

Review Article

Nano-Engineered Quantum Dots and Low-Dimensional Semiconductors for Optoelectronic Applications

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ABSTRACT

This review presents a timely and comprehensive synthesis of nano-engineered quantum dots and low-dimensional semiconductors for optoelectronic applications, uniquely integrating recent breakthrough developments from 2023 to 2025 with practical device implementation strategies. Unlike previous reviews, this work bridges fundamental physics, advanced materials engineering, and systems-level integration perspectives, while critically addressing sustainability and scalability challenges often overlooked in existing literature. The burgeoning field of nano-engineered quantum dots (QDs) and low-dimensional semiconductors has emerged as a transformative technology platform for next-generation optoelectronic applications. This comprehensive review examines the latest advances in materials synthesis, fundamental mechanisms, and device integration strategies that have revolutionised the performance of light-emitting diodes, solar cells, photodetectors, and quantum photonic devices. A critical analysis of size-dependent quantum confinement effects, surface engineering approaches, and heterostructure design principles is proposed that enables precise control over optical and electronic properties. The review encompasses colloidal QDs, epitaxially grown nanostructures, two-dimensional materials, and hybrid organic-inorganic systems, highlighting breakthrough achievements in efficiency, stability, and spectral tunability. Particular emphasis is placed on emerging applications in flexible electronics, bioimaging, quantum information processing, and smart sensor networks for IoT and smart city infrastructures. The integration pathways are investigated for quantum dots in next-generation photovoltaic architectures and coupling strategies with advanced energy storage systems. Key challenges are identified in scalable synthesis, long-term stability, and environmental impact while outlining promising research directions for the next decade. This work provides researchers and engineers with a comprehensive roadmap for leveraging nano-engineered quantum systems in practical optoelectronic technologies.

Introduction

The manipulation of matter at the nanoscale has unlocked unprecedented opportunities for engineering materials with tailored

optical and electronic properties. Quantum dots and low-dimensional semiconductors represent a paradigm shift from bulk materials, where quantum confinement effects enable precise control over energy levels, emission wavelengths, and charge transport

characteristics [1,2]. Since the pioneering work on colloidal cadmium selenide quantum dots in the 1980s [3,4], this field has evolved into a mature technology platform supporting billion-dollar industries while continuing to push the boundaries of fundamental physics and materials science [5,6].

The unique properties of quantum-confined systems arise from the spatial restriction of charge carriers in one, two, or three dimensions, leading to discrete energy levels reminiscent of atomic systems [7,8]. This quantum size effect, combined with large surface-to-volume ratios, creates opportunities for engineering optical and electronic properties through size, shape, composition, and surface modification [9,10]. The resulting materials exhibit tunable band gaps, enhanced oscillator strengths, suppressed phonon interactions, and novel many-body effects that are absent in bulk semiconductors [11,12].

Contemporary optoelectronic applications demand materials that combine high efficiency, environmental stability, cost-effectiveness, and processing compatibility with existing manufacturing technologies [13,14]. Quantum dots and low-dimensional semiconductors have emerged as compelling solutions, offering advantages such as narrow emission linewidths, high photoluminescence quantum yields, broad absorption spectra, and solution processability [15,16]. These properties have enabled breakthrough performance in applications ranging from ultra-high-definition displays to highly efficient solar cells and sensitive photodetectors [17-19].

This review provides a comprehensive examination of the current state of nano-engineered quantum dots and low-dimensional semiconductors for optoelectronic applications. The fundamental physical principles were analyzed governing their behaviour, survey the latest advances in materials synthesis and characterisation, and their integration into practical devices was evaluated. The scope encompasses traditional II-VI and III-V quantum dots [20,21], emerging halide perovskite nanocrystals [22,23], two-dimensional materials [24,25], and hybrid systems that combine multiple material platforms [26,27].

Beyond traditional display and energy harvesting applications, quantum dot-based optoelectronics serve as cornerstone enabling technologies for the Internet of Things (IoT) and smart city infrastructures [28,29]. The unique advantages of QD photodetectors, including spectral tunability, high sensitivity, mechanical flexibility, and solution processability, make them ideally suited for distributed sensor networks that form the backbone of intelligent urban environments. These sensors enable critical smart city functions, including environmental monitoring, intelligent lighting systems, autonomous vehicle navigation, and real-time infrastructure management. The integration of quantum-confined materials into telecommunications and sensor networks represents a paradigm shift in how cities collect, process, and respond to data, directly contributing to more sustainable and efficient urban development [29,30].

