhibit narrow, size-dependent emission spectra, allowing precise control of the emitted wavelength. -Multicolor Capability: A single light source can excite multiple QDs, enabling multicolor imaging without significant spectral overlap. 	<ul style="list-style-type: none"> - Broad Emission: Traditional dyes have broader emission spectra, leading to significant spectral overlap. - Limited Multicolor Capability: Each dye requires a separate excitation source, complicating multicolor imaging.
Photostability	<ul style="list-style-type: none"> -High Stability: QDs are highly resistant to photobleaching and maintain fluorescence intensity over prolonged exposure to light. -Suitable for long-term imaging studies, such as tracking cellular processes over extended periods. 	<ul style="list-style-type: none"> -Low Stability: Traditional dyes photo bleach rapidly, losing fluorescence intensity under continuous light exposure. -Unsuitable for long-term imaging, as signal diminishes quickly.
Toxicity	<ul style="list-style-type: none"> -Moderate (Depends on Coating): Core materials like CdSe may release toxic ions; however, surface coatings (e.g., PEG, silica) can reduce toxicity and improve biocompatibility. -The use of non-toxic QDs like carbon or silicon can further minimize potential toxicity. 	<ul style="list-style-type: none"> -Low (Generally Non-Toxic): Traditional dyes are generally non-toxic but may cause cellular damage at high concentrations or prolonged exposure. -No need for additional surface coatings to reduce toxicity.
Multiplexing Capability	<ul style="list-style-type: none"> -High: QDs enable simultaneous detection of multiple targets due to their distinct, narrow emission peaks and broad absorption spectra. -Allows for multiplexed imaging and diagnostics with minimal spectral overlap, enhancing detection accuracy and efficiency. 	<ul style="list-style-type: none"> -Low: Limited capability for multiplexing due to broad emission spectra and significant spectral overlap. -Difficult to differentiate multiple signals, reducing accuracy in complex imaging applications.

widens as the QD's size contracts, elevates, causing a change in the emission spectrum towards shorter wavelengths (blue shift) (Hai *et al.*, 2021). On the other hand, larger QDs produce light at longer wavelengths (red shift) (Table 2) because they have a smaller energy gap (Park *et al.*, 2020). As such, property allows precise control over the hue of light released by quantum dots simply by adjusting their dimensions. Furthermore, that quantum confinement effect enhances the absorption cross-section of QDs, making them highly efficient at absorbing and emitting light (Chen, 2020). This effect is crucial for applications in optoelectronics, biological imaging, and photonics, where the ability to manipulate light at the nanoscale is essential (Ghobashy *et al.*, 2024). Overall the size-dependent properties imparted by quantum confinement are foundational to the unique functionality among quantum dots in various technological, as well as academic uses (Kagan *et al.*, 2020).

Impact on electronic and optical characteristics

The quantum confinement effect significantly impacts both the optical and electrical characteristics involving Quantum Dots (QDs), distinguishing them from bulk semiconductor materials (Agarwal *et al.*, 2023). One primary impact is the alteration of the energy of the band gap, which consists of the energy differential between the conduction and valence bands, where a single electron-hole pairs (excitons) recombine to emit

photons (Lechiffart *et al.*, 2022). As QDs decrease in size, the gap in the band energy rising as a result of stronger containment in quantum, leading to an alteration to blue in their optical emission (shorter wavelengths) (Emara *et al.*, 2020). Conversely, larger QDs have smaller bandgap energies, resulting in a red shift (longer wavelengths) (Ebe *et al.*, 2022). This size-dependent tunability of the bandgap enables precise control over the emission spectra of QDs, making them highly versatile for applications requiring specific wavelengths of light (Morselli *et al.*, 2021). For example, in optoelectronics, QDs can be tailored to emit desired colours for high-resolution displays and LED technologies (Kim *et al.*, 2024). Their narrow emission spectra and high brightness enhance the colour quality and efficiency of these devices (Zhang *et al.*, 2020).

In electronic applications, the discrete energy levels of QDs lead to distinct electrical characteristics, like size-tuneable charge carrier flexibility as well as enhanced photoconductivity (Masmali *et al.*, 2023). These characteristics are exploited in photovoltaic cells to improve light absorption and conversion efficiency (Wang *et al.*, 2022). In photodetectors, the tuneable bandgap allows for sensitivity to specific wavelengths, enhancing their performance (Yadav *et al.*, 2022). Overall, the quantum confinement effect endows QDs with highly customizable electronic and optical properties, driving innovations in display technologies, solar cells, sensors, and biomedical imaging (Qureshi *et al.*, 2024).

Table 2: Tuneable emission wavelengths based on size.

Quantum Dot Size	Emission Colour	Approximate Emission Wavelength (nm)
Large	Red	620-750
Medium	Green	500-570
Small	Blue	450-490

EMISSION AND ABSORPTION SPECTRA

Explanation

Large Quantum Dots: These have a smaller bandgap due to less quantum confinement, resulting in the emission of red light, which has longer wavelengths (Sadhu *et al.*, 2022).

Medium Quantum Dots: These emit green light, with intermediate wavelengths, due to moderate quantum confinement (Chen *et al.*, 2020).

Small Quantum Dots: These exhibit strong quantum confinement, leading to a larger bandgap and the emission of blue light, which has shorter wavelengths (Mohamed *et al.*, 2021).

High Brightness and Photostability

Quantum dots are known for their high brightness and photostability, which make them superior to traditional fluorescent dyes. Their high quantum yield ensures that a respectable percentage of photons that are absorbed are re-released as fluorescence, resulting in intense brightness (Cheng *et al.*, 2023). Additionally, QDs exhibit exceptional resistance to photobleaching, maintaining their luminescence for prolonged periods of time exposed to light. That, makes them ideal for extended-term imaging uses (Yang *et al.*, 2020).

Spectra of Narrow Emission and Broad Absorption

The quantum dots possess wide-ranging absorption spectra, allowing them to absorb a wide spectrum of wavelengths (Liu *et al.*, 2020). This combination of Spectra with wide absorption and narrow emission enhances their utility in making them versatile for excitation by various light sources (Lupton *et al.*, 2021). Conversely, they have narrow, symmetric emission spectra, which lead to sharp and well-defined fluorescence peaks. multiplexed imaging and allows for the several targets are detected simultaneously with little spectral overlap (Table 3) (Becerril-Castro *et al.*, 2022).

IMAGING APPLICATIONS OF QUANTUM DOTS

Biological and Medical Imaging

Quantum Dots (QDs) are highly effective in cellular and molecular imaging because of their remarkable photostability, brightness, additionally size-tunable fluorescence (Kortel *et al.*, 2020). In cellular imaging, QDs have the potential to conjugated Using biomolecules such as nucleic acids, peptides, or antibodies,

allowing specific targeting of cellular structures and proteins (Hu *et al.*, 2020). This specificity facilitates detailed visualization of cellular processes, interactions, and dynamics at the molecular level. As an illustration, QDs useful for labelling and track individual compounds, enabling real-time observation from biological mechanisms like signal transduction for example, gene expression, and protein trafficking (Bludau *et al.*, 2020). Their strong quantum yield and deterrent to photobleaching make QDs ideal in light of prolonged imaging sessions, surpassing the limitations of conventional fluorescent dyes (Xiao *et al.*, 2021).

In vivo Imaging Techniques

In vivo imaging with QDs offers significant advantages for studying complex biological systems in living organisms (Afshari *et al.*, 2022). QDs able to be designed to target certain tissues instead disease sites, such as tumors, by conjugating them with targeting ligands or antibodies (Abdellatif *et al.*, 2022). Their tunable emission wavelengths allow for imaging using multiplexing, wherein several QDs of various diameters can be employed simultaneously to track various biological targets within the same organism (Ansari *et al.*, 2021). This capability is particularly useful for monitoring disease progression, therapeutic response, and biodistribution of drugs in real-time (Dasgupta *et al.*, 2020). Additionally, the high photostability and brightness of QDs enable deep tissue imaging with minimal signal loss, providing clear and detailed images of internal structures (Pandey *et al.*, 2020). These properties make QDs invaluable tools in preclinical research and potentially in clinical diagnostics, improving improving comprehension of the mechanisms underlying disease and supporting the creation of targeted treatments (Pant *et al.*, 2021).

