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Unlocking the Potential and Versatility of Quantum Dots: from Biomedical to Environmental Applications and Smart Micro/Nanorobots

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Quantum dots (QDs) are recognized as the most promising functional nanotechnology, for which its discoverers are awarded the Nobel Prize in 2023. Their remarkable tunability of optoelectronic properties has attracted significant interest from both researchers and industries, placing QDs at the forefront of developing cutting-edge technologies. This comprehensive review aims to explore the exciting results in terms of fundamental science, present and forthcoming applications. Beyond their contributions to biomedicine, energy, environmental science, quantum sensing, and quantum information processing, QDs have brought important results due to their integration into micro/nanorobotic systems, self-propelled materials representing the state of the art research at the micro and nanoscale. These hybrid systems have demonstrated noteworthy outcomes, unlocking novel possibilities in biomedicine, quantum sensing, and environmental science, accurately reviewed in this article. In conclusion, this review addresses current challenges, offering insights to facilitate further research, stimulate new developments, and enhance the comprehension of the full potential of QDs.

1. Introduction

Over the past several decades, extensive research has been conducted on the reduced dimensionality of semiconductors, giving rise to the intriguing concept of quantum dots (QDs), also known as "artificial atoms" due to their distinct atomic-like electronic states.[1–4] These semiconductor nanocrystals, featuring diameters at the nanometer scale, demonstrate remarkable quantum size effects in their optical and electronic characteristics, bridging the realms of material science, chemistry, and quantum physics. Typically sized from 2 to 10 nanometers, these nanoparticles can fine-tune their bandgap energy.[5–9] Quantum confinement of electrons and holes within the crystal lattice leads to discrete energy levels, resulting in distinct optical and electronic characteristics. For instance, QDs exhibit a remarkable ability to absorb white light and subsequently emit a specific color within a few nanoseconds, with the emission color determined by their bandgap.[10]

Figure 1 provides a representation of the significant milestones in the progression of QDs since their initial discovery in 1985 by Alexei Ekimov.[9,11] The temporal diagram highlights the crucial link between the size of nanometer-scaled materials and their optical properties. Notably, it is worth mentioning that in 1989, Louis Brus achieved a breakthrough by successfully synthesizing the first colloidal semiconductor nanocrystallite solution, setting the stage for further advancements in the field.[7] Additionally, the term "quantum dots" was coined in 1988 by Mark Arthur Reed, who demonstrated these nanostructures' remarkable photoluminescent properties characterized by fully quantized energy states.[7,12] These early contributions laid the foundation for the subsequent exploration and development of QDs, shaping their trajectory as a prominent field of study and application. During the late 1990s, significant advancements were made, primarily focusing on different synthetic processes for colloidal QDs,[13–15] allowing for precise control over the size and shape of the QDs. In 1993, Moungi Bawendi made significant advancements in the field of QDs synthesis, leading to the creation of exceptionally precise particles. This level of precision was essential to enable their effective use in various applications. Starting from the 2000s, QDs found extensive applications across various fields due to their small size, versatility, and ability to produce bright, stable, and tunable fluorescence. Initially, these unique properties presented significant advantages in the biomedical field, enabling precise imaging and diagnostics at both the cellular and molecular levels, as well as facilitating targeted drug delivery and minimally invasive medical procedures.[16–21] Beyond the biomedical context, quantum dots have soon found remarkable utility in various domains, contributing significantly to technological advancements, playing a crucial role in the development of efficient solar cells, light-emitting diodes (LEDs), and various optoelectronic devices.[22–24] Notably, QDs played a crucial role in commercializing the first multicolored LEDs and high-quality displays, and

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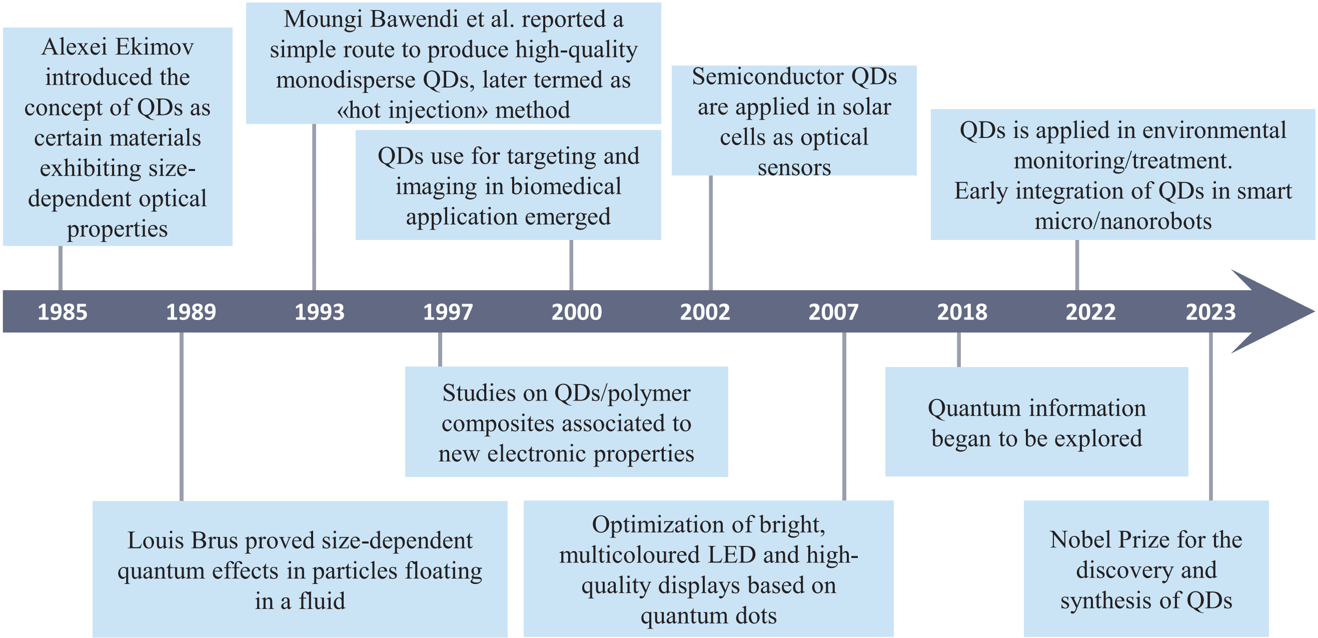

Figure 1. A roadmap illustrating key milestones in the development of QDs technology. The timeline highlights significant events, starting with the introduction of the concept of QDs by Alexei Ekimov in 1985, followed by crucial synthetic advancements in the 1990s and their integration into polymer composites, resulting in novel electronic properties. By 2000, QDs had emerged in biomedical applications for targeting and imaging. Subsequently, QDs found diverse uses as optical sensitizers in solar cells, for multicolored LED and high-quality displays, and in quantum computing, cryptography, environmental monitoring, and treatment. Early integration into smart micro/nanorobots was also evident, and in 2023 M.G. Bawendi, L. E. Brus, and A. I. Ekimov received the Nobel Prize in Chemistry for the discovery and synthesis of QDs.

it's worth mentioning that thanks to the pioneering application of QDs in television screens based on QLED technology, LED lamps, and to map biological tissue, the researchers responsible for these discoveries were duly recognized with the Nobel Prize in Chemistry.[25–27]

Their impact extends into environmental applications and sensing, where their high sensitivity and selectivity prove valuable in monitoring and detecting pollutants, environmental parameters,[28–30] also allowing the development of precise measurements and detection.[31]

Micro- and nanorobots represents the forefront of material science research. These tiny devices refer to miniature robotic systems able to autonomously propel through chemical reactions or external physical field, including ultrasonic, optical, magnetic, and other external fields, as well as microorganisms. These incredibly small devices, often incorporating QDs, offer unprecedented precision in various applications, such as targeted drug delivery within the human body or manipulation at the cellular level.[32,33]

Looking ahead, the field of QDs holds immense promise for future technological advancements and has reached a high level of complexity. Ongoing research focuses on further enhancing their properties, improving their stability, and expanding their capabilities. Efforts are also underway to integrate QDs into various emerging devices, enabling the development of next-generation nanotechnologies.

This Review comprehensively explores recent and impactful research on QDs and is organized into three main sections. The first section thoroughly examines the main classes of QD materials, covering their physicochemical properties and synthesis methods. It investigates the current understanding of the distinct properties exhibited by QDs and how their unique characteristics contribute to their diverse applications across various disciplines. In the second section, we delve into the most recent uses of QD materials in biomedical, environmental, energy, and quantum information applications, emphasizing their role in driving advancements. Specifically, we highlight their integration into the emerging field of micro/nanorobots, where QDs unlock new possibilities for precise sensing, imaging, and manipulation at the nanoscale. By functionalizing QDs with specific molecules or ligands, micro/nanorobots can be tailored for targeted drug delivery and minimally invasive medical procedures, interacting with biological entities with exceptional accuracy.

Moreover, QDs-based micro/nanorobotic systems enable the detection and monitoring of various environmental pollutants and parameters, such as temperature, pH, or chemical analytes. This integration equips micro/nanorobots with high sensitivity and selectivity, allowing them to operate effectively in complex and dynamic environments. The final section focuses on the current problems and challenges of QDs-based materials aiming to offer valuable insights to harness the full potential of QDs and their transformative applications across diverse disciplines.

In conclusion, this comprehensive Review offers a valuable resource, consolidating the state-of-the-art knowledge of quantum dots and their multifaceted applications. By understanding the potential of QDs, researchers, practitioners, and students are empowered to explore new horizons in various disciplines. With an ever-expanding landscape of possibilities, the transformative impact of QDs continues to shape the future of nanotechnology and holds the promise of driving innovation across diverse disciplines.

2. The Science Behind Quantum Dots: Technical Details

The term "quantum dots" can be ambiguous for researchers, especially those new to the fields of nanotechnology or quantum mechanics.[7] It may have different interpretations depending on the context, requiring more detailed specifications. It is well known that QDs generally refer to nanoscale particles that exhibit size-dependent bandgap quantum confinement, with a typical size range of 2 to 10 nm, allowing for bandgap energy adjustment by size tuning. The small size of quantum dots leads to the strong confinement of electrons and holes within the crystal lattice, which quantizes their energy levels. This quantization shifts the absorption and emission spectra of the dots, giving them unique optical and electronic properties. In the early-stage research in this field, this concept is typically called "semiconductor QDs", nanomaterials possessing tunable light absorption, physicochemical functions due to their large surface-to-volume ratio, bright emission of pure colors, and control over electronic transport.[10] However, QDs are not limited to fluorescence abilities, as some later developed families such as "magnetic QDs" and "plasmonic QDs". Thus, the term QDs can more appropriately refer to several sub-20-nanometre-sized families (schematized in **Figure 2**) of nanomaterials with peculiar properties that can gain a deeper appreciation for this rapidly growing field's versatility and exciting potential. Therefore, the following subheadings can concisely summarize and discuss the different QDs families and key properties.

2.1. Semiconductor QDs

Conventional semiconductor QDs can be described as a core-shell structure, where the core is composed of a semiconductor material such as II-VI (e.g., ZnTe, ZnSe, ZnS, ZnO, CdS, CdSe, CdTe, HgTe, HgSe, HgS), III-V (e.g., AlSb, AlAs, AlP, GaSb, GaAs, InGaAs, InAs, InP, InN), and IV-VI (e.g., PbS, PbSe, PbTe) compounds, and the shell is typically made of another semiconductor material (Figure 2a).[23,34–37] The core-shell structure of QDs allows for using different materials for the core and shell components. Adjusting the size (typically ranging from 1–10 nm) and shape (spherical, rod, or tetrapod), it is possible to achieve distinct electronic and optical properties, including strong fluorescence, high quantum yield, and size-dependent emission spectra.[10,38] Notably, the nanocrystal dimensions play a crucial role in determining the energies of excited-state charge carriers, such as electrons and holes. On the other hand, as the size of the QDs decreases, the charge carriers become confined to a smaller region in space. This confinement leads to an increase in their energies and a widening of the electronic bandgap. Consequently, there is a shift in the absorption and emission spectra toward higher energy (shorter wavelength). This phenomenon is a consequence of the quantum confinement effect, where the size of the QDs influences the energy levels of the confined charge carriers. Through synthetic advances over the last two decades, size-tunable QDs can now be readily prepared from a variety of materials, which has yielded emitters throughout the near-ultraviolet, visible, near-infrared and mid-infrared spectra with fluorescence quantum yields approaching 100%.[39] For instance, core-shell QDs with CdSe as the core and ZnS as the shell have been found to exhibit quantum yields greater than 50% due to the incorporation of the ZnS shell that helps to passivate nonradiative recombination sites while effectively reducing nonradiative decay pathways and promoting more efficient radiative recombination.[7] Moreover, the presence of the shell enhances the overall robustness of the QDs under various processing conditions, making them more resilient and stable for diverse applications. The core-shell approach has become widely explored as a versatile method to fine-tune the photophysical properties of QDs for specific applications.