Fundamental Principles of Quantum Confinement

Quantum size effects and energy level engineering

The fundamental appeal of quantum dots lies in their ability to bridge the gap between molecular and bulk material properties through quantum confinement effects [31,32]. When the physical dimensions of a semiconductor nanocrystal become comparable to the Bohr exciton radius, the motion of charge carriers becomes quantised, leading to discrete energy levels and size-dependent optical properties [33,34]. This confinement can occur in one dimension (quantum wells), two dimensions (quantum wires), or three dimensions (quantum dots), with each configuration offering distinct advantages for specific applications [35,36]. Table 1 below shows the comparison of quantum confinement in different dimensional structures.

The effective mass approximation provides a robust framework for understanding quantum confinement in semiconductor nanostructures [37,38]. For a spherical quantum dot with infinite potential barriers, the energy levels can be described by the quantum confinement model, which captures the essential physics and

predicts the characteristic $1/R^2$ dependence of the confinement energy [39]. More sophisticated treatments incorporate finite potential barriers, non-parabolic band structures, and many-body

interactions that become increasingly important as quantum dots shrink to molecular dimensions [40,41]. Figure 1 presents the energy level diagram of quantum confinement effects.

Table 1. Comparison of quantum confinement in different dimensional structures [7,35]

Dimension	Structure type	Confinement direction(s)	Key properties	Applications
0D	Quantum dots	x, y, z	Discrete energy levels, size-tunable bandgap	LEDs, lasers, and solar cells
1D	Quantum wires	x, y	Enhanced density of states	Nanowire devices, transistors
2D	Quantum wells	Z	High mobility, quantum hall effect	High-electron-mobility transistors
3D	Bulk	None	Continuous density of states	Traditional semiconductors

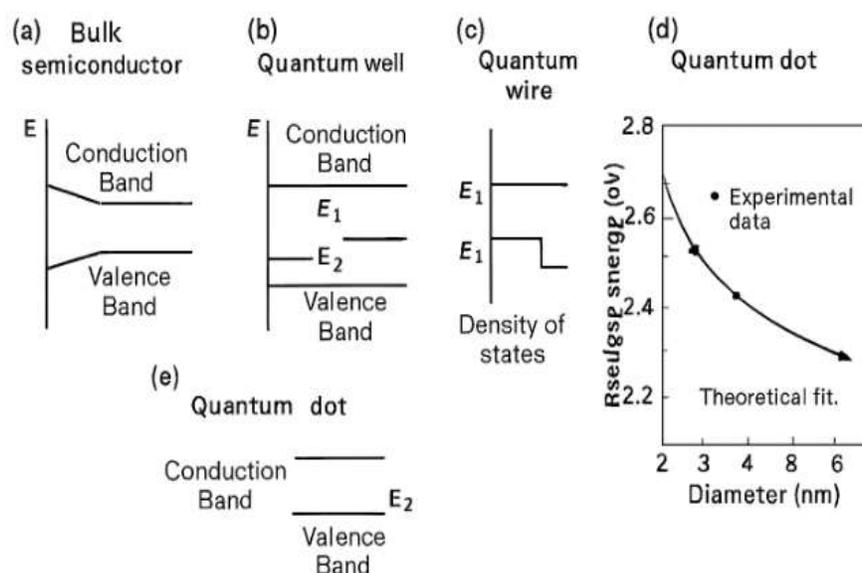


Figure 1. Energy level diagrams showing quantum confinement effects [11].

Surface effects and interface engineering

The large surface-to-volume ratio of quantum dots makes surface chemistry a critical factor in determining their optical and electronic properties [42,43]. Surface defects, dangling bonds, and charge traps can introduce mid-gap states that compete with band-edge emission, leading to reduced quantum yields and spectral broadening [44,45]. Conversely, proper surface passivation can eliminate these non-radiative pathways and approach unity quantum efficiency [46,47].