Diagnostic Imaging

Cancer Detection and Imaging

Quantum Dots (QDs) significantly enhance cancer detection and visualising because of their exceptional optical characteristics and capacity to target specific cancer biomarkers (Badilli *et al.*, 2020). By conjugating QDs loaded with peptides, antibodies, or other ligands that are attached to tumor-specific antigenics, researchers can achieve highly targeted imaging of cancer cells (Todaro *et al.*, 2023). This specificity allows for the precise localization of tumors, even at early stages, providing crucial information for diagnosis and treatment planning (Cao *et al.*, 2021). QDs' exceptional brightness and photostability enable prolonged as well detailed visualisation sessions, facilitating real-time monitoring of tumor growth, metastasis, and response to therapies (Roy *et al.*, 2023). Additionally, QDs' narrow emission spectra and multiplexing capabilities allow simultaneous visualization of multiple cancer markers, offering a comprehensive understanding of tumor heterogeneity and aiding in the development of personalized treatment strategies (Jia *et al.*, 2024).

Table 3: Overview of Quantum Dot Properties and Applications.

Property	Details	Biomedical Application	Advantages
Size	-2 to 10 nm (nanometers). -Smaller size allows for efficient tissue penetration.	-Cellular and molecular imaging. -Drug delivery	-Enables targeting of specific cellular structures. -Efficient penetration in tissues.
Emission Spectrum	-Broad absorption spectrum -Narrow, size-tuneable emission spectrum (450-750 nm)	-High-resolution imaging -Multiplexed imaging -Pathogen detection	-Multicolor imaging capabilities. -Low spectral overlap for multiplexed applications.
Photostability	-High resistance to photobleaching. -Long-term stability under continuous exposure.	-Long-term cellular tracking. - <i>In vivo</i> imaging.	-Suitable for prolonged imaging studies -Consistent signal over time
Biocompatibility	- Depends on surface coating (e.g., PEG, silica) - Reduced toxicity with biocompatible coatings	-Drug delivery - <i>In vivo</i> imaging -Targeted therapy	-Minimizes adverse effects -Improved circulation time and biodistribution

Pathogen Detection

Quantum dots are also highly effective in pathogen detection, offering rapid, sensitive, and specific diagnostic capabilities (Loo *et al.*, 2022). By conjugating QDs with antibodies or nucleic acid probes that specifically bind to pathogenic bacteria, viruses, or other microorganisms, they in fact suitable for detecting same infections in different samples, such as blood, saliva, or environmental swabs (Shen *et al.*, 2021). The strong and stable fluorescence signal of QDs enables the identification of even minimal amounts of pathogens, improving that sensitivity that of diagnostic assays (Wang *et al.*, 2021). Multiplexing with different QDs enables the rapid identification of several infections in one test at the same time, expediting the diagnostic procedure. and providing comprehensive information about infections (Syed *et al.*, 2024). These advantages make QDs a powerful tool to increase precision and efficiency that of pathogen recognition in clinical diagnostics additionally public health observation (Mousavi *et al.*, 2022).

TARGETED DRUG DELIVERY APPLICATIONS

Functionalization of Quantum Dots

Surface Modification with Biomolecules

Functionalizing the surface between Quantum Dots (QDs) with biomolecules is crucial due to their application within targeted drug delivery (Alshamrani, 2022). This process involves attaching biological molecules, for example peptides, tiny compounds, proteins, or nucleic acids, to that surface of QDs (Dos *et al.*, 2020). These modifications enhance how long-lasting and biocompatible QDs are in biological circumstances, reducing potential toxicity (Huang *et al.*, 2024). Additionally, surface biomolecules can be tailored to interact specifically with cellular receptors or other biological targets, assisting in the precise transportation of medicinal substances (Mitchell *et al.*, 2021). For example, Polyethylene Glycol (PEG) can be used to coat QDs, improving the duration of their circulatory circulation and preventing

immune recognition (Gidwani *et al.*, 2021). Such modifications enable QDs to effectively navigate the complex biological milieu and reach their intended targets (Liu *et al.*, 2024).

Targeting Ligands and Antibodies

To achieve targeted drug delivery, QDs are often combined with targeting antigen-recognizing ligands or antibodies and bind to particular surface of the cell markers (Kargozar *et al.*, 2020). These markers are typically overexpressed on diseased cells, such as cancer cells, allowing for selective targeting (Han *et al.*, 2020). For instance, QDs can be functionalized with antibodies against HER2, a receptor overexpressed in certain breast cancers, ensuring that the QDs specifically home in on cancerous cells while sparing healthy tissues (Hesemans *et al.*, 2022). Ligands such as folic acid, which targets the folate receptor commonly overexpressed in various tumors, can also be used. This targeted approach maximizes the drug's effectiveness in treating a condition QDs, reduces impacts that are not intended, and minimizes hazardous systems throughout the body (Fatima *et al.*, 2022). By ensuring that drugs are delivered directly to diseased cells, this method enhances that accuracy and efficacy of the therapies, paving that way for advanced therapeutic strategies in personalized medicine (Lattanzi *et al.*, 2021).

Mechanism of Drug Delivery

Passive Targeting (The effect of enhanced permeability and retention)

Passive targeting leverages the phenomenon known as the Enhanced Permeability and Retention (EPR) effect where minuscule particles, like Quantum Dots (QDs), preferentially form in tumour tissues as a result of the distinct vascular structure of these tissues (Zhang *et al.*, 2022). Tumours typically have leaky vasculature with large endothelial gaps, allowing nanoparticles to penetrate and remain more readily than in normal tissues in the interstitium of the tumour (Ni *et al.*, 2022). Additionally, tumors often have poor lymphatic drainage, which

Table 4: Quantum Dot Functionalization and Targeting Strategies.

Functionalization Technique	Details	Targeting Mechanism	Application
Surface Coating	Coating QDs with biocompatible materials (e.g., PEG, silica) to reduce toxicity and improve stability. -Enhances circulation time in the bloodstream and prevents aggregation.	Passive Targeting -Enhanced Permeability and Retention (EPR) Effect: Exploits the leaky vasculature and poor lymphatic drainage of tumors to accumulate in cancerous tissues.	-Cancer therapy -Long-term imaging -Drug delivery to solid tumors.
Ligand Conjugation	-Attaching ligands such as folic acid, peptides, or small molecules to QDs. -Enables specific binding to receptors overexpressed on target cells (e.g., folate receptor in cancer cells).	Active Targeting -Receptor-mediated Targeting: Ligands bind to specific receptors on target cells, ensuring precise localization and uptake by diseased cells.	-Cancer therapy -Targeted drug delivery -Imaging of specific cellular processes.
Antibody Attachment	-Conjugation of antibodies specific to tumor antigens (e.g., anti-HER2 for breast cancer) or pathogens. -Provides high specificity and affinity for target cells.	Active Targeting -Receptor-mediated Targeting: Antibodies recognize and bind to specific antigens on diseased cells or pathogens, facilitating targeted delivery and imaging.	-Cancer therapy -Pathogen detection -Targeted drug delivery and diagnostics.

SAFETY AND TOXICITY CONCERNS

Potential Cytotoxicity of Quantum dots

Table 5: Influence of Size, Composition, and Surface Coating.

Factor	Influence on Cytotoxicity
Size	Smaller QDs are characterised by increased surface-to-volume ratio, increasing reactivity and potential toxicity.
Composition	Core materials like CdSe can release toxic ions (e.g., cadmium) that pose health risks.
Surface Coating	Biocompatible coatings (e.g., PEG, silica) can stabilize QDs, reduce ion release, improve solubility, and decrease aggregation, thereby reducing toxicity.

further aids in the retention of these nanoparticles (Shinde *et al.*, 2022). By exploiting the EPR effect, drug-loaded QDs can passively accumulate in tumor sites, providing an elevated local dosage of the medicinal substance directly within the tumor environment (Sahu *et al.*, 2022). This passive targeting enhances the maximising the therapeutic outcome while reducing systemic adverse effects (Zhi *et al.*, 2020).