The semiconductor core-shell type QDs are synthesized using a top-down approach, which involves reducing bulk semiconductor materials to form nanoscale structures. This is accomplished using electron beam lithography, reactive-ion etching, and wet chemical etching. On the other hand, these techniques have limitations, such as structural imperfections caused by patterning and impurities introduced during synthesis, leading to non-uniform size distribution and reduced quantum yield, which strongly influence their applicability. Indeed, many synthetic efforts have made them attractive for various applications, such as optoelectronics, solar cells, lighting, and displays.

2.2. Colloidal Nanocrystals

Colloidal nanocrystals (NCs) are a subset of semiconductor QDs, sub-20-nanometer-sized crystals composed of a few hundreds to a few thousands atoms. The inorganic core is surrounded by "ligands" (organic or inorganic functional groups or molecules) that prevent agglomeration and provide stability (Figure 2b), allowing their bottom-up assembly.[13,26,40] NCs can be made of various materials, such as metals, oxides, or semiconductors, and are commonly synthesized using solution-phase methods, including sol-gel, hydrothermal, or co-precipitation methods (see **Figure 3** for general synthetic strategies). NCs exhibit higher quantum yields compared to conventional QDs, owing to several factors. First, the smaller size of NCs allows for more efficient confinement of charge carriers, reducing non-radiative recombination pathways. Additionally, the bright luminescence in NCs arises from the rational design of organic ligands surrounding the QD core. This design results in reduced surface-related defects, minimizing non-radiative processes and contributing to higher photoluminescence quantum yields. Furthermore, the crystalline nature of NCs, characterized by well-defined facets and structures, enhances radiative recombination efficiency compared to the often more amorphous nature of QDs. These combined factors make NCs particularly attractive for biological imaging and sensing applications. However, the polydispersity of NCs can be a limitation in some applications, and the synthesis and purification methods are still being optimized to improve their properties and reduce toxicity. Recently, Wood et al. reviewed how individual NCs can self-assemble into phononic crystals. By arranging QDs in a periodic array, it is possible to create materials with a periodic variation in acoustic properties that can control the propagation of acoustic waves. This

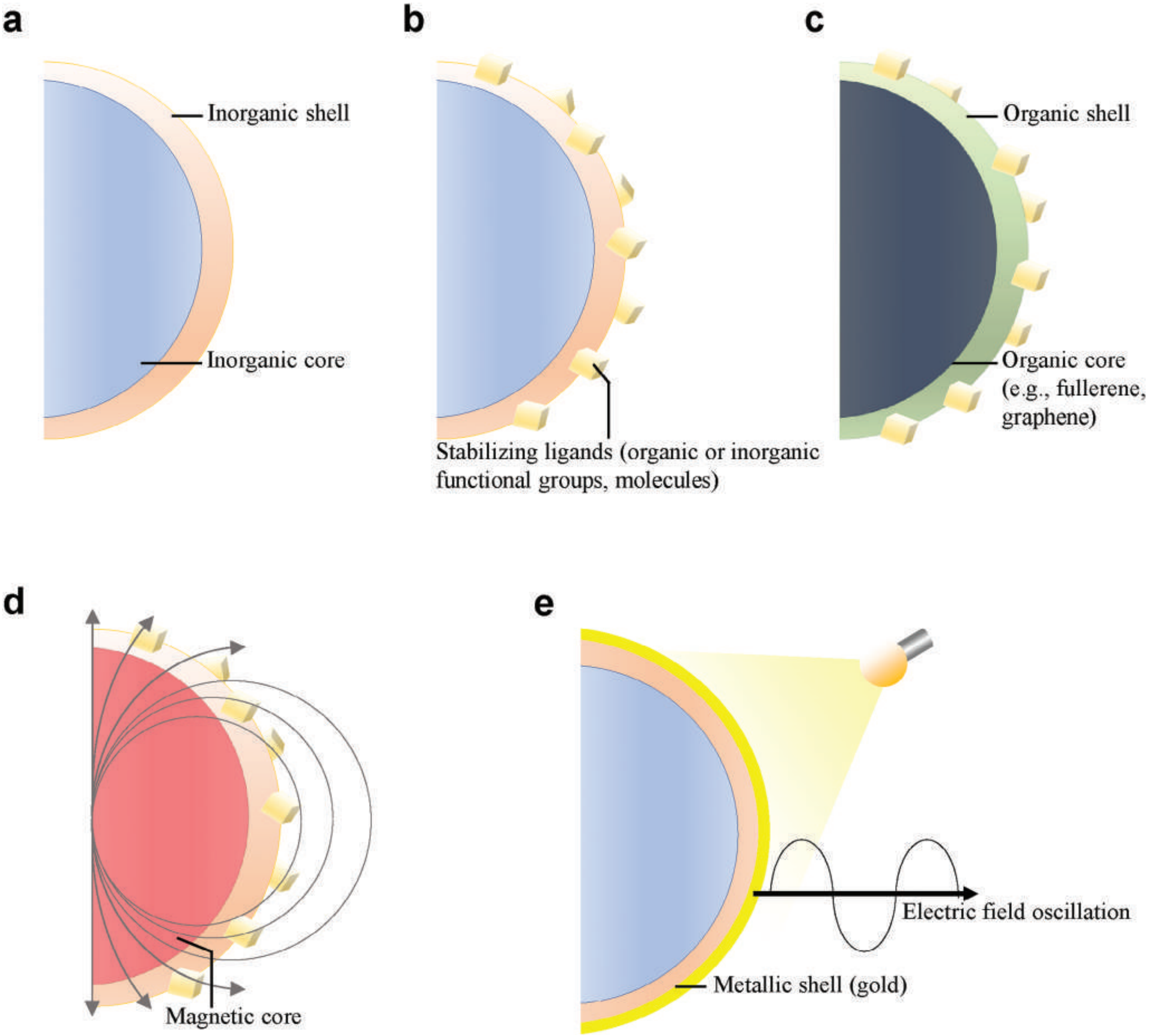

Figure 2. Overview of different classes of QDs materials. a) Semiconductor QDs, are characterized by a core-shell structure, where the core consists of various semiconductor materials such as II-, III-V, and IV-VI compounds. The shell is typically made of another semiconductor material. b) Colloidal QDs, a subset of semiconductor QDs, comprise sub-20-nanometer-sized crystals composed of a few hundreds to a few thousands atoms. The inorganic core is surrounded by "ligands" (organic or inorganic functional groups or molecules) that prevent agglomeration and provide stability. c) Organic and hybrid QDs, an advancement of colloidal QDs including carbon dots, bioconjugated polymers, protein-based QDs, and perovskite QDs. d) Magnetic QDs, combine magnetism and quantum confinement properties, typically composed of a magnetic core (ferromagnetic or superparamagnetic) and a shell of different semiconductor materials. e) Plasmonic QDs, are typically composed of metal nanoparticles (commonly gold or silver) combined with semiconductor quantum dots/nanocrystals or organic dyes as either the core or the shell.

peculiar property can provide a powerful tool for using NC superlattices for nanophononics, optomechanics, and acoustic metamaterials.[40] The self-assembly of colloidal nanocrystals into phononic crystals offers exciting potential for developing new materials and devices for various technological applications. Future research in this area will continue exploring the unique properties of colloidal nanocrystals and their potential for phononic applications.

2.3. Organic and Hybrid QDs

Advances in the last decade in colloidal QDs chemistry mostly focused on formulating hybrid structures, such as a type of QDs composed of organic or hybrid organic/inorganic materials (Figure 2c). The most exploited classes of organic and hybrid QDs are carbon dots, bioconjugated polymers, protein-based QDs, and perovskite QDs, which have recently emerged as promising

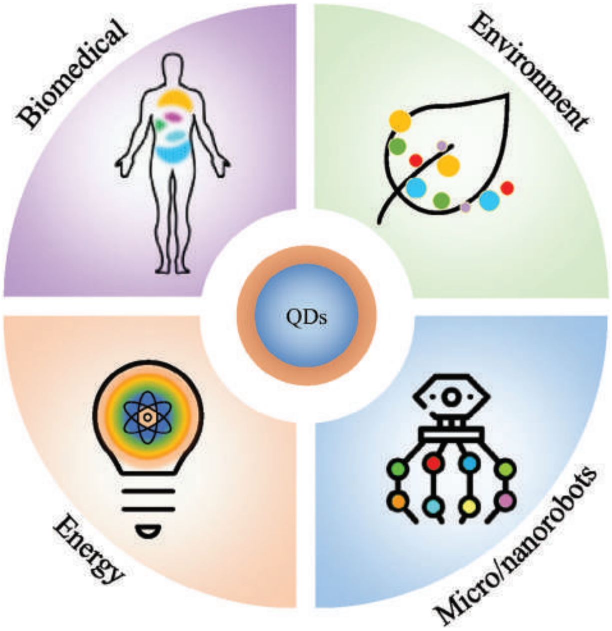

Figure 3. Main areas where QDs nanomaterials can advance the performance of existing and new technologies.

alternatives to conventional inorganic QDs for applications in photovoltaics and light-emitting diodes.[41] Additionally, the high biocompatibility and low toxicity of organic and hybrid QDs make them attractive for biological applications such as cell imaging, drug delivery, and biosensing, even though the low stability and limited size tunability of these QDs are some of the challenges that need to be addressed for further developments. Hybrid QDs possess a variety of structures and compositions mostly dependent on the synthetic methods used. Generally, they are composed of small organic molecules organized in a nanoscale structure with strong fluorescence properties. For instance, carbon dots are typically quasi-spherical nanoparticles of a carbon core (e.g., fullerenes, carbon nanotubes, graphene) surrounded by organic functional groups. Among these, graphene-based QDs (GQDs) are described as single- to few-layer patches of graphene sheets with lateral dimensions in the nanometer range. The reduction of the graphene sheet size can introduce a bandgap opening and thus fluorescence properties, even though the relationship between size and fluorescence is still complex to be determined due to its “quasi-molecular” nature. The most used approaches for synthesizing GQDs are top-down methods which involve breaking down through exfoliation and/or cutting of carbon precursors (graphite, graphene, graphene oxide, carbon fibers, carbon black, fullerenes, and carbon nanotubes) into smaller pieces to form GQDs. Several top-down approaches have been developed for synthesizing GQDs, including mechanical, physical, chemical, and electrochemical methods.[36]