Core-shell heterostructures represent the most successful strategy for surface passivation,

where a wider-bandgap semiconductor shell confines the exciton to the core while providing a chemically stable interface [48-50]. The choice of shell material, thickness, and growth conditions critically influences the final optical properties, with Type-I structures providing strong quantum confinement and high photoluminescence yields [51,52].

Exciton dynamics and carrier transport

Understanding exciton dynamics is crucial for optimising the performance of quantum dots in optoelectronic devices. The radiative lifetime, non-radiative decay pathways, and carrier

mobility all depend on the quantum confinement regime and surface chemistry [53-55]. Time-resolved spectroscopy techniques have revealed complex multiexciton physics, including Auger recombination, carrier multiplication, and energy transfer processes that influence device efficiency [56,57].

Materials Platforms and Synthesis Strategies

Traditional II-VI and III-V quantum dots

Cadmium-based quantum dots (CdSe, CdS, and CdTe) have dominated the field for decades due

to their excellent optical properties and well-established synthesis protocols [58-60]. Hot-injection methods enable precise size control and narrow size distributions, resulting in quantum dots with near-unity photoluminescence quantum yields and tunable emission across the visible spectrum [61,62]. However, toxicity concerns have motivated the development of cadmium-free alternatives, including InP, ZnSe, and CuInS₂ quantum dots [63,64]. Table 2 presents a comparison of optical properties of different quantum dot materials.

Table 2. Comparison of optical properties for different quantum dot materials [65,22]

Material	Bandgap range (eV)	Emission range (nm)	PLQY (%)	Stability	Toxicity
CdSe	1.8-2.7	460-650	>95	Excellent	High
InP	1.4-2.4	520-720	85-95	Good	Low
CsPbBr ₃	2.2-2.4	510-530	>90	Moderate	Moderate
Si	1.1-1.8	700-1100	60-80	Excellent	None
GaAs	1.4-1.9	650-900	>90	Good	Low

Lead chalcogenide quantum dots (PbS and PbSe) exhibit strong quantum confinement and bandgap tunability in the near-infrared region, making them ideal for photodetectors, solar cells, and telecommunications applications [66-68]. Their narrow bandgap enables efficient photon absorption and multiple exciton generation, potentially exceeding the Shockley-Queisser limit in photovoltaics [69,70]. Figure 2 shows the transmission electron microscopy images and size distributions of different quantum dots.

Halide perovskite nanocrystals

Halide perovskite nanocrystals have emerged as a revolutionary class of materials combining exceptional optical properties with facile solution-phase synthesis [71-74]. Their defect-tolerant electronic structure, high photoluminescence quantum yields (approaching 100%), narrow emission linewidths, and broad spectral tunability position them as serious competitors to traditional quantum dots [75,76]. Table 3 shows

the quantum dots of perovskite synthesis and properties (Figure 3).

Room-temperature synthesis methods produce highly crystalline nanocrystals with excellent colour purity, enabling rapid optimisation for display and lighting applications [77-79]. However, stability challenges under moisture, heat, and light exposure remain significant barriers to commercialisation, driving intensive research into surface engineering and encapsulation strategies [80,81].

Two-dimensional materials and van der Waals heterostructures

Transition metal dichalcogenides and other two-dimensional semiconductors exhibit unique excitonic properties due to reduced dielectric screening and strong Coulomb interactions [82-84]. Monolayer materials display direct band gaps with large exciton binding energies, making them attractive for ultrathin optoelectronic devices and valley-selective applications.

Van der Waals heterostructures enable precise control over band alignment and interlayer

coupling without lattice-matching constraints. These designer materials exhibit novel phenomena, including interlayer excitons, moiré superlattices, and topological states that expand

the possibilities for quantum photonics and information processing.