Active Targeting (Receptor-Mediated Targeting)

Active targeting is the process of functionalising QDs using particular ligands or antibodies that attach to target cells, including cancer cells, that have their receptors overexpressed (da *et al.*, 2021). This receptor-mediated targeting ensures that QDs selectively bind to and are internalized by the target cells, delivering their therapeutic payload directly to the diseased site

(Gopalan *et al.*, 2020). For example, QDs conjugated potentially target cancer cells that overexpress folate receptors by using folic acid, or antibodies against the HER2 receptor can direct QDs to HER2-positive breast cancer cells (Rajani *et al.*, 2020). This precise targeting enhances the therapeutic efficacy by increasing the accumulation of the drug around the location of the illness and reducing off-target effects unintended consequences (Ouyang *et al.*, 2022). Active targeting Moreover, improves medication administration specificity however, additionally allows for the possible application of lower drug doses, lowering the possibility of negative consequences and enhancing patient outcomes (Rahim *et al.*, 2021).

Advantages of QDs in Drug Delivery

Enhanced Targeting Precision

Quantum Dots (QDs) offer significant advantages in drug delivery due to their enhanced targeting precision (Wang *et al.*, 2020). By functionalizing QDs Using particular ligands or antibodies, they are able to selectively attach to the intended cells, such as cancer cells, overexpressing certain receptors (Shukla *et al.*, 2023). This precision targeting ensures that therapeutic agents are sent out directly to the diseased site, minimizing damage to healthy tissues and reducing systemic side effects (Manzari *et al.*, 2021). Because QDs are tiny, they can penetrate tissues and cellular barriers effectively, enhancing the delivery of drugs to intracellular targets (Veselov *et al.*, 2022). The elevated ratio of QDs' surface area to volume also permits the attachment that of multiple targeting

molecules and therapeutic agents, improving targeting accuracy and therapeutic payload delivery (Tan *et al.*, 2020). This precise targeting can lead to improved treatment efficacy, particularly in complex diseases like cancer, where targeting specific cell populations is crucial (Table 4) (Bejarano *et al.*, 2021).

Monitoring and Tracking Drug Distribution in Real Time

The capacity of QDs to provide real-time tracking and monitoring of medication distribution is another significant benefit of using them in drug delivery within the body (Sarkar *et al.*, 2024). The intrinsic fluorescence properties of QDs allow them to be visualized using various imaging techniques, providing detailed insights into their biodistribution and pharmacokinetics (Aladesuyi *et al.*, 2022). This real-time tracking capability allows researchers and clinicians to monitor the delivery and release of drugs making certain that the medicinal ingredients are present at the intended location reach their intended destination and remain there for the desired duration (Rana *et al.*, 2023). It also helps to make the adjustment that of Various therapy regimens determined on the distribution that was seen patterns, optimizing therapeutic outcomes (Hakami *et al.*, 2024). Additionally, this capability can be used to track the clearance and potential accumulation of QDs, addressing safety and toxicity concerns (Wang *et al.*, 2021). The ability to keep track of medications delivery in the moment thus enhances that precision and effectiveness of treatments, enabling the development of more customised and adaptive therapeutic techniques (Balogun *et al.*, 2023).

FUTURE PERSPECTIVES AND CHALLENGES

Clinical Translations and Applications

Progress towards Clinical Trials and Medical Applications

Quantum Dots (QDs) are making strides towards clinical translation and medical applications, Since they have special optical qualities and developments in biocompatibility (Tripathi *et al.*, 2023). Recent years have seen QDs with enhanced safety characteristics are being developed, including those with non-toxic cores and biocompatible coatings (Reddy *et al.*, 2024). These innovations have enabled the initiation of preclinical studies and early-phase clinical trials (Cho *et al.*, 2023). For instance, QDs are being tested for their efficacy in imaging-guided surgery, where their bright fluorescence helps surgeons visualize tumor margins more accurately (Li *et al.*, 2021). While regulatory approval remains a challenge, the growing body of safety and efficacy data is paving the way for more extensive clinical trials (Tables 5 and 6) (Galderisi *et al.*, 2022).

Potential impact on personalized medicine

Quantum dots have the capacity to completely transform customised treatment by making more exact diagnostics and focused treatments (Guo *et al.*, 2024). Their ability to provide

detailed molecular and cellular imaging can help identify specific biomarkers associated with individual patients' diseases, facilitating tailored treatment plans (Weber *et al.*, 2020). For example, QD-based imaging can distinguish between different types of tumors or detect subtle changes in disease states, enabling more precise diagnoses and monitoring that of treatment reactions (Ali *et al.*, 2023). By targeting particular cells or tissues with QDs, medication delivery can be optimised to reduce side effects and enhance therapeutic effectiveness (Yetisgin *et al.*, 2020). This precision medicine approach guarantees that patients are given therapies that are most productive for their unique genetic and molecular profiles, ultimately leading to better outcomes and more efficient healthcare (Dlamini *et al.*, 2022). The incorporating QDs into medical procedures could thus significantly enhance the customization of patient care (Dai *et al.*, 2022).

Advances in Technology

Novel Approaches in QD synthesis and functionalization

Recent advancements in Quantum Dot (QD) synthesis and functionalization have significantly enhanced their potential for biomedical applications (Thangadurai *et al.*, 2022). Innovations in synthesis techniques have focused on creating QDs with precise size, shape, and composition control, resulting in uniform and highly tuneable optical properties (Yang *et al.*, 2022). Methods such as hot-injection, colloidal synthesis, and chemical vapor deposition have been refined to create QDs that are stable and have a high quantum yield (Meng, 2023). These improved synthesis protocols have also led to the progression of nontoxic heavy metal-free QDs, including carbon, silicon, and perovskite QDs, which address safety concerns associated with traditional cadmium-based QDs.

Functionalization advancements have focused on improving QDs' capacity to target and be biocompatible (Singh *et al.*, 2024). Surface alteration techniques, including ligand exchange, encapsulation with biocompatible polymers (e.g., polyethylene glycol), and the attachment of biomolecules (e.g., antibodies, peptides, and aptamers), have been optimized to improve QD solubility, stability, and specificity in biological environments (Eroğlu *et al.*, 2020). These functionalized QDs are capable of binding to specific target cells or tissues, facilitating exact imaging additionally targeted drug delivery (Zhang *et al.*, 2020).

CONCLUSION

Quantum Dots (QDs), semiconductor nanoparticles, exhibit unique optical properties such as size-tuneable emission wavelengths, high brightness, and photostability due to quantum confinement. These properties allow QDs to emit light in various colors depending on their size, with narrow emission spectra and broad absorption, making them ideal for high-resolution, multicolour imaging. Their application in biological and medical imaging is significant, providing detailed visualization at cellular

and chemical levels. In drug delivery, QDs can be functionalized with biomolecules for precise targeting and effective therapeutic administration, reducing side effects and improving outcomes. QDs enable prolonged, high-accuracy observation of biological processes, enhancing diagnostic precision. Their multicolour imaging capability allows simultaneous detection of multiple targets, offering insights into complex interactions. Additionally, real-time tracking of drug distribution enhances therapeutic efficacy. Innovations in QD technology include developing non-toxic QDs from materials like carbon or silicon, multifunctional QDs for imaging and therapy (theranostics), improved targeting mechanisms, integration with advanced imaging techniques, and personalized medicine approaches. These advancements position QDs as a critical tool in enhancing diagnostic and therapeutic precision, particularly in personalized medicine.

ACKNOWLEDGEMENT

The authors are extremely thankful Raghavendra Institute of Pharmaceutical Education and Research for their extreme support and knowledge.

CONFLICT OF INTEREST

The authors declare that they have no conflict of interest.

ABBREVIATIONS

QD: Quantum Dot; **LED:** Light Emitting Diode; **QLED:** Quantum Light Emitting Diode; **LCD:** Liquid Crystal Display; **OLED:** Organic Light Emitting Diode.