2.4. Magnetic QDs

The unique and attractive features of QDs have inspired the fabrication of nanostructures exhibiting both magnetism and quantum confinement properties. Magnetic quantum dots (MQDs) are composed of a magnetic (ferromagnetic or superparamagnetic) core and shell made of different semiconductor materials, such as CdSe or ZnS, typically designed to confine the electrons and holes within the MQD structure (Figure 2d).[42–44] MQDs can be synthesized using a top-down approach, where magnetic materials such as Fe_3O_4), cobalt (Co), or manganese oxide (MnO) are incorporated into the QD structure during the synthetic procedure. For example, a core/shell Co/CdSe nanocomposite can be prepared by controlled deposition of CdSe QDs onto preformed Co nanocrystals. Alternatively, Fe_3O_4 can be incorporated into CdSe/CdS core-shell QDs by a one-pot synthesis method, where the magnetic nanoparticles are directly incorporated during the synthesis. MQDs have found promising results in various applications, ranging from biomedical imaging to spintronics or magnetic data storage. For instance, MQDs can be used as spin injectors to inject spin-polarized electrons into a semiconductor material, leading to an increase in the spin polarization of the material. In addition, superparamagnetic MQDs exhibit high resistance to thermal fluctuations, making them ideal candidates for use in high-density magnetic data storage devices. Recently, QD-based diluted magnetic semiconductors have gained attention. These materials are also known as semi-magnetic semiconductors, where transition metal ions are used to dope semiconductor nanocrystals. These new classes of QDs can generate spin currents, which is important for small-size spin and charge-based devices. This has resulted in significant attention in the emerging field of “spintronics,” where electron spins are controlled to transmit information, providing new functionality to semiconductor devices such as semiconducting alloys and thin films.[45]

2.5. Plasmonic QDs

Exploring plasmon–exciton interactions at the level of individual nanostructures is of great importance for developing exciting new materials that can strongly affect various research fields ranging from nanophotonics to nanomedicine. Plasmonic quantum dots (PQDs) are peculiar nanostructures typically composed of metal nanoparticles (typically gold or silver) and semiconductor quantum dots/nanocrystals or organic dyes that can function as a core or a shell (Figure 2e).[46,47] The coupling between metal nanostructures and quantum systems allows the instauration of peculiar properties. For instance, it can support localized plasmon resonance (LSPR), enhancing light absorption and scattering while exhibiting quantum confinement effects, which produce size-dependent optical properties.[48] The combination of plasmonic and quantum confinement effects leads to strong light-matter interaction in PQDs, making them useful in applications such as Raman spectroscopy and fluorescence. However, precise tuning over the spacing between the metal and QDs was necessary to prevent fluorescence quenching, for example, by encapsulating modified QDs with a gold shell. Promising results have been reported by coating QDs with a layer of peptide, poly-L-histidine (PLH), as the gold deposition template. Importantly, PLH has the advantage of possessing groups capable of immobilizing Au^{3+} ions at very high packing density for thin and smooth gold shell deposition.[46] Owing to this arrangement

PQDs also exhibit high photostability, and improved biocompatibility, making them a promising candidate for sensing and imaging applications in various fields, including biology and medicine.

One of the most commonly used methods for preparing PQDs is colloidal synthesis. In this approach, PQDs are synthesized by mixing a solution of metal precursors with a solution of semiconductor precursors in the presence of a surfactant. The metal and semiconductor precursors react to form a core-shell structure, with the semiconductor acting as the core and the metal acting as the shell. The surfactant helps to stabilize the nanoparticles and prevent them from agglomerating. The size and shape of the nanoparticles can be controlled by adjusting the ratio of the metal and semiconductor precursors and the reaction conditions. Epitaxial growth is another method for preparing PQDs. PQDs are grown on a substrate using techniques such as molecular beam epitaxy (MBE) or metal-organic chemical vapor deposition (MOCVD) in this method.[49] The substrate provides a template for the growth of the PQDs, and the size and shape of the nanoparticles can be controlled by adjusting the growth conditions. Template-assisted methods are also used for preparing PQDs. This approach uses a template to guide the formation of the nanoparticles, which can be a porous material, such as a membrane, a polymer, or a patterned substrate. The size and shape of the nanoparticles can be controlled by adjusting the size and shape of the template. Directed self-assembly is an alternative approach SA can include templating surfaces, chemical functionalization, or specific substrate designs that guide the quantum dots into the desired arrangements. By carefully engineering these guiding factors, researchers can achieve control over the size, spacing, and orientation of quantum dots on a substrate, thereby influencing their collective properties and behavior. More recently,

2.6. QDs Synthesis and Property Modification

As it possible to appreciate from **Table 1**, the fabrication methods strongly contribute to the structure and properties of QDs families.[27,43,50–56] Recent efforts in preparation strategies aim to achieve non-toxicity, environmental friendliness, precision, and cost-effectiveness with improved size and shape control. Traditional methods, including hot-injection, and thermal methods, often employ toxic precursors and harsh conditions, limiting their applicability. Consequently, researchers are exploring more sustainable approaches for large-scale production, such as using non-toxic precursors and environmentally friendly solvents. Methods like hydrothermal and solvothermal techniques have gained traction, enabling the preparation of QDs in high-pressure, high-temperature aqueous environments. By adjusting parameters like temperature, time, and reagent content, researchers can achieve precise control over the size and shape of QDs.

Recently, biosynthesis of QDs through a bio-based approach utilizing microorganisms like bacteria, fungi, and mammalian cells represent a promising strategy. This method not only conducts synthetic reactions under environmentally friendly conditions but also imparts biostability and biocompatibility to the resulting QDs. The unique capabilities of living microorganisms, attributed to redox enzymes, metal binding domains, and specific biochemicals within their cells, allow for the initiation of synthesis nanoclusters at ambient temperature, pressure, and neutral pH. Fungi-based systems, with easy handling and extracellular synthesis, have an advantage in large-scale production, while bacterial synthesis involves directed evolution or genetic manipulation.

Finally, electrochemical approaches, specifically electrochemical deposition (ECD), provide a direct, simple, and cost-effective

Table 1. Main QDs-based materials fabrication methods. Table information refers to references.[33–40]

Fabrication Method	Technique	Structure	Advantages	Limitations	Ref.
Physical	Laser Ablation, Laser Irradiation, Arc discharge, Molecular beam epitaxy, Ultrasonic	Semiconductor QDs, Carbon dots (e.g., Graphene QDs)	High purity, precise and high control over composition and crystallinity	High equipment costs, complex processes, limited scalability	[27,34]
Chemical	Wet Chemical Etching, Pyrolysis, Microwave, Solvothermal, Hydrothermal, Co-precipitation, Re-precipitation	Colloidal QDs, Carbon dots (e.g., graphene QDs), magnetic QDs, semiconductor QDs	High control over quality, size/shape, and compositions. Large-scale production	Require high temperatures and toxic precursors. The removal of capping agents can be challenging	[50,52]
Self-assembly	Directed Assembly	Colloidal QDs with tunable architectures and ordered arrays	Low energy consumption, complex structure formulation, versatility, the potential for functionalization	Low control of the assembly conditions, low scale-up potential, low monodispersed, long fabrication times	[43]
Bio-based	Bio-based precursors materials treated via physical and chemical approaches, microbial synthesis, biomolecule-assisted synthesis	Colloidal QDs, Carbon dots (e.g., graphene QDs), Semiconductor QDs	Low-cost, sustainability	Slow synthesis rates, low yields, difficult control of size/shape	[51,53,56]
Electrochemical	Electrochemical oxidation, Electrochemical deposition	Plasmonic QDs, nanocrystalline noble metals	Controlled growth, the potential for shape tunability	Low control over size/shape,	[57]

way to deposit metals on a conducting substrate. ECD is a powerful tool for synthesizing various materials relevant to energy conversion and storage applications. Beyond conventional ECD, diverse electrochemical techniques have been developed to control metal nanostructure size, shape, porosity, and location in one, two, and three dimensions, with a spatial resolution reaching down to one nanometer.

To summarize, the section discusses the technical aspects of QDs, emphasizing their diverse interpretations and applications in fields like nanotechnology and quantum mechanics, exploring various types of QDs, including semiconductor, colloidal, organic/hybrid, magnetic, and plasmonic QDs, each with distinct features and synthesis methods. Semiconductor QDs, for example, exhibit core-shell structures, offering tunability in electronic and optical properties. Colloidal QDs, a subset of semiconductors, boast high quantum yields and find applications in biological imaging. Organic/hybrid QDs, such as carbon dots, offer biocompatibility. Magnetic QDs combine magnetism and quantum confinement, promising applications in biomedical imaging and spintronics. Plasmonic QDs, composed of metal nanoparticles and semiconductor or organic materials, exhibit strong light-matter interactions, making them useful for sensing and imaging applications. The section concludes by discussing various synthesis methods for QDs, including sustainable approaches like biosynthesis and electrochemical deposition, aiming for precise control over size, shape, and properties.

3. QDs in Action

This section will explore the various applications of QDs summarized in Figure 3, highlighting the potential for future advancements and innovations. Their tunable emission spectra, high quantum yields, photostability, and versatile surface chemistry make them attractive for various applications across different fields. The following subheadings will delve into some of the most notable and recent uses of QDs, focusing on the developments in the most recent years. With their unique properties and adaptability, QDs are poised to play a transformative role in a wide array of cutting-edge applications, opening new possibilities for technology and research.

3.1. Biomedicine

Due to their broad absorption spectra compared to conventional organic dyes and fluorescent proteins, QDs have become a promising tool for imaging, sensing, and diagnostics in biomedical applications. Compared to conventional organic dyes and fluorescent proteins, QDs possess broad absorption spectra, providing exceptional imaging, sensing, and diagnostic capabilities. Their advantages extend to tunable emission wavelengths, high photostability, and the ability to conjugate with various ligands, antibodies, or biomolecules, making them attractive for diverse applications across different fields.[58] One particularly notable category of QDs, known as carbon dots (CDs), has garnered significant interest in biomedicine. Derived from the abundant element carbon, CDs are typically synthesized through more environmentally friendly methods.[56,59] They can be classified into four categories: GQDs, carbon quantum dots (CQDs), carbon nano-dots (CNDs), and carbonized polymer dots (CPDs). These categories are generally biocompatible and exhibit low cytotoxicity, a crucial factor for ensuring material safety. CQDs possess excellent photostability, are often water-soluble, and can be easily modified for enhanced specificity and selectivity. Recently, researchers have focused on multicolor fluorescence, enabling the simultaneous detection of multiple targets in complex biological systems, which in turn provide a better understanding of biological processes at the molecular level. By using a single light source to excite the multicolor fluorescence emission of QDs with varying particle sizes, it becomes possible to label multiple signal sources simultaneously.[60] In early studies, it was shown that Hela cells incubated in a CQDs solution for 2 h emitted strong blue, green, yellow, and red fluorescence, primarily distributed in the cytoplasm when exposed to a single wavelength light of 405 nm.[61] The authors proposed a novel solvent-controlled synthetic route for producing CQDs with highly efficient photoluminescence, and systematically explored the influence of different solvents on the growth processes of QDs, demonstrating the controllable modulation of particle size. More recently, researchers have made progress in using polychromatic QDs (including CQDs) for simultaneous labeling and multicolor fluorescence imaging of multiple immune cells in liver-frozen sections. They developed a new method to label Kupffer cells, T cells, and B cells using various QDs conjugated with specific antibodies, allowing for a more detailed and comprehensive understanding of cellular interactions in the liver tissue. The QDs were applied below freezing points to minimize potential interference from ice crystals in the tissue samples, demonstrating their ability to effectively label and differentiate multiple immune cell types in liver-frozen sections. Furthermore, the multicolor fluorescence imaging facilitated clear visualization of the distribution and interaction of these immune cells in the tissue samples, underscoring their potential for simultaneous analysis of multiple immune cells in biological samples. This approach offers a valuable tool for researchers studying immune cell interactions and functions in various diseases and pathological conditions, even though in vivo targeting and multimodal molecular bioimaging are still challenged.[62,63]

GQDs, particularly those in the protein-sized range (dozens of kDa), exhibit enhanced biocompatibility and ease of clearance compared to typical semiconductor QDs with necessary surface coating and other CQDs, representing a more suitable option for biological targeting and molecular imaging. For example, GQDs were used as targeted tumor imaging and long-term visualization of local pharmacokinetics (**Figure** 4a). Specifically, the GQDs are in situ planted in a poly(ethylene glycol) (PEG) layer of PEGylated nanoparticles, thus enabling specific binding to tumor cells and resulting in 7–8 times increased tumor accumulation compared to pristine GQDs in vivo. This targeted approach resulted in enhanced tumor imaging, allowing for improved detection and diagnosis of tumors. Additionally, the GQDs exhibited long-term visualization of local pharmacokinetics (more than four times prolonged blood circulation), providing valuable insights into drug distribution and effectiveness within the tumor microenvironment.[63]