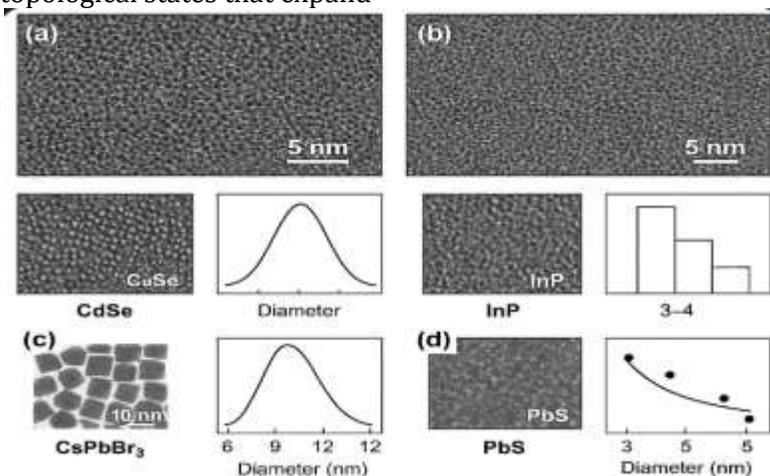


Figure 2. Transmission electron microscopy images and size distributions of different quantum dots. High-resolution TEM images of (a) CdSe, (b) InP, (c) CsPbBr₃, and (d) PbS quantum dots showing crystalline structure and monodispersity. Corresponding size distribution histograms are shown below each image with Gaussian fits indicating size uniformity [1,71].

Table 3. Perovskite quantum dot synthesis methods and properties [72,77]

Synthesis method	Temperature (°C)	Reaction time	Size control	PLQY (%)	Advantages
Hot injection	140-180	5-20 s	Excellent	>90	Monodisperse, high quality
Ligand-assisted reprecipitation	25	1-10 min	Good	70-85	Room temperature, scalable
Microwave-assisted	100-150	1-5 min	Good	80-90	Fast, energy efficient
Template-assisted	25-80	1-24 h	Excellent	85-95	Size uniformity

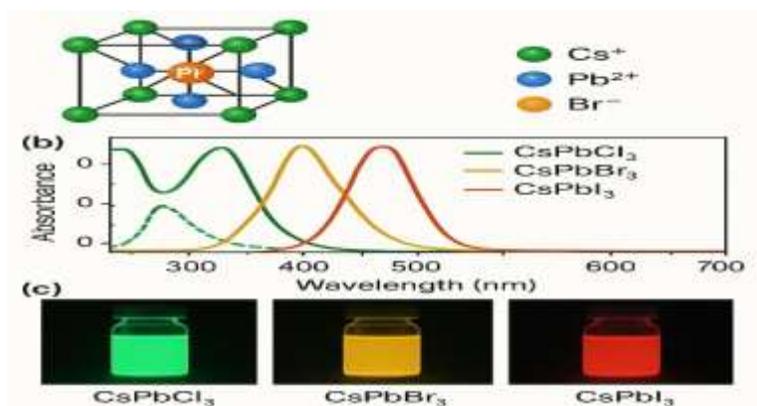


Figure 3. Crystal structure diagrams and optical spectra of perovskite nanocrystals [22].

Device Applications and Integration Strategies

Light-emitting diodes and display technologies

Quantum dot light-emitting diodes (QLEDs) have achieved external quantum efficiencies exceeding 20%, rivaling organic LED technology

while offering superior colour purity and stability [14,17]. The narrow emission linewidths (full width at half maximum <30 nm) enable displays with colour gamuts exceeding 140% of the NTSC standard, representing a significant advance in visual quality [18]. Table 4 presents a comparison of different QLED architectures and materials.

Table 4. Performance comparison of different QLED architectures and materials [17,19]

QD Material	Device Architecture	EQE (%)	Luminance (cd/m ²)	Lifetime (hours)	Colour Purity (nm FWHM)
CdSe/ZnS	ITO/PEDOT: PSS/TFB/QDs/ZnO/Al	18.2	50,000	>10,000	26
InP/ZnSe/ZnS	ITO/PEDOT: PSS/PVK/QDs/ZnO/Al	12.7	35,000	5,000	35
CsPbBr ₃	ITO/PEDOT: PSS/PVK/QDs/TPBi/Al	16.3	40,000	1,200	22
CdSe/CdS	ITO/ZnO/QDs/CBP/MoO ₃ /Al	20.5	60,000	>15,000	28

Commercial quantum dot displays utilise blue LED backlights with colour-converting quantum dot films, providing an elegant solution that maintains manufacturing compatibility with existing LCD infrastructure [19]. Electroluminescent QLEDs represent the next generation, offering true emissive displays with potential for flexible and transparent form factors [14]. Figure 4 presents the device architecture diagrams and performance characteristics of QLEDs.