REFERENCES

- Abbas, A., Luo, Y., Ahmad, W., Mustaqeem, M., Kong, L., Chen, J., Zhou, G., Tabish, T. A., Zhang, Q., & Liang, Q. (2024). Recent progress, challenges, and opportunities in 2D materials for flexible displays. *Nano Today*, 56, Article 102256. <https://doi.org/10.1016/j.nantod.2024.102256>
- Abdellatif, A. A. H., Younis, M. A., Alsharidah, M., Al Rugaie, O., & Tawfeek, H. M. (2022). Biomedical applications of quantum dots: Overview, challenges, and clinical potential. *International Journal of Nanomedicine*, 17, 1951–1970. <https://doi.org/10.2147/IJN.S357980>
- Abdel-Salam, M., Omran, B., Whitehead, K., & Baek, K.-H. (2020). Superior properties and biomedical applications of microorganism-derived fluorescent quantum dots. *Molecules*, 25(19), 4486. <https://doi.org/10.3390/molecules25194486>
- Afshari, M. J., Li, C., Zeng, J., Cui, J., Wu, S., & Gao, M. (2022). Self-illuminating NIR-II bioluminescence imaging probe based on silver sulfide quantum dots. *ACS Nano*, 16(10), 16824–16832. <https://doi.org/10.1021/acsnano.2c06667>
- Agarwal, K., Rai, H., & Mondal, S. (2023). Quantum dots: An overview of synthesis, properties, and applications. *Materials Research Express*, 10(6), Article 062001. <https://doi.org/10.1088/2053-1591/acda17>
- Aladesuyi, O. A., Lebepe, T. C., Maluleke, R., & Oluwafemi, O. S. (2022). Biological applications of ternary quantum dots: A review. *Nanotechnology Reviews*, 11(1), 2304–2319. <https://doi.org/10.1515/ntrev-2022-0136>
- Al-Douri, Y., Khan, M. M., & Jennings, J. R. (2023). Synthesis and optical properties of II-VI semiconductor quantum dots: A review. *Journal of Materials Science: Materials in Electronics*, 34(11), 993. <https://doi.org/10.1007/s10854-023-10435-5>
- AlGhamdi, J. M., AlOmar, S., Gondal, M. A., Moqbel, R., & Dastageer, M. A. (2020). Enhanced efficiency of dye co-sensitized solar cells based on pulsed-laser-synthesized cadmium-selenide quantum dots. *Solar Energy*, 209, 108–117. <https://doi.org/10.1016/j.solener.2020.08.091>
- Alharbi, H. M. (2024). Exploring the frontier of biopolymer-assisted drug delivery: Advancements, clinical applications, and future perspectives in cancer nanomedicine. *Drug Design, Development and Therapy*, 18, 2063–2087. <https://doi.org/10.2147/DDDT.S441325>
- Ali, M. K., Javaid, S., Afzal, H., Zafar, I., Fayyaz, K., Ain, Q. U., Rather, M. A., Hossain, M. J., Rashid, S., Khan, K. A., & Sharma, R. (2023). Exploring the multifunctional roles of quantum dots for unlocking the future of biology and medicine. *Environmental Research*, 232, Article 116290. <https://doi.org/10.1016/j.envres.2023.116290>
- Alshamrani, M. (2022). Broad-spectrum theranostics and biomedical application of functionalized nanomaterials. *Polymers*, 14(6), 1221. <https://doi.org/10.3390/polym14061221>
- Ansari, A. A., Thakur, V. K., & Chen, G. (2021). Functionalized upconversion nanoparticles: New strategy towards FRET-based luminescence bio-sensing. *Coordination Chemistry Reviews*, 436, Article 213821. <https://doi.org/10.1016/j.ccr.2021.213821>
- Augustine, R., Al Mamun, A. A., Hasan, A., Salam, S. A., Chandrasekaran, R., Ahmed, R., & Thakor, A. S. (2021). Imaging cancer cells with nanostructures: Prospects of nanotechnology driven non-invasive cancer diagnosis. *Advances in Colloid and Interface Science*, 294, Article 102457. <https://doi.org/10.1016/j.cis.2021.102457>
- Badilli, U., Mollarasouli, F., Bakirhan, N. K., Ozkan, Y., & Ozkan, S. A. (2020). Role of quantum dots in pharmaceutical and biomedical analysis, and its application in drug delivery. *TrAC Trends in Analytical Chemistry*, 131, Article 116013. <https://doi.org/10.1016/j.trac.2020.116013>
- Balogun, O. D., Ayo-Farai, O., Ogundairo, O., Maduka, C. P., Okongwu, C. C., Babarinde, A. O., & Sodamade, O. T. (2023). Innovations in drug delivery systems: A review of the pharmacist's role in enhancing efficacy and patient compliance. *World Journal of Advanced Research and Reviews*, 20(3), 1268–1282. <https://doi.org/10.30574/wjarr.2023.20.3.2587>
- Becerril-Castro, I. B., Calderon, I., Pazos-Perez, N., Guerrini, L., Schulz, F., Feliu, N., et al. (2022). Gold nanostars: Synthesis, optical and SERS analytical properties. *Analysis & Sensing*, 2(3), Article e202200005.
- Bejarano, L., Jordão, M. J. C., & Joyce, J. A. (2021). Therapeutic targeting of the tumor microenvironment. *Cancer Discovery*, 11(4), 933–959. <https://doi.org/10.1158/2159-8290.CD-20-1808>
- Biswas, P., Saha, A., Sridhar, B., Patel, A., & Desai, B. M. A. (2024). Quantum dots as functional nanosystems for enhanced biomedical applications. *Journal of Biological Regulators and Homeostatic Agents*, 38(3), 1831–1857.
- Bludau, I., & Aebersold, R. (2020). Proteomic and interactomic insights into the molecular basis of cell functional diversity. *Nature Reviews. Molecular Cell Biology*, 21(6), 327–340. <https://doi.org/10.1038/s41580-020-0231-2>
- Böer, K. W., & Pohl, U. W. (2023). *Excitons. Semiconductor physics: Springer* (pp. 529–591).
- Cao, Y., Zhong, X., Diao, W., Mu, J., Cheng, Y., & Jia, Z. (2021). Radiomics in differentiated thyroid cancer and nodules: Explorations, Application, and Limitations [Application]. *Cancers*, 13(10), 2436. <https://doi.org/10.3390/cancers13102436>
- Cardoso Dos Santos, M. C., Algar, W. R., Medintz, I. L., & Hildebrandt, N. (2020). Quantum dots for Förster resonance energy transfer (FRET). *TrAC Trends in Analytical Chemistry*, 125, Article 115819. <https://doi.org/10.1016/j.trac.2020.115819>
- Chen, B., Li, D., & Wang, F. (2020). InP quantum dots: Synthesis and lighting applications. *Small*, 16(32), Article e2002454. <https://doi.org/10.1002/smll.202002454>
- Chen, C., Peng, J., Sun, S.-R., Peng, C.-W., Li, Y., & Pang, D.-W. (2012). Tapping the potential of quantum dots for personalized oncology: Current status and future perspectives. *Nanomedicine*, 7(3), 411–428. <https://doi.org/10.2217/nnm.12.9>
- Chen, J.-S. (2020). Optical and electronic properties of low-dimensional semiconductor nanohybrids based on quantum dots and 2D materials. State University of New York at Stony Brook.
- Cheng, J., Huang, H., Chen, Y., & Wu, R. (2023). Nanomedicine for diagnosis and treatment of atherosclerosis. *Advanced Science*, 10(36), Article e2304294. <https://doi.org/10.1002/advs.202304294>
- Cho, N. S., Wong, W. K., Nghiemphu, P. L., Cloughesy, T. F., & Ellingson, B. M. (2023). The future glioblastoma clinical trials landscape: Early Phase 0, window of opportunity, and adaptive Phase I–III studies. *Current Oncology Reports*, 25(9), 1047–1055. <https://doi.org/10.1007/s11912-023-01433-1>
- Dai, T., & Tayur, S. (2022). Designing AI-augmented healthcare delivery systems for physician buy-in and patient acceptance. *Production and Operations Management*, 31(12), 4443–4451. <https://doi.org/10.1111/poms.13850>
- Dasgupta, A., Biancacci, I., Kiessling, F., & Lammers, T. (2020). Imaging-assisted anticancer nanotherapy. *Theranostics*, 10(3), 956–967. <https://doi.org/10.7150/thno.38288>
- Devi, S., Kumar, M., Tiwari, A., Tiwari, V., Kaushik, D., Verma, R., Bhatt, S., Sahoo, B. M., Bhattacharya, T., Alshehri, S., Ghoneim, M. M., Babalghith, A. O., & Batiha, G. E.-S. (2022). Quantum dots: An emerging approach for cancer therapy. *Frontiers in Materials*, 8, Article 798440. <https://doi.org/10.3389/fmats.2021.798440>
- Dhas, N., Pastagia, M., Sharma, A., Khera, A., Kudarha, R., Kulkarni, S., Soman, S., Mutalik, S., Barnwal, R. P., Singh, G., & Patel, M. (2022). Organic quantum dots: An ultrasmall nanopatform for cancer theranostics. *Journal of Controlled Release*, 348, 798–824. <https://doi.org/10.1016/j.jconrel.2022.06.033>
- Diaz-González, M., de la Escosura-Muñoz, A., Fernandez-Argüelles, M. T., Alonso, F. J. G., & Costa-Fernandez, J. M. (2020). Quantum dot bioconjugates for diagnostic applications. Surface-modified nanobiomaterials for electrochemical and biomedical applications (pp. 133–176).