The unique physicochemical properties of QDs have also been widely explored to increase the efficacy of drug delivery

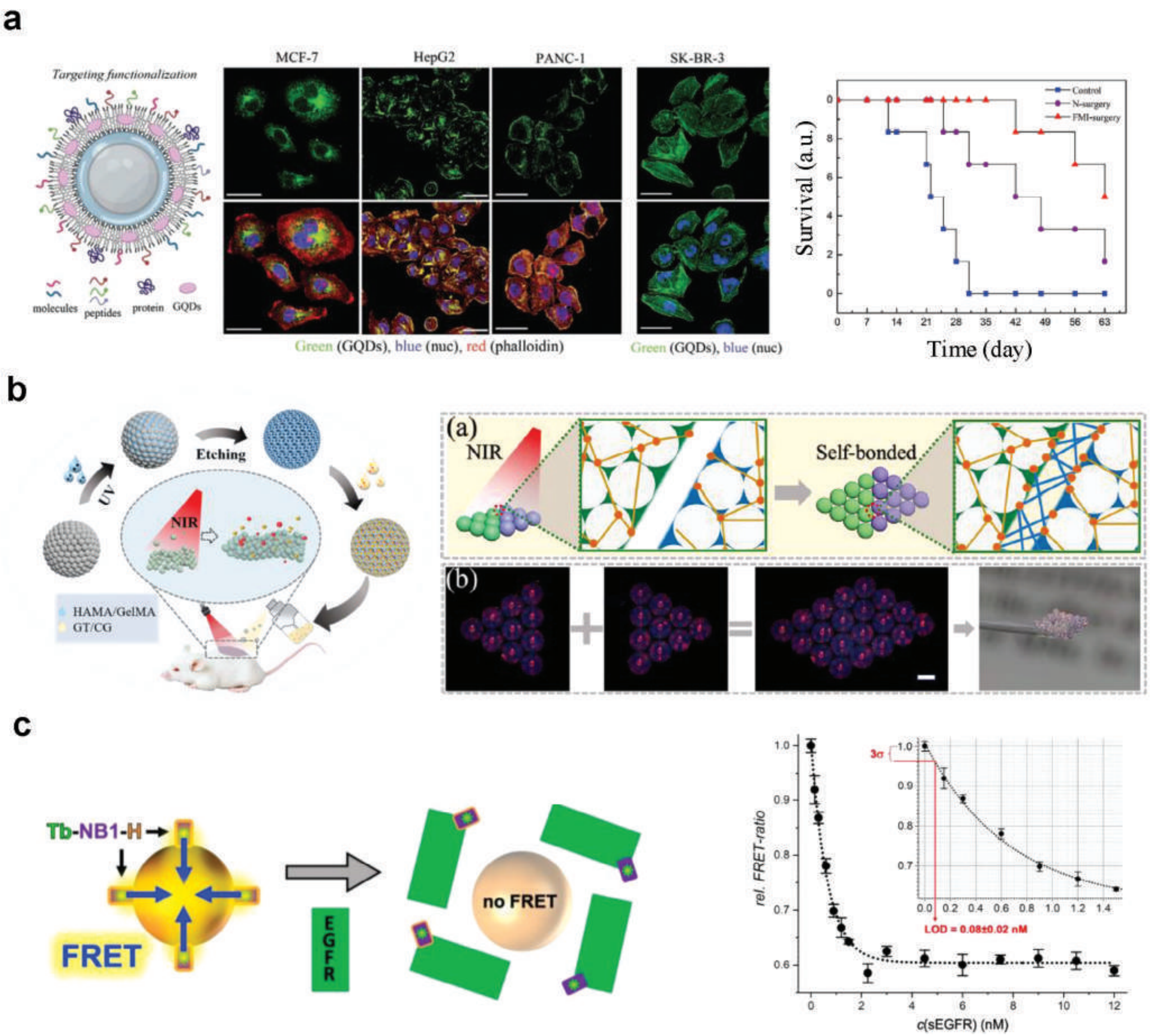

Figure 4. Impactful recent uses of QDs-based nanomaterials for biomedical applications. a) In vitro and in vivo targeted tumor imaging based on multifunctional, targeted nanoprobe nanoparticle core-graphene quantum dots- poly(ethylene glycol) (NPC-GQDs-PEG) nanomaterials. NPC-GQDs-PEG/2-Deoxyglucose probes effectively labeled MCF-7 breast cancer cells and successfully detected cancer markers Glypican-3 in HepG2 liver cancer cells and plectin-1 in PANC-1 pancreatic cancer cells. Additionally, NPC-GQDs-PEG conjugated with phalloidin specifically stained F-actin in SK-BR-3 breast cancer cells, demonstrating their specific targeting ability for different cancer cell types. Survival rates of mice (n = 6 in each group) in the fluorescence-imaging-guided surgery (FMI-surgery) are significantly higher compared to the normal surgery (N-surgery) and control groups. Adapted from ref.[63] from John Wiley and Sons, copyright 2023. b) Scheme of the preparation, self-bonding, and controlled release of drugs-loaded particles from HAMA/GelMA Hydrogel containing GO QDs. The self-bonded hydrogels melt under near-infrared (NIR) irradiation releasing the encapsulated drugs at the same time. After the NIR irradiation the melted hydrogel recondense connecting neighboring particles and forming a patch. Adapted from ref.[64] with permission from American Chemical Society, copyright 2022. c) Terbium complex (Tb)- tagged nanobodies were transferred from QD surfaces via EGFR-nanobody binding, leading to a FRET signal. The detection limit of 80 ± 20 pM (16 ± 4 ng mL^{-1}) resulted from was three times lower than the clinically established threshold for soluble EGFR and up to ten times lower compared to traditional sandwich FRET assays that necessitate a pair of distinct nanobodies. Adapted from ref.[67] with permission from John Wiley and Sons, copyright 2022.

and reduce off-target side effects. Ultimately the photothermal properties of QDs were deeply exploited to improve their ability as carriers. For instance, hydrogel particles of biocompatible hyaluronic acid methacryloyl (HAMA) and gelatin methacryloyl (GelMA) were doped with graphene oxide QDs during their formulation (Figure 4b). The potential synergy between intelligent inverse opal hydrogel and self-healing or self-bonding capabilities holds promise for advancing the design of more tailored particle systems. Furthermore, the hybrid particles combine the photothermal conversion capabilities of GQDs favoring the release of encapsulated amoxicillin and VEGFs during the NIR irradiation process, making it suitable for use as a controllable drug delivery system.[64] The demand for a novel drug delivery system with intelligent drug release capabilities is becoming increasingly urgent. Existing biomaterials employed in this regard are characterized by relatively simple structures and face challenges in achieving site-specific drug release. One promising solution rely in the remarkable photothermal effect of black phosphorus quantum dots (BPQDs), which, compared to conventional ones, can facilitate targeted drug release and offer crucial advantages when combined with other nanostructures. Recent reports have highlighted the use of BP inclusion within inverse opal films as a responsive drug release medium under near-infrared (NIR) irradiation for spinal cord injury (SCI) repair.[65] Interestingly, combining BP with Ni_2P QDs can convert NIR-I responsiveness into NIR-II (1000–1500 nm) photothermal activation, enabling the fabrication of a multifunctional nano-platform for complete tumor ablation.[66] This innovative approach could pave the way for the design of a multimodal cancer treatment strategy.

QDs can also serve in the development of optical and electrochemical biosensors for real-time monitoring of cellular processes and environmental changes within living organisms. Assays based on Förster resonance energy transfer (FRET) are recognized as highly sensitive and very easy to perform and do not require any separation or washing steps. However, FRET can work when the distance between the donor-acceptor is below 10 nm. In this context, to design a quick, wash free, mix-and-measure immunoassay for the epidermial growth factor receptor (EGFR), several biocompatible QDs were opportunely modified with Terbium complex (Tb)-labeled hexahistidine-tagged nanobodies by varying the C-terminal tags. The result was an EGFR concentration-dependent reduction of the Tb-to-QD Förster resonance energy transfer (FRET) signal. The detection limit of 80 ± 20 pM (16 ± 4 ng mL^{-1}) was three times lower than the clinically established threshold for soluble EGFR and up to ten times lower compared to traditional sandwich FRET assays that necessitate a pair of distinct nanobodies (Figure 4c).[67] QDs possess high electron transfer rates and electrocatalytic activity, which make them suitable candidates for electrochemical biosensing applications. They can serve as redox mediators, enhancing the electron transfer between the recognition element (e.g., enzyme, antibody) and the electrode surface. By modifying the electrode with QD-conjugated recognition elements, electrochemical biosensors can achieve improved sensitivity and specificity in detecting target analytes. Organic electrochemical transistor (OECT) biosensors, replacing the traditional gate electrode with light-sensitive semiconductor electrode, have recently attracted increasing attention in biosensing applications. In particular, by using CdS QDs as light-sensitive material, it was possible to demonstrate the enhanced optical response, and facilitate the energy transfer process, thus resulting in an advanced hydrogel/GO hybrid OPECT system exhibiting ultra-sensitive response toward the specific external stimulus and could serve as a general bio-detection platform with zero gate bias.

It is also worth mentioning that QDs have shown promise in the development of rapid and sensitive diagnostic tools, particularly for point-of-care (POC) devices. These devices aim to provide timely and accurate diagnostic information at the patient's bedside, which is critical for effective disease management. QD-based lateral flow assays, similar to traditional paper-based test strips, have been developed for the detection of various analytes, such as pathogens, biomarkers, and small molecules.

Moreover, QDs have been employed in microfluidic devices for lab-on-a-chip applications, which integrate multiple laboratory processes into a single miniaturized platform. These devices can offer rapid and high-throughput analysis with minimal sample and reagent consumption, making them ideal for POC diagnostics in resource-limited settings.[17,20]

3.2. Energy

QDs possess unique characteristics that make them highly promising for utilization in energy conversion and storage fields. One of their notable features is the ease of tuning the photoinduced charge carriers, which allows for precise control over their behavior in response to light. This tunability enables efficient charge transfer processes, facilitating the conversion of light energy into electrical energy.[24] Additionally, QDs exhibit abundant active sites on their surfaces, promoting enhanced interactions between the QDs and electron donors/acceptors.[68] This increased interaction surface area contributes to improved charge transport properties and enhances the overall efficiency of energy conversion processes. In recent years, QDs have emerged as a promising alternative for use in solar cells. Their unique properties, such as size-tunable bandgaps and the ability to absorb a broad spectrum of light, make them ideal candidates for capturing solar energy. By carefully engineering the composition and size of the QDs, researchers can optimize their absorption and emission properties to match the solar spectrum, maximizing energy conversion efficiency.[69]

Furthermore, QDs can be integrated into various types of solar cell architectures, including thin-film solar cells and hybrid organic-inorganic solar cells. Their high quantum yields and exceptional photostability contribute to long-term performance and improved durability of solar cell devices. The utilization of QDs in solar cells is an active area of research, with ongoing efforts focused on enhancing their efficiency, stability, and scalability. Through innovative approaches and advancements in synthesis and device engineering, QDs hold the potential to play a significant role in the future of solar energy conversion, contributing to the development of efficient and sustainable photovoltaic technologies. QD-based solar cells offer a significant advantage over traditional solar cells due to their exceptional capacity to absorb light across a wide spectrum of wavelengths. Unlike conventional solar cells, which are limited in the range of light they can effectively harness, QDs can be precisely engineered in terms of both size and composition. This engineering allows researchers to tailor the properties of quantum dots to closely match the solar spectrum, spanning from ultraviolet to visible and near-infrared wavelengths.