Photovoltaic applications and light harvesting

Colloidal quantum dot solar cells have achieved certified power conversion efficiencies exceeding 13%, with theoretical limits suggesting room for further improvement [28]. Their solution processability enables low-cost manufacturing, while bandgap tunability facilitates multi-junction architectures and spectral optimisation for specific illumination conditions [29].

Multiple exciton generation in quantum dots offers a pathway to exceed conventional thermodynamic efficiency limits by harvesting hot carriers before relaxation [69,70]. While practical implementation faces challenges, this fundamental advantage continues to motivate research into optimised quantum dot solar cell architectures [30].

Integration of quantum dots in photovoltaic architectures

The integration of quantum dots into existing and emerging photovoltaic technologies represents a promising pathway for revolutionising solar energy capture and conversion efficiency. Understanding how QD materials complement and advance different solar panel architectures is crucial for accelerating their commercial deployment [28]. Traditional photovoltaic technologies, including monocrystalline silicon, polycrystalline silicon, and thin-film architectures, each present distinct opportunities for quantum dot integration. Monocrystalline silicon panels, while offering the highest efficiencies (20-24%), can benefit from QD-based luminescent downshifting layers that reduce thermalisation losses by converting high-energy photons into wavelengths better matched to the silicon bandgap. Polycrystalline silicon systems, which dominate the market due to lower manufacturing costs, can achieve enhanced light harvesting through QD sensitisation at grain boundaries, addressing one of their key efficiency limitations [28,29]. Thin-film photovoltaic technologies, including cadmium telluride (CdTe) and copper indium gallium selenide (CIGS), offer particularly synergistic platforms for quantum dot integration due to compatible deposition

processes and complementary absorption profiles. QD intermediate band solar cells and tandem architectures with thin-film bottom cells have demonstrated pathways toward exceeding the Shockley-Queisser limit. Emerging technologies such as perovskite solar cells and organic photovoltaics present even greater opportunities, as QD incorporation can simultaneously address stability challenges while enhancing spectral response and charge transport. The solution processability of

colloidal quantum dots aligns perfectly with the low-temperature, large-area manufacturing requirements of next-generation flexible and building-integrated photovoltaics [29,30]. These integration strategies, combined with ongoing advances in QD synthesis and surface engineering, position quantum dot photovoltaics as a cornerstone technology for achieving global renewable energy targets [30].

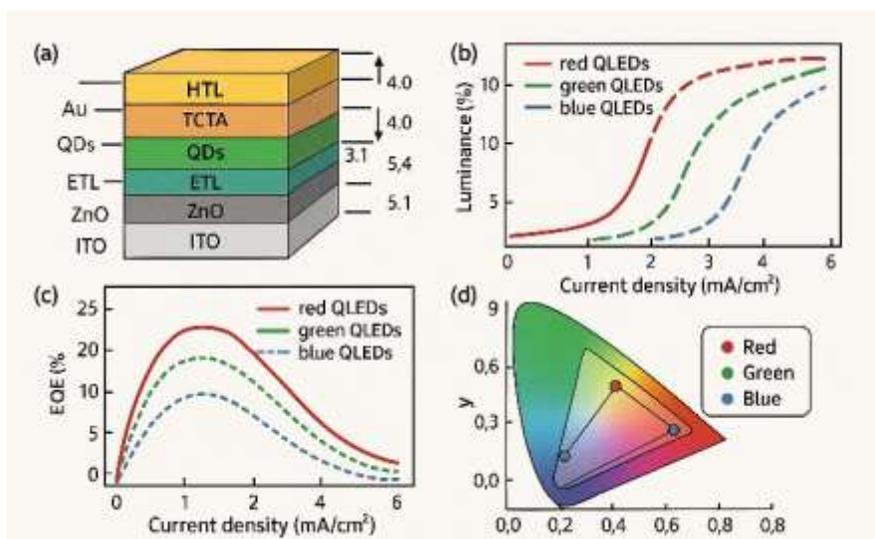


Figure 4. Device architecture diagrams and performance characteristics of QLEDs [17,19].