- Diez-Pascual, A. M. (2022). Surface engineering of nanomaterials with polymers, biomolecules, and small ligands for nanomedicine. *Materials*, 15(9), 3251. <https://doi.org/10.3390/ma15093251>
- Dlaminii, Z., Skepu, A., Kim, N., Mkhabele, M., Khanyile, R., Molefi, T., Mbatha, S., Setlai, B., Mulaudzi, T., Mabongo, M., Bida, M., Kgoebane-Maseko, M., Mathabe, K., Lockhat, Z., Kgotho, M., Chauke-Malinga, N., Ramagaga, S., & Hull, R. (2022). AI and precision oncology in clinical cancer genomics: From prevention to targeted cancer therapies-an outcomes based patient care. *Informatics in Medicine Unlocked*, 3(1), Article 100965. <https://doi.org/10.1016/j.imu.2022.100965>
- Ebe, H., Wang, Y.-K., Shinotsuka, N., Cheng, Y.-H., Uwano, M., Suzuki, R., Dong, Y., Ma, D., Lee, S., Chiba, T., Sargent, E. H., & Kido, J. (2022). Energy transfer between size-controlled CsPbI₃ quantum dots for light-emitting diode application. *ACS Applied Materials and Interfaces*, 14(15), 17691–17697. <https://doi.org/10.1021/acsami.2c03971>
- Emara, M. M., & Van Patten, P. G. (2020). Effect of oxygen and polymer matrix on photo-induced changes in CdSe quantum dots. *Materials Chemistry and Physics*, 256, Article 123652. <https://doi.org/10.1016/j.matchemphys.2020.123652>
- Erkaboev, U., Rakhimov, R., & Azimova, N. (2023). Determination of oscillations of the density of energy states in nanoscale semiconductor materials at different temperatures and quantizing magnetic fields. *Global Scientific Review*, 12, 33–49.
- Eroglu, I., & Ibrahim, M. (2020). Liposome-ligand conjugates: A review on the current state of art. *Journal of Drug Targeting*, 28(3), 225–244. <https://doi.org/10.1080/1061186X.2019.1648479>
- Fatima, M., Sheikh, A., Hasan, N., Sahebkar, A., Riadi, Y., & Kesharwani, P. (2022). Folic acid conjugated poly (amidoamine) dendrimer as a smart nanocarriers for tracing, imaging, and treating cancers over-expressing folate receptors. *European Polymer Journal*, 170, Article 111156. <https://doi.org/10.1016/j.eurpolymj.2022.111156>
- Galderisi, U., Peluso, G., & Di Bernardo, G. (2022). Clinical trials based on mesenchymal stromal cells are exponentially increasing: Where are we in recent years? *Stem Cell Reviews and Reports*, 18(1), 23–36. <https://doi.org/10.1007/s12015-021-10231-w>
- García de Arquer, F. P., Talapin, D. V., Klimov, V. I., Arakawa, Y., Bayer, M., & Sargent, E. H. (2021). Semiconductor quantum dots: Technological progress and future challenges. *Science*, 373(6555), Article eaaz8541. <https://doi.org/10.1126/science.aaz8541>
- Ghobashy, M. M., Alkhursani, S. A., Alqahtani, H. A., El-damhougy, T. K., & Madani, M. (2024). Madani M. Gold nanoparticles in microelectronics advancements and biomedical applications. *Materials Science and Engineering*, 301, Article 117191. <https://doi.org/10.1016/j.mseb.2024.117191>
- Gidwani, B., Sahu, V., Shukla, S. S., Pandey, R., Joshi, V., Jain, V. K., & Vyas, A. (2021). Quantum dots: Prospectives, toxicity, advances and applications. *Journal of Drug Delivery Science and Technology*, 61, Article 102308. <https://doi.org/10.1016/j.jddst.2020.102308>
- Gong, B. (2024). Research Progress of potential solar cells alternative. *Highlights in Science, Engineering and Technology*, 83, 655–661. <https://doi.org/10.54097/yf1th717>
- Gopalan, D., Pandey, A., Udupa, N., & Mutalik, S. (2020). Receptor specific, stimuli responsive and subcellular targeted approaches for effective therapy of Alzheimer: Role of surface engineered nanocarriers. *Journal of Controlled Release*, 319, 183–200. <https://doi.org/10.1016/j.jconrel.2019.12.034>
- Guo, W., Song, X., Liu, J., Liu, W., Chu, X., & Lei, Z. (2024). Quantum dots as a potential multifunctional material for the enhancement of clinical diagnosis strategies and cancer treatments. *Nanomaterials*, 14(13), 1088. <https://doi.org/10.3390/nano14131088>
- Guo, Z., & Cui, Z. (2021). Fluorescent nanotechnology for *in vivo* imaging. *Wiley Interdisciplinary Reviews. Nanomedicine and Nanobiotechnology*, 13(5), Article e1705. <https://doi.org/10.1002/wnan.1705>
- Hai, O., Pei, M., Yang, E., Ren, Q., Wu, X., Zhao, Y., & Du, L. (2021). Tunable luminescent color from green to blue on long afterglow materials using CsPbBr₃ quantum dots. *Applied Surface Science*, 568, Article 150941. <https://doi.org/10.1016/j.apsusc.2021.150941>
- Hakami, M. A. (2024). Harnessing machine learning potential for personalised drug design and overcoming drug resistance. *Journal of Drug Targeting*, 32(8), 918–930. <https://doi.org/10.1080/1061186X.2024.2365934>
- Han, J., Won, M., Kim, J. H., Jung, E., Min, K., Jangili, P., & Kim, J. S. (2020). Cancer stem cell-targeted bio-imaging and chemotherapeutic perspective. *Chemical Society Reviews*, 49(22), 7856–7878. <https://doi.org/10.1039/d0cs00379d>
- Hao, J. (2020). Revisiting induced chirality and gold photodeposition on CdSe/CdS semiconductors with various controlled morphologies: Université de Bordeaux.
- Hesemans, E., Buttiens, K., Manshian, B. B., & Soenen, S. J. (2022). The role of optical imaging in translational nanomedicine. *Journal of Functional Biomaterials*, 13(3), 137. <https://doi.org/10.3390/jfb13030137>
- Hu, X.-L., Kwon, N., Yan, K.-C., Sedgwick, A. C., Chen, G.-R., He, X.-P., James, T. D., & Yoon, J. (2020). Bio-conjugated advanced materials for targeted disease theranostics. *Advanced Functional Materials*, 30(13), Article 1907906. <https://doi.org/10.1002/advfm.201907906>
- Huang, S., & Huang, G. (2024). The utilization of quantum dot labeling as a burgeoning technique in the field of biological imaging. *RSC Advances*, 14(29), 20884–20897. <https://doi.org/10.1039/d4ra04402a>
- Huang, Y.-M., Singh, K. J., Liu, A.-C., Lin, C.-C., Chen, Z., Wang, K., Lin, Y., Liu, Z., Wu, T., & Kuo, H.-C. (2020). Advances in quantum-dot-based displays. *Nanomaterials*, 10(7), 1327. <https://doi.org/10.3390/nano10071327>
- Jia, D., Cui, M., & Ding, X. (2024). Visualizing DNA/RNA, proteins, and small molecule metabolites within live cells. *Small*, 20(46), Article e2404482. <https://doi.org/10.1002/smll.202404482>
- Jiao, M., Portniagin, A. S., Luo, X., Jing, L., Han, B., & Rogach, A. L. (2022). Semiconductor nanocrystals emitting in the second near-infrared window: Optical properties and application in biomedical imaging. *Advanced Optical Materials*, 10(14), Article 2200226. <https://doi.org/10.1002/adom.202200226>
- Jin, K.-T., Yao, J.-Y., Ying, X.-J., Lin, Y., & Chen, Y.-F. (2020). Nanomedicine and early cancer diagnosis: Molecular imaging using fluorescence nanoparticles. *Current Topics in Medicinal Chemistry*, 20(30), 2737–2761. <https://doi.org/10.2174/156802620666200922112640>
- Kagan, C. R., Bassett, L. C., Murray, C. B., & Thompson, S. M. (2021). Colloidal quantum dots as platforms for quantum information science. *Chemical Reviews*, 121(5), 3186–3233. <https://doi.org/10.1021/acs.chemrev.0c00831>
- Kambhampati, P. (2021). Nanoparticles, nanocrystals, and quantum dots: What are the implications of size in colloidal nanoscale materials? *The Journal of Physical Chemistry Letters*, 12(20), 4769–4779. <https://doi.org/10.1021/acs.jpcclett.1c00754>
- Kargozar, S., Hoseini, S. J., Milan, P. B., Hooshmand, S., Kim, H.-W., & Mozafari, M. (2020). Quantum dots: A review from concept to clinic. *Biotechnology Journal*, 15(12), Article e2000117. <https://doi.org/10.1002/biot.202000117>
- Khan, S., & Hossain, M. K. (2022). Classification and properties of nanoparticles. *Nanoparticle-based polymer composites* (pp. 15–54). Elsevier.
- Kim, J., Roh, J., Park, M., & Lee, C. (2024). Recent advances and challenges of colloidal quantum dot light-emitting diodes for display applications. *Advanced Materials*, 36(20), Article e2122220. <https://doi.org/10.1002/adma.202122220>
- Kortel, M., Mansuriya, B. D., Vargas Santana, N., & Altintas, Z. (2020). Graphene quantum dots as flourishing nanomaterials for bio-imaging, therapy development, and micro-supercapacitors. *Micromachines*, 11(9), 866. <https://doi.org/10.3390/mi11090866>
- Kumar Shukla, M. K., Parihar, A., Karthikeyan, C., Kumar, D., & Khan, R. (2023). Multifunctional QDs for receptor targeting, drug delivery, and bioimaging in pancreatic cancer. *Nanoscale*, 15(36), 14698–14716. <https://doi.org/10.1039/d3nr03161f>
- Lattanzi, W., Ripoli, C., Greco, V., Barba, M., Iavarone, F., Minucci, A., Urbani, A., Grassi, C., & Parolini, O. (2021). Basic and preclinical research for personalized medicine. *Journal of Personalized Medicine*, 11(5), 354. <https://doi.org/10.3390/jpm11050354>
- Lechiffart, P., Paleari, F., & Attacalite, C. (2022). Excitons under strain: Light absorption and emission in strained hexagonal boron nitride. *SciPost Physics*, 12(5), 145. <https://doi.org/10.21468/SciPostPhys.12.5.145>
- Li, S., Cheng, D., He, L., & Yuan, L. (2021). Recent progresses in NIR-III fluorescence imaging for surgical navigation. *Frontiers in Bioengineering and Biotechnology*, 9, Article 768698. <https://doi.org/10.3389/fbioe.2021.768698>
- Li, W., Kaminski Schierle, G. S., Lei, B., Liu, Y., & Kaminski, C. F. (2022). Fluorescent nanoparticles for super-resolution imaging. *Chemical Reviews*, 122(15), 12495–12543. <https://doi.org/10.1021/acs.chemrev.2c00050>
- Liu, G., Wang, X., Han, G., Yu, J., & Zhao, H. (2020). Earth abundant colloidal carbon quantum dots for luminescent solar concentrators. *Materials advances*, 1(2), 119–138.
- Liu, X.-Y., Li, R.-F., Jia, J., & Yu, Z.-L. (2024). Antibacterial micro/nanomotors: Current research progress, challenges, and opportunities. *Theranostics*, 14(3), 1029–1048. <https://doi.org/10.7150/thno.92449>
- Loo, K.-Y., Law, J. W.-F., Tan, L. T.-H., Pusparajah, P., Letchumanan, V., & Lee, L.-H. (2022). Diagnostic techniques for rapid detection of *Vibrio* species. *Aquaculture*, 561, Article 738628. <https://doi.org/10.1016/j.aquaculture.2022.738628>
- Lupton, J. M., & Vogelsang, J. (2021). Photon correlations probe the quantized nature of light emission from optoelectronic materials. *Applied Physics Reviews*, 8(4). <https://doi.org/10.1063/5.0059764>
- Majumder, J., & Minko, T. (2021). Multifunctional and stimuli-responsive nanocarriers for targeted therapeutic delivery. *Expert Opinion on Drug Delivery*, 18(2), 205–227. <https://doi.org/10.1080/17425247.2021.1828339>
- Manzari, M. T., Shamay, Y., Kiguchi, H., Rosen, N., Scaltriti, M., & Heller, D. A. (2021). Targeted drug delivery strategies for precision medicines. *Nature Reviews. Materials*, 6(4), 351–370. <https://doi.org/10.1038/s41578-020-00269-6>
- Masmali, N. A., & Osman, Z. (2023). CdSe and Ag₂S quantum dots: Synthesis, effects of doping, and applications. In *Quantum dots* (pp. 267–285). Elsevier. <https://doi.org/10.1016/B978-0-323-85278-4.00017-9>
- Meng, H. (2023). Colloidal quantum dot light emitting diodes. *Materials and Devices*. John Wiley & Sons.
- Mitchell, M. J., Billingsley, M. M., Haley, R. M., Wechsler, M. E., Peppas, N. A., & Langer, R. (2021). Engineering precision nanoparticles for drug delivery. *Nature Reviews. Drug Discovery*, 20(2), 101–124. <https://doi.org/10.1038/s41573-020-0090-8>
- Mohamed, W. A. A., Abd El-Gawad, H., Mekkey, S., Galal, H., Handal, H., Mousa, H., & Labib, A. (2021). Quantum dots synthesis and future prospect applications. *Nanotechnology Reviews*, 10(1), 1926–1940. <https://doi.org/10.1515/ntrev-2021-0118>