By adjusting the size and composition of QDs, scientists can fine tune their absorption characteristics, enabling them to efficiently capture a broader range of solar energy. This capability enhances the overall efficiency of QD-based solar cells, as they can exploit a larger portion of the solar spectrum compared to traditional counterparts. In solar cells, the device's sensitivities and efficiencies can be optimized by minimizing energy losses

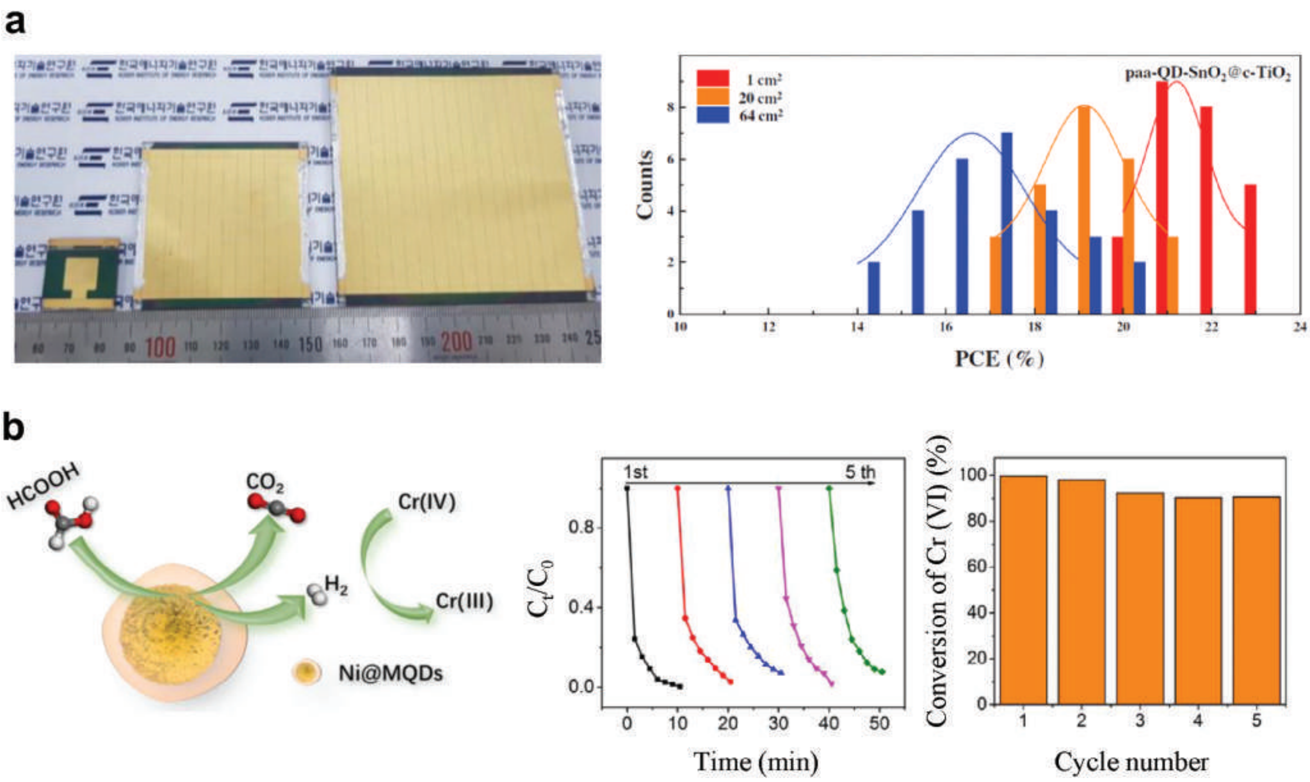

Figure 5. QDs-based devices used in energy applications. a) Photo of perovskite solar cells (PSCs) realized by replacing the commonly used mesoporous–titanium dioxide electron transport layer with a thin layer of polyacrylic acid–stabilized tin(IV) oxide quantum dots. The devices possess pixel sizes of 1, 20, and 64 cm^2. On the right a graph of statistical distribution of PCE for the paa-QD-SnO_2@c-TiO_2–based. Adapted from ref.[71] from science, copyright 2022. b) Scheme of mechanism in the outstanding catalytic performance for Cr(VI) reduction in the presence of formic acid (HCOOH) by flower-like hybrid materials Nickel@MXene quantum dots (Ni@MQDs). The plots report the cycle performance of Ni@MQDs to catalytically reduce Cr (VI) with HCOOH with the conversion efficiency of Cr (VI) reduction for each cycle. Adapted from ref.[74] from Elsevier, copyright 2023.

due to recombination or reflections. Recently, fundamental studies have shown that choosing a redox mediator with low reorganization energy is an important route to improve charge transfer rates from QDs by orders of magnitude,[70] and substantial improvements to perovskite solar cells (PSCs) were performed by replacing the commonly used mesoporous–titanium dioxide electron transport layer with a thin layer of polyacrylic acid–stabilized tin(IV) oxide quantum dots (**Figure 5a**). As a result, the compact tin(IV) oxide quantum dots enhanced light capture and largely suppressed nonradiative recombination at the electron transport layer–perovskite interface. The use of QDs as electron-selective contact enabled a power conversion efficiency (PCE) of 25.7% and high operational stability and facilitated the scale-up of the PSCs to larger areas. Using QDs, there is also the possibility to dramatically reduce production costs because they can be prepared by using a variety of methods, including inkjet printing and solution processes that offer low operational costs and less energy consumption compared to traditional solar cells, thus offering a more environmentally friendly alternative.[71]

Beyond solar cells, QDs have also shown promise in LED technology improving their brightness and energy efficiency. For example, a novel and interesting approach has enabled high performances through the heterogeneous integration of established semiconductor technology and emerging 2D materials. To achieve red and green colors, CdSe/ZnS green and red colloidal QDs mixed with a transparent epoxy-based SU-8 photoresist were patterned on MoS_2-on-GaN micro-LED by standard photolithography, allowing for scalable full-color micro-LED display fabrication.[72] The absorption and photoluminescence spectra of the optimized QDs conversion layers showed excellent characteristics as a color converter for the display with an external quantum efficiency of 27.76% and 26.30% for green and red QDs, respectively. The green and red QDs exhibited significant absorption at 450 nm, the wavelength emitted by the GaN-based blue micro-LEDs. As a result, the blue micro-LEDs can stimulate these QDs, causing them to emit red and green light at wavelengths of 640 and 530 nm, respectively.

This strategy creates possibilities for the integration of optoelectronic devices that require the inclusion of semiconductor materials with heterogeneous characteristics. The utilization of materials like III–V compound semiconductors, silicon (Si), and 2D materials in these devices holds potential not only for active matrix displays but also for optical and biological sensors with optimal performance. Notable, QDs serve as efficient and tunable emissive elements within light-emitting metasurfaces, enabling dynamic control over emission properties. Their integration with metasurfaces allows for enhanced light manipulation capabilities beyond what either component could achieve alone. By utilizing QDs within reconfigurable nanophotonic devices, real-time modulation of emission characteristics becomes feasible.[73]

The small size, high surface area of QDs, and their ability to generate reactive species under light irradiation make them attractive for a range of chemical reactions. The excited electrons and holes generated in QDs can facilitate redox reactions, leading to the degradation of pollutants, water splitting for hydrogen production, and carbon dioxide reduction into valuable chemicals. In electrocatalysis, the ability to modify electronic properties through surface functionalization or doping allows improved catalytic activity and selectivity in several reactions, such as oxygen reduction, hydrogen evolution, and nitrogen reduction. Also, QDs can serve as cocatalysts when combined with other nanoparticles or semiconductors leading to improved reaction kinetics, and enhanced stability, reducing simultaneously the usage of precious metals for more cost-effective and sustainable processes. MXene quantum dots (MXeneQDs) are recognized as a recently developed class of QD materials derived from layered MXenes. They have emerged as potential electrode materials with applications ranging from bioimaging, catalysis, sensing, and energy storage. MXeneQDs not only preserve the intrinsic properties of MXenes but also present distinct physicochemical characteristics attributed to quantum confinement effects, making them a promising support material for decorating metal nanoparticles. Despite these advantages, modern research lacks the synthesis of metal NPs matched with MXeneQDs and the corresponding studies on their catalytic activities. For instance, flower-like Ni@MXene QD hybrids reported in Figure 5b have been used as an excellent catalyst to reduce Cr (VI) to Cr (III), calculating lower activation energy and higher kinetic constant. DFT calculations also revealed that the strong interaction between Ni and MXeneQD caused an up-shift of the position of the active Ni sites, leading to enhanced adsorption of $HCOOH/H_{act}$ and a reduced barrier for Cr(IV) reduction. Also, it has been found that the material possesses improved conductivity properties which further favor the reaction kinetics.[74]

3.3. Environment

Integrating QDs into sensors and environmental remediation systems holds immense potential for applications such as monitoring, pollutant detection and remediation, and clean energy generation. QDs, known for their high sensitivity to environmental changes, serve as innovative sensors in water and air monitoring, acting as fluorescent probes for detecting specific molecules, ions, or physical parameters like temperature and pressure. Moreover, QDs exhibit enzyme-mimicking activity and offer superior advantages over other nanomaterials due to their cost-effectiveness, metal-free nature, and unique properties, including electrical and optical features, good dispersibility, and high chemical stability, thus making them an economical and practical choice for enhancing catalytic activity in nanozymes. For instance, kanamycin (KAN) is an aminoglycoside antibiotic mostly used in veterinary medicine for animal husbandry and aquaculture. It was recently found that its overuse causes residue in food and the environment representing a huge risk to human health. Boron nitride quantum dots (BNQDs) combined with porous CeO_2 nanorods have been identified as key components in creating a nanozyme-based colorimetric analysis for the detection of KAN (**Figure** 6a). This simple and cost-effective method offers potential for on-site applications. The BNQDs/CeO_2 mixture catalyzes the decomposition of hydrogen peroxide, producing hydroxyl radicals that oxidize tetramethylbenzidine (TMB) into blue compounds. Adding a KAN-specific aptamer to the QDs-based material enhances hydroxyl radical production and increases the interaction between the aptamer and TMB. This strengthens substrate affinity and improves the catalytic performance of the nanozyme, resulting in a more intense blue signal. When KAN is present, the aptamer separates from the nanozyme due to its stronger affinity to KAN, causing a decrease in the color signal.[75]

Real-time monitoring and early detection of pollutants using QDs are crucial for facilitating remediation measures in environmental protection. QDs are recognized for their capability to improve the photocatalytic performance of semiconductors through surface decoration, a process that enhances light absorption and catalytic activity. Integrating QDs into semiconductor materials creates hybrid structures with superior photocatalytic performance, surpassing conventional heterojunctions and Z-scheme constructions, thereby enabling more efficient utilization of solar energy for catalytic reactions aimed at pollution remediation and sustainable energy applications. For instance, graphitic carbon nitride quantum dots ($g\text{-}C_3N_4$ or CNQDs) have recently gained considerable attention in photocatalysis due to their suitable band potentials, significant quantum confinement effect, up-conversion effect, and sensitization effect. As a result, CNQDs emerge as promising candidates for modifying semiconductors to improve broad-spectrum photocatalytic performance. Taking these studies into account has been demonstrated that anchoring CNQDs onto morphologically engineered $CuFe_2O_4$ it is possible to construct a novel 0D/3D nanojunction architecture that features outstanding peroxymonosulfate activation and photocatalytic ability degrading the 99.4% of 5-fluorouracil contaminant, one of the most representative cytotoxic drugs used in anticancer therapies.[76]