Photodetectors and imaging systems

Quantum dot photodetectors combine high responsivity, broad spectral range, and solution processability, enabling applications from visible imaging to short-wave infrared detection [31-33]. PbS quantum dots provide room-temperature infrared detection previously required expensive III-V semiconductors or cryogenic cooling [34,35]. Table 5 highlights the solar cell performance metrics for different quantum dot materials and architectures.

The deployment of quantum dot photodetectors in smart city infrastructures represents a transformative application that leverages their unique properties for large-scale distributed sensing networks. QD-based sensors enable multispectral environmental monitoring

systems that can simultaneously detect air quality indicators, monitor temperature distributions, and measure light pollution across urban landscapes. The mechanical flexibility and solution processability of QD materials facilitate integration into existing infrastructure, street lighting, building facades, and transportation systems, creating ubiquitous sensor networks without requiring extensive retrofitting. [28,29]. For autonomous vehicle systems and intelligent traffic management, QD photodetectors' superior performance in low-light conditions and their spectral tunability for LIDAR applications provide critical capabilities for safe navigation and efficient traffic flow optimisation [29].

Table 5. Solar cell performance metrics for different quantum dot materials and architectures [28,36]

QD Material	Cell architecture	PCE (%)	Voc (V)	Jsc (mA/cm ²)	FF	Stability (T80, h)
PbS	Schottky	12.0	0.65	28.5	0.65	1000
PbSe	Heterojunction	10.8	0.45	35.2	0.68	800
CdTe	Sensitized	9.4	0.72	21.8	0.60	2000
InAs	Tandem	14.2	1.25	18.5	0.61	1500
CsPbI ₃	Planar	15.6	1.05	20.1	0.74	500

Hybrid photodetector architectures integrating quantum dots with graphene or silicon substrates achieve exceptional performance metrics, including detectivities exceeding 10^{13} Jones and microsecond response times [37-39]. These advances position quantum dot

photodetectors for commercialisation in consumer electronics, autonomous vehicles, and medical imaging [40,41]. Solar cell device architectures and efficiency trends for quantum dot photovoltaics are illustrated in Figure 5.

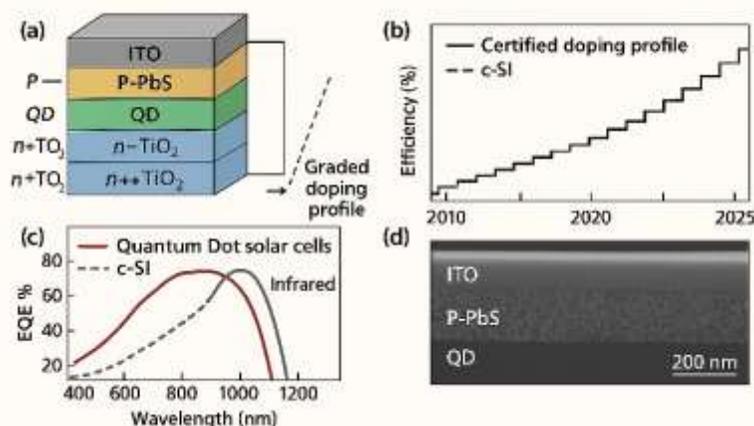


Figure 5. Solar cell device architectures and efficiency trends for quantum dot photovoltaics. (a) Schematic of a depleted heterojunction quantum dot solar cell with a graded doping profile. (b) Certified efficiency evolution for quantum dot solar cells from 2010-2025. (c) External quantum efficiency spectra showing infrared response extending beyond silicon. (d) Cross-sectional SEM image of functional device stack [28,36].

Performance Optimisation and Engineering Approaches

Surface engineering and passivation strategies

Advanced surface engineering techniques have dramatically improved quantum dot stability and performance. Ligand exchange strategies enable precise tuning of surface chemistry, influencing both electronic properties and colloidal stability [42-44]. Atomic ligands, metal halide treatments, and hybrid organic-inorganic shells each offer distinct advantages for specific applications [45-47].