- Morselli, G., Villa, M., Fermi, A., Critchley, K., & Ceroni, P. (2021). Luminescent copper indium sulfide (CIS) quantum dots for bioimaging applications. *Nanoscale Horizons*, 6(9), 676–695. <https://doi.org/10.1039/d1nh00260k>
- Mousavi, S. M., Hashemi, S. A., Yari Kalashgrani, M., Omidifar, N., Lai, C. W., Vijayakameswara Rao, N., Gholami, A., & Chiang, W.-H. (2022). The pivotal role of quantum dots-based biomarkers integrated with ultra-sensitive probes for multiplex detection of human viral infections. *Pharmaceuticals*, 15(7), 880. <https://doi.org/10.3390/ph15070880>
- Murar, M., Albertazzi, L., & Pujals, S. (2022). Advanced optical imaging-guided nanotheranostics towards personalized cancer drug delivery. *Nanomaterials*, 12(3), 399. <https://doi.org/10.3390/nano12030399>
- Ni, N., Wang, W., Sun, Y., Sun, X., & Leong, D. T. (2022). Inducible endothelial leakiness in nanotherapeutic applications. *Biomaterials*, 287, Article 121640. <https://doi.org/10.1016/j.biomaterials.2022.121640>
- Osyptiw, A. R., Lee, S., Jung, S.-M., Leoni, S., Smowton, P. M., Hou, B., et al. (2022). Solution-processed colloidal quantum dots for light emission. *Materials advances*, 3(17), 6773–6790.
- Ouyang, Q., Meng, Y., Zhou, W., Tong, J., Cheng, Z., & Zhu, Q. (2022). New advances in brain-targeting nano-drug delivery systems for Alzheimer's disease. *Journal of Drug Targeting*, 30(1), 61–81. <https://doi.org/10.1080/1061186X.2021.1927055>
- Pandey, S., & Bodas, D. (2020). High-quality quantum dots for multiplexed bioimaging: A critical review. *Advances in Colloid and Interface Science*, 278, Article 102137. <https://doi.org/10.1016/j.cis.2020.102137>
- Pant, A., Mackraj, I., & Govender, T. (2021). Advances in sepsis diagnosis and management: A paradigm shift towards nanotechnology. *Journal of Biomedical Science*, 28(1), 6. <https://doi.org/10.1186/s12929-020-00702-6>
- Park, S., Son, C., Kang, S., Baek, S., Kim, Y., Kwon, O.-P., Park, J., & Kim, S.-W. (2020). Development of highly efficient blue-emitting ZnSexTe1-x/ZnSe/ZnS quantum dots and their electroluminescence application. *Journal of Industrial and Engineering Chemistry*, 88, 348–355. <https://doi.org/10.1016/j.jiec.2020.05.003>
- Pellico, J., Gawne, P. J., & T M de Rosales, R. T. (2021). Radiolabelling of nanomaterials for medical imaging and therapy. *Chemical Society Reviews*, 50(5), 3355–3423. <https://doi.org/10.1039/d0cs00384k>
- Qureshi, Z. A., Dabash, H., Ponnamma, D., & Abbas, M. K. G. (2024). Carbon dots as versatile nanomaterials in sensing and imaging: Efficiency and beyond. *Heliyon*, 10(11), Article e31634. <https://doi.org/10.1016/j.heliyon.2024.e31634>
- Rahim, M. A., Jan, N., Khan, S., Shah, H., Madni, A., Khan, A., Khan, S., Elhissi, A., Hussain, Z., Aziz, H. C., Sohail, M., Khan, M., & Thu, H. E. (2021). Recent advancements in stimuli responsive drug delivery platforms for active and passive cancer targeting. *Cancers*, 13(4), 670. <https://doi.org/10.3390/cancers13040670>
- Rajani, C., Borisa, P., Karanwad, T., Borade, Y., Patel, V., Rajpoot, K., & Tekede, R. K. (2020). Cancer-targeted chemotherapy: Emerging role of the folate anchored dendrimer as drug delivery nanocarrier. *Pharmaceutical applications of dendrimers* (pp. 151–198). Elsevier.
- Ramburrun, P., Khan, R. A., & Choonara, Y. E. (2022). Design, preparation, and functionalization of nanobiomaterials for enhanced efficacy in current and future biomedical applications. *Nanotechnology Reviews*, 11(1), 1802–1826. <https://doi.org/10.1515/ntrev-2022-0106>
- Rana, A., Adhikary, M., Singh, P. K., Das, B. C., & Bhatnagar, S. (2022). 'Smart' drug delivery: A window to future of translational medicine. *Frontiers in Chemistry*, 10, Article 1095598. <https://doi.org/10.3389/fchem.2022.1095598>
- Reddy, K. T. K., Madhavi Latha, B., Gupta, J. K., Chaitanya, A., Srinivasa Babu, P., Manikanta, Y., & Sahithi, A. (2024). Discovery and history of quantum dots. *Quantum dots based nanocomposites: Design, fabrication and emerging applications*: Springer (pp. 13–34).
- Reddy, K. T. K., Venkatesan, N., Saranya, M., Somasundaram, J., Gupta, J. K., Priya, N. S., et al. (2024). Cytotoxicity of quantum dots based nanocomposites. *Quantum dots based nanocomposites: Design, fabrication and emerging applications*: Springer (pp. 207–229).
- Roy, S., Bag, N., Bardhan, S., Hasan, I., & Guo, B. (2023). Recent progress in NIR-II fluorescence imaging-guided drug delivery for cancer theranostics. *Advanced Drug Delivery Reviews*, 197, Article 114821. <https://doi.org/10.1016/j.addr.2023.114821>
- Sadhu, A. S., Huang, Y.-M., Chen, L.-Y., Kuo, H.-C., & Lin, C.-C. (2022). Recent advances in colloidal quantum dots or perovskite quantum dots as a luminescent downshifting layer embedded on solar cells. *Nanomaterials*, 12(6), 985. <https://doi.org/10.3390/nano12060985>
- Sahu, B. P., Baishya, R., Hatiboruah, J. L., Laloo, D., & Biswas, N. (2022). A comprehensive review on different approaches for tumor targeting using nanocarriers and recent developments with special focus on multifunctional approaches. *Journal of Pharmaceutical Investigation*, 52(5), 539–585. <https://doi.org/10.1007/s40005-022-00583-x>
- Santos, E. D. S., Nogueira, K. A. B., Fernandes, L. C. C., Martins, J. R. P., Reis, A. V. F., Neto, J. B. V., Júnior, I. J. D. S., Pessoa, C., Petrilli, R., & Eloy, J. O. (2021). EGFR targeting for cancer therapy: Pharmacology and immunoconjugates with drugs and nanoparticles. *International Journal of Pharmaceutics*, 592, Article 120082. <https://doi.org/10.1016/j.ijpharm.2020.120082>
- Sarkar, S., Srivastava, T. P., Sahoo, O. S., Shankar, A., Rai, A., Pethusamy, K., Dhar, R., & Karmakar, S. (2024). Applications of quantum dots in preventive oncology. *Asian Pacific Journal of Cancer Prevention: APJCP*, 25(3), 747–756. <https://doi.org/10.31557/APJCP.2024.25.3.747>