It is clear that QDs offer significant advantages over bulk materials in photocatalysis, which suffer from low separation efficiency of charge carriers and limited catalytic sites. Their nanoscale dimensions provide abundant exposed active sites, facilitating efficient charge transport and promoting superior photocatalytic performance. Additionally, the incorporation of cocatalysts further improves electron-hole pair separation and reduces reaction barriers, making QDs a promising avenue for enhancing photocatalytic efficiency. This is particularly impactful in the context of climate change, where QDs also represent a valuable alternative for mitigating air pollution, including CO_2 emissions, by capturing and converting the greenhouse gas into useful chemicals or fuels. Efficient photoconversion of CO_2 has been realized by using 0D black phosphorus quantum dots (BPQDs)-decorated 1D carbon nitride nanotubes (CNNT) photocatalyst to efficiently reduce CO_2 at with a rate much higher than similar photocatalysts and pristine carbon nitride nanotubes (Figure 6b). In particular, the construction of an atomic-level N-P charge transfer channel effectively facilitates charge transfer, thus improving the catalytic rate.[77]

Lastly, QDs have showcased antimicrobial properties (Figure 6c), making them effective candidates for eliminating or reducing drug-resistant pathogens in the environment. QDs take advantage of their ability to produce reactive oxygen

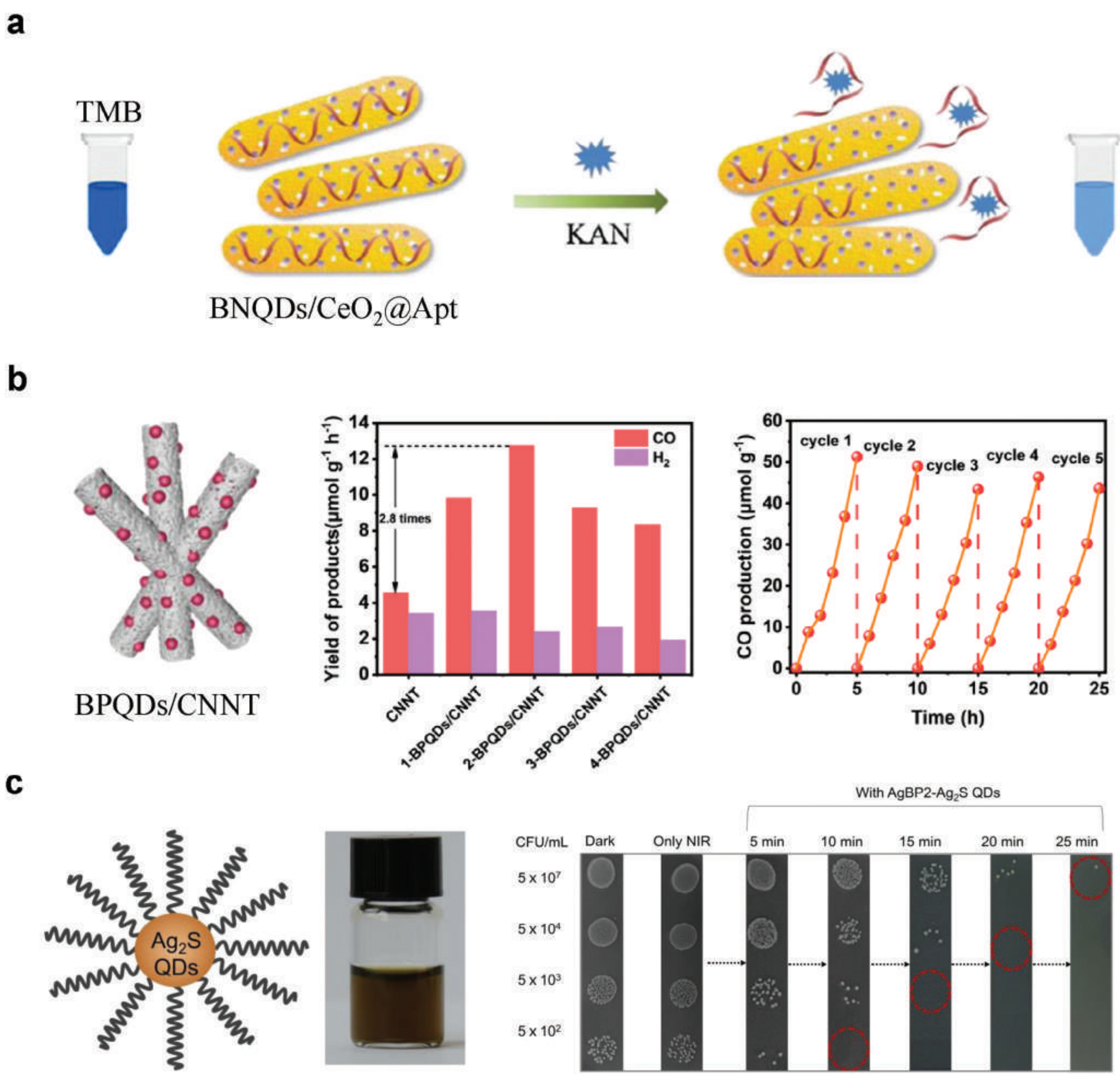

Figure 6. QDs in environmental uses. a) Scheme reporting the colorimetric method for the detection of kanamycin by the use of aptamer nanozyme activity of boron nitride quantum dots anchored on porous CeO_2 nanorods (BNQDs/CeO_2). Adapted from ref.[75] with permission from Elsevier, copyright 2021. b) black phosphorus quantum dots-decorated 1D carbon nitride nanotubes (BPQDs@CNNT) for boosted CO_2 reduction. The production yield of CO is reported in the bar graph by comparing the effect of the amounts of quantum dots used. It is also demonstrated the number of recycling cycle by using 1-BPQDs@CNNT. Adapted from ref.[77] with permission from Elsevier, copyright 2023. c) Schematic picture of fluorescent silver-binding peptide quantum dots (AgBP$_2$-Ag_2S QDs) and images of the synthesized aqueous phase solution for a rapid and effective bacterial disinfection method, along with photographs of bacterial colonies collected in the plate-sensitivity assay. Notably, all the E. coli colonies without AgBP$_2$-Ag_2S QDs survived after NIR irradiation for 25 min, whereas the treated colonies displayed significant disinfection efficacy under the same conditions. Adapted from ref.[78] with permission from John Wiley and Sons, copyright 2023.

species (ROS), and their small size can facilitate penetration into microorganisms inducing cellular damage and subsequent degradation or excretion through bodily processes, minimizing impact on organs and tissues. Biocompatible silver-based BP$_2$-Ag_2S quantum dots have been employed to serve dual functions: as a photothermal agent for near-infrared (NIR) photothermal conversion and as a photocatalyst for ROS generation. These QDs exhibit excellent photocatalytic properties, enabling them to harness NIR light for energy conversion and simultaneously generate ROS, which are highly reactive molecules capable of damaging cellular structures in microorganisms. The AgBP$_2$-Ag_2S QDs demonstrated an impressive disinfection efficiency of

99.06% against Escherichia coli within 25 min of NIR exposure. This high level of effectiveness can be attributed to the synergistic effects of ROS production during photocatalysis, and the elevated temperature caused by photothermal conversion. By combining these two mechanisms, $AgBP_2$-Ag_2S QDs provide a robust and efficient approach for antimicrobial applications and environmental remediation.[78]

Alternatively, carbon dots play a crucial role as antimicrobial agents, offering advantages over traditional antibiotics and other nanomaterials. They possess excellent water solubility, low cytotoxicity, and high biocompatibility, along with enduring bactericidal activity, distinguishing them from metal nanoparticles that rely on metal ion consumption. Of particular interest are carbon dots synthesized from natural sources, which ensure excellent biocompatibility while retaining the antimicrobial activity of the natural source itself. Moreover, through proper functionalization, carbon dots can enhance their existing physicochemical properties and explore new ones, thereby improving selectivity and sensitivity to targeted bacteria, expanding their applications to wound dressings, antibacterial coatings, food packaging, and eyedrops, showing significant potential for commercialization and diversification.[79] As a recent example, nitrogen and sulfur self-doped antimicrobial carbon dots were synthesized using a straightforward one-step hydrothermal method, employing garlic as the carbon source, renowned for its natural antibacterial properties. The results unveiled that the garlic-derived carbon dots exhibited a positively charged surface, excellent fluorescence characteristics, and ultrafine particle size, aligning with typical carbon dot properties. Notably, the garlic-derived carbon dots demonstrated superior effectiveness against multidrug-resistant bacteria compared to conventional antibiotics, showing comparable efficacy to chemically synthesized carbon dots, and also exhibited the ability to inhibit biofilm formation. Furthermore, the materials derived from biomass displayed high biocompatibility in both cytotoxicity assays and hemolysis tests, underscoring their potential for safe biomedical applications.[80]

3.4. Micro- and Nanorobotic

Micro- and nanorobots are tiny machines, typically measuring less than 100 µm, that can be programmed to perform specific tasks autonomously. Formerly known as micro- and nanomotors, they can harvest energy from the surrounding environment and convert it into powerful locomotion. The self-propulsion capabilities of these particles induce efficient solution mixing, which can accelerate chemical operations. Micro- and nanorobots have demonstrated excellent results in a variety of applications, including biomedicine,[32,81–87] sensing,[88] optical imaging,[89] and environmental remediation.[90–95]

When integrated with microrobots, QDs can enhance their functionality and performance in various ways. For example, the small size of QDs allows for miniaturization and precise control of microrobot movements, enabling them to navigate through complex environments with greater agility and precision. Additionally, the stability of QDs ensures long-term performance and reliability of the microrobots, even under challenging conditions. Moreover, the light-emitting properties of quantum dots can be exploited for sensing, imaging, and communication purposes, further enhancing the capabilities of the microrobots. Overall, the combination of microrobots with quantum dots represents a significant advancement over conventional materials, offering improved functionality, efficiency, and versatility for various applications in fields such as healthcare, manufacturing, and environmental monitoring. For instance, CQDs were used to enhance further the photocatalytic performances in pollutant degradations of $BiOBr/Bi_2WO_6$ microrobots. In particular, CQDs were loaded on the material's surface to form a ternary heterojunction $CQD/BiOBr/Bi_2WO_6$. The composite microrobots were compared to the pure phase materials and subjected to mixed antibiotic degradation experiments, registering a higher degradation rate, better applicability of mixed antibiotics, and higher recycling performance.[96] Alternatively, microrobots primarily of antimony sulfide (Sb_2S_3) and adorned with magnetite nanoparticles, have been meticulously engineered for the purpose of microplastics degradation (**Figure 7a**). The propulsion mechanism of these microrobots operates via two distinct and independent physical modes: one facilitated by a magnetic field and the other by exposure to light irradiation. Leveraging phoretic interactions, these microrobots exhibit a pronounced affinity for poly(3-hydroxybutyrate) (PHB) and poly(lactic acid) (PLA) microplastics, thereby enabling their subsequent transportation within a transversely rotating magnetic field.[91]

However, it is recognized that QDs have been shown to have the strongest impact on biomedical self-propelled programmable devices. Indeed, they were mainly useful as contrast reagents in fluorescence or other molecular imaging. QDs-based microrobots appeared for the first time in 2015, where the outer surface of poly(3,4-ethylenedioxythiophene) (PEDOT)/Pt tubular bubble-propelled microrobots were covered with fluorescence CdTe QDs to present a novel approach for a real-time sensing concept toward the selective Hg^{2+} detection in the presence of other coexisting ions, demonstrating great promise for speciation studies. Through the motion, the microrobots can allow and favor the "on-the-fly" molecular recognition around the sample, greatly accelerating target–receptor interactions. Moreover, the authors demonstrated the possibility of tuning the fluorescent intensity by increasing CdTe QD loading, thus opening their potential use for further applications.[97] Later, the same researchers proposed magnetocatalytic hybrid Janus micromotors encapsulating phenylboronic acid (PABA) modified GQDs as ultrafast sensors for detecting deadly bacteria. Here, it is reported that an easy and effective integration of QDs with microrobots owing to the good water solubility of GQDs. The fluorescent microrobots implemented a dual-mode driving method and resulted in mobile organic QD fluorescent platforms whose enhanced fluid intermixing increased the reaction rate between the lipopolysaccharide (LPS) contaminated solution and microrobots compared to the static counterpart. In particular, GQDs interacted with LPS, and PABA acted as a specific recognition receptor. The microrobots also showed highly selective screening capabilities when glucose, galactose, and fructose were mixed in the same solution.[98]