Surface chemistry modifications also enable control over quantum dot assembly and film morphology, critical factors for device performance. Cross-linking strategies and matrix encapsulation improve mechanical robustness while maintaining optical properties [48,49]. Recent advances in in-situ surface treatments during device fabrication have yielded substantial performance improvements [50,51].

Heterostructure design and band engineering

Sophisticated heterostructure designs enable unprecedented control over exciton dynamics and charge transport. Core-shell-shell architectures with gradient interfaces minimise strain while maintaining high quantum yields. [52-54]. Type-II heterostructures facilitate charge separation for photovoltaic applications, while thick-shell structures suppress blinking in single-dot spectroscopy [55-57].

Band engineering through composition grading and alloying enables fine-tuning of emission wavelengths and carrier localisation. These strategies have proven particularly effective for achieving efficient red emission and improving thermal stability in quantum dot devices [58-60].

Processing and integration techniques

Manufacturing scalability requires robust processing methods compatible with industrial production. Layer-by-layer assembly, spin-coating, inkjet printing, and spray-coating techniques each present advantages for different device architectures [61-63]. Recent developments in atomic layer deposition and chemical vapour deposition enable conformal quantum dot integration in complex three-dimensional structures [64,65].

Emerging Applications and Future Directions

Flexible and wearable electronics

The mechanical flexibility and solution processability of quantum dot materials enable integration into flexible and stretchable substrates. Demonstrations include flexible displays, conformable photodetectors, and wearable sensors with performance approaching rigid device counterparts [66,67]. Encapsulation strategies that protect against moisture and oxygen while maintaining flexibility represent critical enabling technologies [68].

Bio-imaging and medical applications

Quantum dots offer unique advantages for biological imaging, including photostability, narrow emission, and multiplexing capabilities. Surface functionalization enables specific targeting of cells and biomolecules, while near-infrared-emitting quantum dots facilitate deep-tissue imaging [69,70]. Clinical translation requires addressing toxicity concerns and developing biocompatible quantum dot formulations [71].

Quantum computing and communication

Single quantum dots function as solid-state quantum emitters for quantum information applications. Demonstrations include single-photon sources, entangled photon pair generation, and spin-photon interfaces for quantum networks. Deterministic positioning and high collection efficiency remain key challenges [72-74]. Integration with photonic cavities and waveguides enhances light-matter coupling for scalable quantum photonic circuits [75].

Challenges and Limitations

Stability and degradation mechanisms

Long-term operational stability under realistic conditions remains a primary challenge for quantum dot devices. Photochemical degradation, oxidation, ligand desorption, and ion migration can severely limit device lifetimes. Understanding degradation mechanisms through accelerated ageing studies and *in situ* characterisation guides the development of stabilisation strategies. Barrier layers, encapsulation materials, and device architecture optimisation all contribute to improved stability [76,77].

Scalability and manufacturing considerations

Transitioning from laboratory synthesis to industrial-scale production requires maintaining strict quality control while reducing costs. Batch-to-batch variations, continuous flow synthesis methods, and automated

characterisation systems represent active areas of development (as shown in Figure 6 below). Manufacturing yield optimisation and defect management become increasingly important as

devices approach commercialisation [78,79]. Table 6 highlights the manufacturing challenges and scalability factors for different quantum dot synthesis methods.

Table 6. Manufacturing challenges and scalability factors for different quantum dot synthesis methods [78,80]

Synthesis route	Scalability	Cost factor	Quality control	Waste generation	Energy requirement
Hot injection	Moderate	High	Excellent	Low	High
Continuous flow	High	Moderate	Good	Very low	Moderate
Microwave	High	Low	Good	Low	Low
Sonochemical	Moderate	Low	Moderate	Moderate	Moderate
Green synthesis	High	Very low	Moderate	Very low	Very low