- Sarkar, S. K. (2023). Quantum dots as optical materials: Small wonders and endless frontiers. *Handbook of materials science. In Optical materials*: Springer, 1 (pp. 545–596).
- Shao, B., Liu, Z., Zeng, G., Wang, H., Liang, Q., He, Q., Cheng, M., Zhou, C., Jiang, L., & Song, B. (2020). Two-dimensional transition metal carbide and nitride (MXene) derived quantum dots (QDs): Synthesis, properties, applications and prospects. *Journal of Materials Chemistry A*, 8(16), 7508–7535. <https://doi.org/10.1039/D0TA01552K>
- Shen, Y., Zhang, Y., Gao, Z. F., Ye, Y., Wu, Q., Chen, H.-Y., & Xu, J.-J. (2021). Recent advances in nanotechnology for simultaneous detection of multiple pathogenic bacteria. *Nano Today*, 38, Article 101121. <https://doi.org/10.1016/j.nantod.2021.10.1121>
- Shinde, V. R., Revi, N., Murugappan, S., Singh, S. P., & Rengan, A. K. (2022). Enhanced permeability and retention effect: A key facilitator for solid tumor targeting by nanoparticles. *Photodiagnosis and Photodynamic Therapy*, 39, Article 102915. <https://doi.org/10.1016/j.pdpdt.2022.102915>
- Singh, P. K., Singh, S., Sachan, K., Verma, V., & Garg, S. (2024). Recent development and advancement in quantum dots in pharmaceutical and biomedical fields for the delivery of drugs. *Current Nanoscience*, 20(4), 425–435. <https://doi.org/10.2174/1573413719666230517111856>
- Syed, S., Rahaman, A., Mondal, A., Shaligram, S., & Pawar, S. P. (2024). Diagnosis of infectious diseases: Complexity to convenience. *Sensors & Diagnostics*, 3(3), 354–380. <https://doi.org/10.1039/D3SD00236E>
- Tan, Y. Y., Yap, P. K., Xin Lim, G. L. X., Mehta, M., Chan, Y., Ng, S. W., Kapoor, D. N., Negi, P., Anand, K., Singh, S. K., Jha, N. K., Lim, L. C., Madheswaran, T., Satija, S., Gupta, G., Dua, K., & Chellappan, D. K. (2020). Perspectives and advancements in the design of nanomaterials for targeted cancer theranostics. *Chemico-Biological Interactions*, 329, Article 109221. <https://doi.org/10.1016/j.cbi.2020.109221>
- Tessitore, G., Mandl, G. A., Maurizio, S. L., & Capobianco, J. A. (2021). Lanthanide-doped nanoparticles in biological imaging and bioassays. *Modern applications of lanthanide luminescence*: Springer (pp. 93–128).
- Thangadurai, T. D., Manjubaashini, N., Nataraj, D., Gomes, V., & Lee, Y. I. (2022). A review on graphene quantum dots, an emerging luminescent carbon nanolights: Healthcare and Environmental applications. *Materials Science and Engineering*, 278, Article 115633. <https://doi.org/10.1016/j.mseb.2022.115633>
- Todaro, B., Ottalagana, E., Luin, S., & Santi, M. (2023). Targeting peptides: The new generation of targeted drug delivery systems. *Pharmaceutics*, 15(6), 1648. <https://doi.org/10.3390/pharmaceutics15061648>
- Tripathi, D., Hajra, K., & Maity, D. (2023). Current development of bio-inspired nanoparticles in cancer Theragnostics.
- Veselov, V. V., Nosyrev, A. E., Jicsinszky, L., Alyautdin, R. N., & Cravotto, G. (2022). Targeted delivery methods for anticancer drugs. *Cancers*, 14(3), 622. <https://doi.org/10.3390/cancers14030622>
- Wang, C., Wang, Q., Zhou, Z., Wu, W., Chai, Z., Gao, Y., & Kong, D. (2020). Temperature dependence of photoluminescence properties in InP/ZnS core-shell quantum dots. *Journal of Luminescence*, 225, Article 117354. <https://doi.org/10.1016/j.jlumin.2020.117354>
- Wang, L., Xu, D., Gao, J., Chen, X., Duo, Y., & Zhang, H. (2020). Semiconducting quantum dots: Modification and applications in biomedical science. *Science China Materials*, 63(9), 1631–1650. <https://doi.org/10.1007/s40843-020-1330-7>
- Wang, Q., Pornrungraj, C., Linley, S., & Reisner, E. (2021). Strategies to improve light utilization in solar fuel synthesis. *Nature Energy*, 7(1), 13–24. <https://doi.org/10.1038/s41560-021-00919-1>
- Wang, T., Chen, L., Chikkanna, A., Chen, S., Brusius, I., Sbu, N., & Veedu, R. N. (2021). Development of nucleic acid aptamer-based lateral flow assays: A robust platform for cost-effective point-of-care diagnosis. *Theranostics*, 11(11), 5174–5196. <https://doi.org/10.1016/j.thno.2021.05.047>
- Wang, X. (2020). *Semiconductor nanocrystals: Synthesis, optical properties and environmental impact*. University of Connecticut.
- Wang, X., Zhong, X., Li, J., Liu, Z., & Cheng, L. (2021). Inorganic nanomaterials with rapid clearance for biomedical applications. *Chemical Society Reviews*, 50(15), 8669–8742. <https://doi.org/10.1039/d0cs00461h>
- Weber, W. A., Czernin, J., Anderson, C. J., Badawi, R. D., Barthel, H., Bengel, F., Bodei, L., Buwat, I., DiCarli, M., Graham, M. M., Grimm, J., Herrmann, K., Kostakoglu, L., Lewis, J. S., Mankoff, D. A., Peterson, T. E., Schelbert, H., Schöder, H., Siegel, B. A., & Strauss, H. W. (2020). The future of nuclear medicine, molecular imaging, and theranostics. *Journal of Nuclear Medicine*, 61(Suppl. 2), 263S–272S. <https://doi.org/10.2967/jnumed.120.254532>
- William, P., Jawale, M. A., Pawar, A. B., Korde, S. K., Rakshe, D. S., & Deshpande, N. (2023). Investigation of the electronic and optical properties of nanostructured glasses and composites. *Journal of Nano- and Electronic Physics*, 15(4), 04005–04001. [https://doi.org/10.21272/jnep.15\(4\).04005](https://doi.org/10.21272/jnep.15(4).04005)
- Xiao, Z. (2021). *Development of smartphone-based flow cytometry for selective cell counting*. University of British Columbia.
- Yadav, P., Dewan, S., Mishra, R., & Das, S. (2022). Review of recent progress, challenges, and prospects of 2D materials-based short wavelength infrared photodetectors. *Journal of Physics: Part D*, 55(31), Article 313001. <https://doi.org/10.1088/1361-6463/ac6635>
- Yang, G., Zhao, J., Yi, S., Wan, X., & Tang, J. (2020). Biodegradable and photostable Nb2C MXene quantum dots as promising nanofluorophores for metal ions sensing and