In light of this, the GQDs-based microrobots offered the first promising biocompatible alternative to static fluorescent dyes, posing the bases for important advancements in bioimaging and as contrast agents for tumor targeting, combining the high sensitivity, selectivity, and non-destructive character of fluorescence imaging with the possibility to control the movement of the

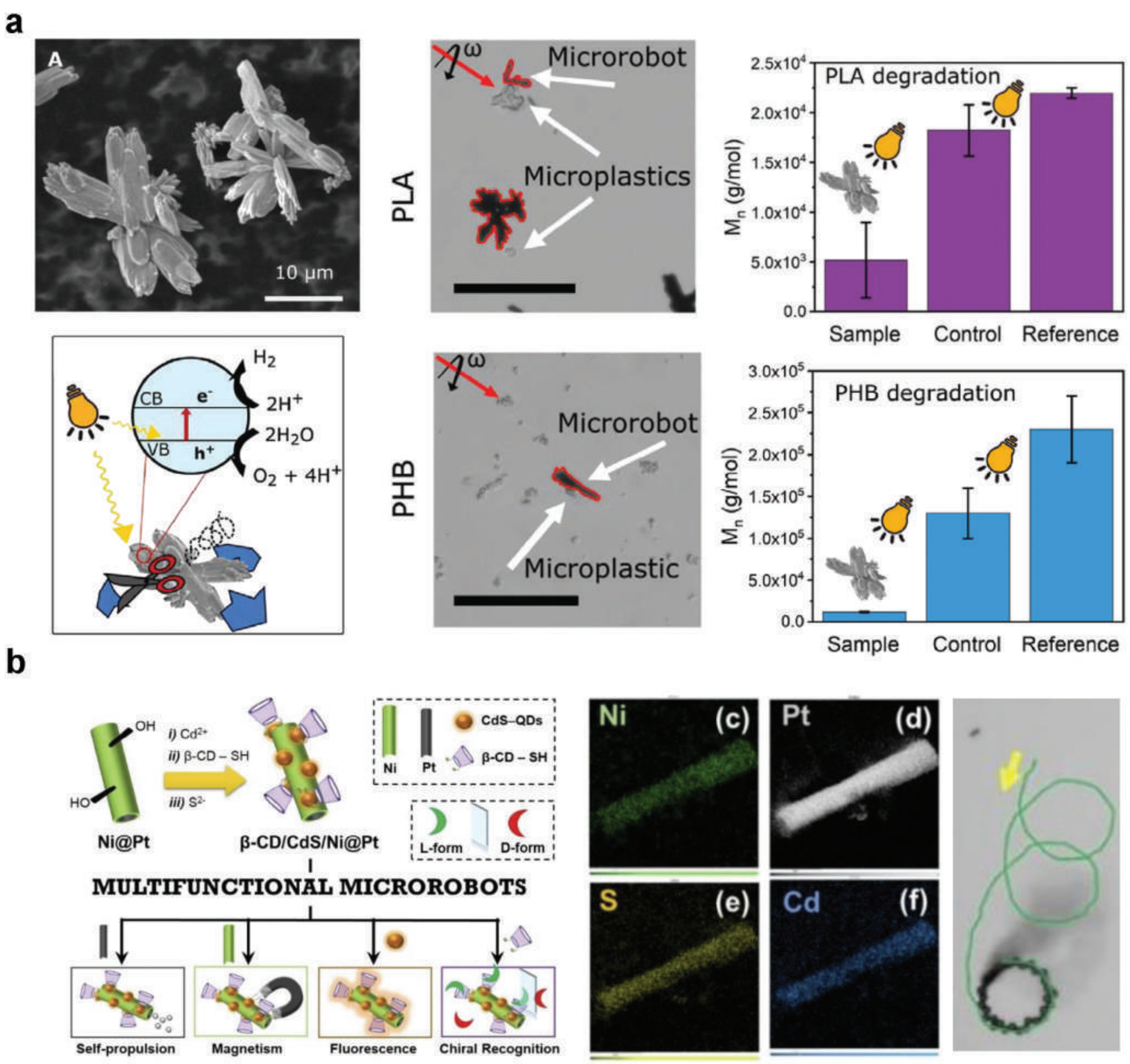

Figure 7. Novel QDs materials for micro-nanorobotic applications. a) Quantum material based microrobots for the capture, transport and degradation of microplastics. The image reports SEM micrograph of Sb_2S_3 microrobots, their affinity toward PHB and PLA microplastics and the influence of microrobots motion in the degradation of microplastics after their capture. Adapted from ref.[91] with permission from John Wiley and Sons, copyright 2023. b) Scheme depicting the preparation of self-propelled chiral-magneto-fluorescent microrobots Ni@Pt microrockets and their surface engineering with QDs to create multifunctional β-CD/CdS/Ni@Pt microrobots. Using supramolecular host-guest interactions, the resulting QDs-based materials were investigated as bimodal (optical and electrical) "enantiorecognition-on-the-fly" devices for chiral targets. Adapted from ref.[101] with permission from John Wiley and Sons, copyright 2023.

microrobots remotely. GQDs exhibit high solubility, low toxicity, and excellent water solubility, characteristics that, combined with their sp^2-like skeleton, render them suitable for various carrier tasks in both aqueous and physiological environments. Notably, the sp^2-like structure of GQDs allows them to participate in fluorescence resonance energy transfer (FRET) processes, acting as acceptors or donors through noncovalent interactions with biomaterials such as single-strand DNA (ssDNA).[99]

Nevertheless, biocompatible fluorescent QDs/microrobots still need to be fully explored. For instance, their activation and control under NIR light are highly relevant, especially for fluorescence imaging tracking in complex biological environments. PbS QD-doped Cu_2O-modified GO microrobots were recently formulated to be driven under NIR light and tested in different fuel fluids to simulate complicated biological media. The established heterojunction structure of Cu_2O@PbS microrobots demonstrated prominent and stable NIR-II fluorescence (emission wavelength: 1100 nm) activity, offering promising potential to visualize their position in vivo biological applications.[100]

In addition to swimming abilities and enhanced fluid mixing abilities, microrobots are also required to perform more complicated tasks contemporary. A fascinating example of QDs-based multifunctional microrobots has been conceived via surface engineering of magnetically navigable nickel-coated platinum microrockets with CdS QDs and a supramolecular host biomolecule β-cyclodextrin for the precise and fast molecular enantiorecognition of tryptophan enantiomers as proof chiral targets (Figure 7b). As a result, the combined chiral, magnetic, and fluorescent functionalities in one self-propelled micromachine have enabled the formulation of smart host-guest devices which can be externally manipulated using an external magnetic field for new insights not only in the field of micro/nanorobots, but also in chiral (bio)sensors, (opto)electronic devices and biomedical applications.[101]

3.5. Quantum Information

Quantum information relies on data processing and problem-solving using a quantum system as an information carrier. The major areas of quantum information technologies can be divided into quantum computing, quantum communications, and quantum sensing involving the use and dissemination of bits of information encoded in quantum, so-called qubits, the unit representing the amount of quantum information that can be stored in the state of the simplest quantum system.[102]

0D semiconducting QDs have been considered one of the major platforms currently used as promising hardware for implementing stationary and flying qubits in the solid state. This is because the individual charge carriers in QDs can be generated, manipulated, coherently controlled, and strongly decoupled from their environment.[103] In this context, the community of semiconductor quantum optics has made significant steps forward in spin manipulation, exploiting indistinguishable single and entangled photon states, monitoring the light–matter interaction, and spin–photon entanglement. It has been recently demonstrated that fully optically patterned silicon QDs and qubits can be made in a 300 mm wafer process line containing 82 unit cells (die) with a total of more than 10 000 QD arrays of various lengths, with up to 55 finger gates per fin, like those used for commercial advanced integrated circuits. The advanced manufacturing method allows the formulation in QD samples to show easily tunable double dots bodes, making them promise in the implementation of two-qubit gates.[104]

Semiconductor QDs are particularly appealing for realizing practical on-demand quantum light sources in quantum communications technologies. Much effort has been made from the first report on a QD single-photon source based on a microdisk cavity that can configure localized light.[103] Gated quantum dots were employed in an open, tunable microcavity. The heterostructure is grown by molecular beam epitaxy , based on an n-i-p diode with self-assembled InGaAs QDs. This way, QD frequency can be tuned via the dc Stark effect and QD charging via Coulomb blockade. Owing to the material design, the provided gate allowed to control of the charge and electrical tuning of the emission frequency, resulting in a single-photon source with an end-to-end efficiency of 80%.[105]

Recently, the combination of molecular approaches with inorganic systems have been represented a powerful route for qubit applications. For instance, single-walled carbon nanotubes (SWCNTs), representing an entirely carbon-based 1D structure, have garnered significant attention as a promising candidate for the realization of electronic spin qubits with extended coherence times. SWCNTs additionally present a wide spectrum of controllable parameters for qubit manipulation and sensing, enabling an expanded repertoire of functionalities that are not accessible to bulk systems. Chen et al. reported the confinement of electron spins in SWCNTs through mild covalent doping using diazonium salts. This method allowed the introduction of sp^3 defects with well-controlled density, recording long coherence time of 8.2 μs and spin-lattice relaxation time of 13 ms, making them appealing for highly reproducible and integratable alternatives in spintronic and quantum devices.[106]

In a different approach, Zhao et al. proposed molecular nanomagnets as promising candidates for information storage, spintronic and quantum computing. In contrast to traditional spins, quantum magnets represent spin systems that interact through exchange interactions and exhibit collective quantum phenomena. The realm of molecular magnetism has traditionally centered around d/f-transition metals, but the presence of spin-orbit coupling, and crystal field effects introduces significant magnetic anisotropy, disrupting the rotational symmetry of quantum spins. Hence, it becomes imperative to construct quantum nanomagnets in metal-free frameworks. The authors have successfully synthesized individual quantum nanomagnets using metal-free multi-porphyrin systems. Initially, covalent chains consisting of two to five porphyrins were meticulously fabricated on an Au(111) substrate within an ultrahigh vacuum environment. Subsequently, hydrogen atoms were selectively removed from specific carbon sites employing a scanning tunneling microscope tip. This process facilitated the conversion of distinct porphyrin units into radical or biradical states, thereby allowing precise tuning of the intra- and inter-porphyrin magnetic interactions. Through the detailed characterization of the collective magnetic properties of these engineered chains, it was observed that the $S = 1/2$ antiferromagnets exhibited a distinct energy gap in their excitation spectrum, while the $S = 1$ antiferromagnets displayed distinctive end states based on the even- and odd-numbered spin chains, in accordance with theoretical Heisenberg model calculations.[107]

In summary, this section highlights the versatile advantages of QDs across biomedicine, energy, environmental monitoring, and quantum information technologies. A selection of the most recent papers is reported in **Table 2**. In biomedicine, QDs offer superior imaging, sensing, and drug delivery capabilities, enhancing targeted therapies and tissue analysis. Moreover, they play a critical role in advancing micro- and nanorobotics by improving functionality and enabling real-time sensing and imaging in biomedical applications. In energy applications, QDs show promise for solar energy conversion and LED technology, while in environmental contexts, they serve as efficient sensors and photocatalysts for pollutant remediation. Lastly, in quantum information, semiconductor QDs serve as promising platforms for implementing qubits, alongside exploration of molecular

Table 2. Selection of recent (2022-2023) examples of QDs-based micro/nanomaterials and their applications.

Material	Size [nm]	Application	Advancements	Ref.
PL-tunable CQDs	1.8 – 7.6	CQDs/PVA films with color-tunable emission; bioimaging	39% Quantum Yield	[61]
CQDs fluorescent probes	–	Labeling and multicolor simultaneous imaging of multiple immune cells	Fluorescent images at – 20 °C; high fluorescent intensity in the presence of KCl	[62]
Planted GQDs	3 – 4	In vivo fluorescent, sustainable and multimodality tumor bioimaging	Prolonged blood circulation	[63]
HAMA/GelMA GQDs doping	15	Wound tissue healing and drug delivery monitoring	Physical self-bonded and controllable release of drugs	[64]
Ag_2Te QD-based Mn single-atom catalyst	4.5	Imaging-guided therapy of BBB breakdown	Rapid reconstruction of BBB and recovery of neurological function	[108]
BPQDs – SIOF	5	Spinal cord injury repair	Intelligent and controllable drug release	[65]
NB-QD	4.6	Ultrasensitive bioassay FRET	3-fold below the clinical cut-off level LOD	[67]
BPQDs@ssFe3O4@C	5	Drug release	pH- NIR- and redox-responsive behavior, facilitate triple-stimuli for continuous drug release	[109]
HO-ECL CdTe	–	POCT	Amplified detection signals	[20]
Cd chalcogenide QDs	3 – 4	Photoinduced charge transfer from QDs to Co-based mediators	Reduction of energy reorganization of redox mediators	[70]
Flower-like Ni@MQDs	6	Treatment of Cr (VI) polluted wastewater	Improved conductivity With superior catalytic reaction kinetics	[74]
Oleic-acid-capped red and green QDs (CdSe/ZnS)	6.2 ÷ 9.3	Color conversion of GaN micro-LED	Full-color active-matrix micro-LED display	[72]
Paa-QD-SnO_2@TiO_2	4	Electron-selective contact in PSCs	0.08 square centimeters PSCs with 25.7 PCE and facilitated scale-up	[71]
$AgBP_2$-Ag_2S QDs	10	Disinfection against *Escherichia coli* under NIR	Improved photocatalytic and photothermal efficiency	[110]
BPQDs-CNNT	3 – 5	Photocatalytic CO_2 reduction	Construction of atomic level N-P charge transfer channel enhancing 3 times the CO_2 photoreduction	[111]
FeOOH QDs/UPCN	2 – 5	Photo-Fenton degradation of OTC	H_2O_2 production to enhance photo-Fenton degradation efficiency	[112]
CNQDs@CFO	–	PMS oxidation and visible-light photocatalysis	Improved recycling stability and degradation efficiency under Visible light	[76]
$Bi_2Sn_2O_7$ QDs/TiO_2	6.6	PEC degradation of SMT	Realization of S-scheme heterojunction for efficient synergy between photo and electricity in a PEC process	[68]
Cu_2O@PbS	–	Self-propelled systems in environmentally friendly solutions	NIR-I light-driven photocatalytic propulsion and NIR-II fluorescence	[100]
β-CD/CdS/Ni@Pt	–	On-the-fly enantiorecognition for Trp enantiomers determination	Nanotemplates to immobilize thiolated β-CD via S-S bond formation	[101]
CQD/Bi_2WO_6/BiOBr	12.6	Photocatalytic degradation of antibiotics in water	Ternary heterojunction with enhanced motion abilities under visible light for enhanced degradation efficiency	[96]
Confined Spins SWCNTs	–	Qubit applications	Scalable and reproducible quantum materials through covalent doping of SWCNTs by diazonium salts	[106]

(Continued)

Table 2. (Continued)

Material	Size [nm]	Application	Advancements	Ref.
TMDCs	–	Quantum information technologies	Bright single-photon source of strain-engineered WSe_2 monolayer for quantum key distribution	[113]
Quantum nanomagnets	–	Conversion of specific porphyrin units to their radical or biradical state and tuning the intra-inter-porphyrin magnetic coupling	Engineerable platform for quantum magnetisms in magnetic plateau, spin liquid state or spin-Peierls states	[107]

PL, photoluminescence; CDs, carbon dots; PVA, polyvinialchol; GQDs, graphene quantum dots; HAMA, hyaluronic acid methacryloyl; GelMA, gelatin methacryloyl; GOQDs, graphene oxide quantum dots; BBB, blood-brain-barrier; BPQDs, black phosphorous quantum dots; SIOF, stretched inverse opal film; NB-QD, nanobodies quantum dot; FRET, Förster resonance energy transfer; LOD, limit of detection; HO-ECL, homogeneous electrochemiluminescence; POCT, point-of-care testing; MODs, MXene quantum dots; LED, light emitting diode; Paa, polyacrylic acid; PSCs, perovskite solar cells; CNNT, carbon nitride nanotubes; UPCN, coupled ultrathin porous g-C_3N_4; OTC, oxytetracycline; CNQDs, g-C_3N_4 quantum dots; CFO, $CuFe_2O_4/Cu^0$ hollow microspheres; PMS, peroxymonosulfate; PEC, photoelectrocatalytic; SMT, β-CD sulfamethazine; β-CD, beta-cyclodextrin; TMDCs, transition metal dichalcogenides.

nanomagnets and carbon nanotubes, expanding the potential for practical quantum computing and communication technologies.

4. Conclusion and Outlook

Figure 8 illustrates the conclusion and outlook of this Review, which aimed to introduce the fundamentals of QDs. It also provides insights into the most recent synthesis and assemblies to obtain more advanced platforms and effective QD-specific devices that have found significant importance for various applications. The Review discusses the most recent uses of QDs-based materials navigating their potential across different application areas. Focusing on the past few years, we have identified five main areas where using QDs has demonstrated significant advancements: biomedicine, energy, environment, self-propelled micro/nanosystems, and quantum information.

We discussed the role of QDs-based materials in these areas and how each constituent and the resulting combinations can impact specific applications. For instance, the quantization size effect, more precisely, tuning the bandgap size across a broad range of energies, is crucial for the variation of the QDs properties. Overall, the examples reported in this Review illustrate how the use of QDs can confer unique features, leading to the formulation of advanced systems with distinctive capabilities, which can address future challenges and capitalize on emerging opportunities, mostly in QD solar cells, lighting and displays, sensing, in-vivo bioimaging, biosensors, quantum computers, micro- and nanorobotics and photocatalytic applications. In this context, using QDs has proven to be vast and exciting.

Beginning in 2013, commercial applications of semiconducting QDs emerged as displays to improve LED backlighting in LCD screens. Using InP-based QDs instead of CdSe ones represented a step forward in the market. However, the integration of QDs in different important commercial products is expected in the near future.

QDs are revolutionizing multiple fields due to their exceptional properties, signing a significant change from conventional materials. Their precise tunability of optoelectronic properties has revolutionized applications ranging from biomedicine to environmental sensing. QDs offer superior versatility, enabling tailored solutions in drug delivery, bioimaging, and cancer therapy. Unlike traditional materials, QDs exhibit exceptional stability and biocompatibility, promising safer and more efficient biomedical interventions. Their broad absorption spectra and narrow emission peaks make them ideal candidates for sensitive detection in biosensing and diagnostic applications.

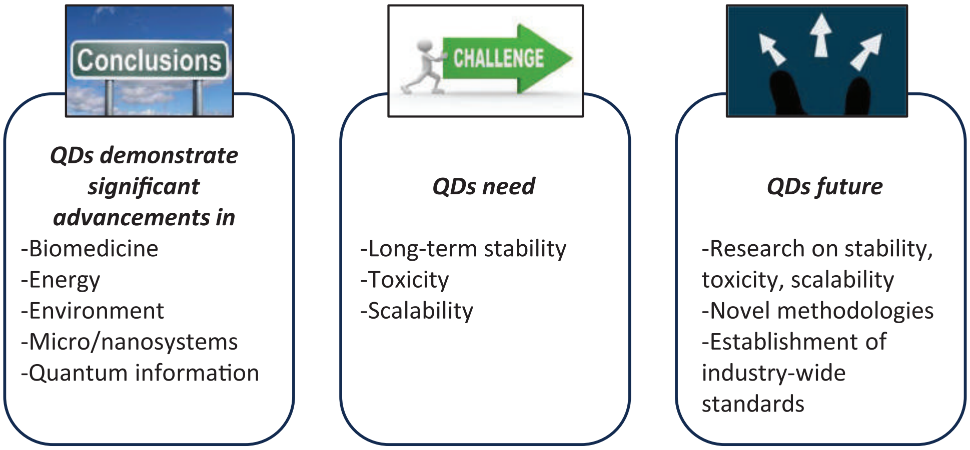

Figure 8. Diagram illustrating the conclusion and outlook of the Review, highlighting the significant advancements, challenges, and future directions in the field of QDs research.

Furthermore, QDs' integration into micro/nanorobotic systems has unlocked unprecedented possibilities for precise manipulation at the nanoscale. In energy applications, QDs surpass conventional materials by maximizing light absorption and energy conversion efficiency in solar cells and light-emitting devices. As QDs continue to evolve, their role in advancing technologies such as quantum information processing and environmental monitoring becomes increasingly pivotal. With their remarkable performance and versatility, QDs are not just augmenting but supplanting conventional materials, shaping the landscape of future technological advancements across diverse domains. Despite recent advancements, several major challenges must be addressed before full translation can occur:

4.1. Long-Term Stability

Nanomaterials, including QDs, are typically more metastable compared to their bulk counterparts. These quantum dots are particularly sensitive to factors such as temperature and other environmental conditions, which can influence their morphology and chemical stability. For materials composed of semiconductors smaller than 10 nm, it is crucial to have a profound understanding of phenomena such as sintering and grain growth. For instance, processes like the coalescence of quantum dots into larger particles and the expansion in the size of crystalline regions within the QD material – known as grain growth – can negatively impact their performance. Recent research has proposed various approaches to address these stability issues.[58] These include using organic or inorganic ligands to passivate the surface of QDs and encapsulating them within a polymer matrix to prevent coalescence. Despite these advancements, the stability of QDs continues to pose a significant challenge. Applications of QDs in photochemistry are still in their preliminary stages, and maintaining the stability of QDs under extended exposure to light and heat remains a considerable concern.

4.2. Toxicity

The use of QDs presents a considerable challenge due to their potential toxicity, particularly in biological applications where the risk of severe acute and long-term toxicity strongly limits the effective clinical translation. Due to their small dimensions, QDs can more easily penetrate cell membranes and accumulate in tissues, potentially harmful to biological systems. While carbon-based QDs have been proposed as safer alternatives to heavy metal-based QDs, the relationship between their physicochemical properties and their pharmacokinetic and pharmacodynamic behaviors has to be fully understood. Researchers need to develop novel methodologies to modify the surface chemistry of QDs to reduce their toxicity level and improve their biocompatibility. This could lead to better control over the release of QDs in the body, and further studies regarding the encapsulation of QDs in biodegradable compounds represent an important area of investigation. In addition, the integration into biological micro- and nanorobots that can be remotely controlled can represent an innovative approach for the future. However, significant work is required to address the challenges of QDs toxicity and ensure their safe and effective use in a range of biological applications.

4.3. Scalability

The large-scale production of QDs is critical for the effective and successful integration of QDs into various applications. It is vital to pay attention to synthesis, integration, standardization, and environmental impact to achieve large-scale production of QDs. As mentioned above, several synthetic methods are potentially advantageous to produce high-quality QDs with reproducible and uniform properties while minimizing costs and environmental impacts. Besides, QDs must be efficiently integrated into existing and emerging technological platforms by designing and developing new fabrication techniques, materials, and architectures that accommodate QDs without compromising the performance of original applications. In addition to this, establishing industry-wide standards for QD properties and performance will ensure compatibility across different devices and systems. Lastly, considerations about the environmental impact are vital for the scalability of QDs. This involves optimizing synthetic methods to minimize environmental effects and understanding their potential toxicity and health risks.

It is crucial to note that the upcoming decade will be pivotal for the future of QDs, and the concerted effort of researchers, engineers, and policy-makers will determine their potential to transform various industries and improve the quality of human life.

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Conflict of Interest

The authors declare no conflict of interest.

Keywords

biomedical imaging, environmental monitoring, micromotors, nanoparticles, optoelectronics, quantum technology, semiconductor quantum dots

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