- fluorescence imaging. *Sensors and Actuators B*, 309, Article 127735. <https://doi.org/10.1016/j.snb.2020.127735>
- Yang, W., Li, X., Fei, L., Liu, W., Liu, X., Xu, H., & Liu, Y. (2022). A review on sustainable synthetic approaches toward photoluminescent quantum dots. *Green Chemistry*, 24(2), 675–700. <https://doi.org/10.1039/D1GC02964A>
- Yetisgin, A. A., Cetinel, S., Zuvun, M., Kosar, A., & Kutlu, O. (2020). Therapeutic nanoparticles and their targeted delivery applications. *Molecules*, 25(9), 2193. <https://doi.org/10.3390/molecules25092193>
- Yoon, H., Park, M., Kim, J., Novak, T. G., Lee, S., & Jeon, S. (2021). Toward highly efficient luminescence in graphene quantum dots for optoelectronic applications. *Chemical Physics Reviews*, 2(3). <https://doi.org/10.1063/5.0049183>
- Zhang, H., Su, Q., & Chen, S. (2020). Quantum-dot and organic hybrid tandem light-emitting diodes with multi-functionality of full-color-tunability and white-light-emission. *Nature Communications*, 11(1), 2826. <https://doi.org/10.1038/s41467-020-16659-x>
- Zhang, P., Li, Y., Tang, W., Zhao, J., Jing, L., & McHugh, K. J. (2022). Theranostic nanoparticles with disease-specific administration strategies. *Nano Today*, 42, Article 101335. <https://doi.org/10.1016/j.nantod.2021.101335>
- Zhang, Q., Liang, J., Yun, S. L. J., Liang, K., Yang, D., & Gu, Z. (2020). Recent advances in improving tumor-targeted delivery of imaging Nanoprobes. *Biomaterials Science*, 8(15), 4129–4146. <https://doi.org/10.1039/d0bm00761g>
- Zhao, M., Zhang, Q., & Xia, Z. (2020). Narrow-band emitters in LED backlights for liquid-crystal displays. *Materials Today*, 40, 246–265. <https://doi.org/10.1016/j.mattod.2020.04.032>
- Zhi, D., Yang, T., Yang, J., Fu, S., & Zhang, S. (2020). Targeting strategies for superparamagnetic iron oxide nanoparticles in cancer therapy. *Acta Biomaterialia*, 102, 13–34. <https://doi.org/10.1016/j.actbio.2019.11.027>

Cite this article: Yamuna B, Kumar VSSB, Ismael K, Mahammed N, Reddy SS, Shahid S, *et al.* Quantum Dots in Nanotechnology: Advances in Therapeutics, Drugs Delivery and Imaging. *Int. J. Pharm. Investigation*. 2025;15(3):759-69.