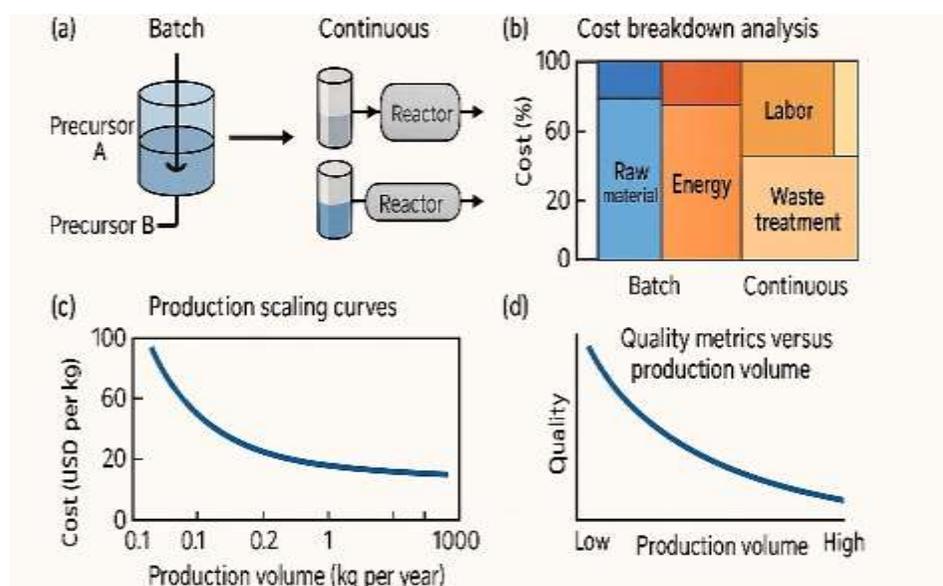


Figure 6. Process flow diagrams and cost analysis for quantum dot manufacturing. (a) Comparison of batch versus continuous flow synthesis processes showing reactor configurations and material flow. (b) Cost breakdown analysis for different synthesis routes, including raw materials, energy, labour, and waste treatment. (c) Production scaling curves showing economies of scale for kilogram-level manufacturing. (d) Quality metrics versus production volume trade-offs [78].

Environmental and regulatory concerns

The presence of heavy metals in many high-performance quantum dots raises environmental and regulatory concerns. Cadmium restrictions in consumer electronics have accelerated the development of cadmium-free alternatives, though performance gaps remain in certain applications. Lead-based quantum dots face similar regulatory scrutiny. Green synthesis methods, recycling strategies, and lifecycle assessment studies inform

sustainable development of quantum dot technologies [81,82].

Systems integration: coupling optoelectronics with energy storage

The realisation of high-efficiency quantum dot optoelectronic devices as practical energy solutions requires seamless integration with advanced energy storage systems. While QD-based solar cells and photodetectors excel at energy harvesting, the complete energy system must address generation, storage, and

utilisation as an integrated whole [83]. Recent advances in flexible and wearable energy storage devices, including thin-film batteries, micro supercapacitors, and hybrid systems, present complementary technologies that share similar form-factor requirements, mechanical properties, and manufacturing compatibility with quantum dot optoelectronics. The convergence of flexible QD photovoltaics with stretchable energy storage enables self-powered wearable systems for health monitoring, while the integration of QD-based sensors with distributed energy storage supports autonomous IoT networks in smart cities [83,84]. Critical research directions include developing unified architectures where QD light-harvesting layers are monolithically integrated with energy storage electrodes, optimising charge transfer interfaces, and engineering materials systems that maintain both optoelectronic performance and electrochemical stability. As both technologies mature, their synergistic integration will be essential for realising next-generation self-powered, sustainable electronic systems [84]. However, there are other significant issues, such as long-term stability, environmental footprint and manufacturability. The next step in the further evolution and implementation of quantum dot technologies will be the creation of materials resistant to degradation, sustainable synthesis processes, and low-cost production methods.

All signs are encouraging that the future of quantum dots and low-dimensional semiconductors is bright, with continuing research efforts aimed at both improving current limitations and investigating new uses and capabilities. Materials science, device physics, and manufacturing engineering may converge to further innovate in this fast-growing field and eventually usher in transformative technologies that can change the optoelectronics industry.

The integration of quantum dot optoelectronics into smart city infrastructures, renewable energy systems, and telecommunications networks demonstrates the far-reaching societal impact of this technology. By enabling efficient energy harvesting, sensitive environmental monitoring, and high-performance displays,

quantum dots serve as multifunctional platforms addressing global challenges from climate change mitigation to urban sustainability. The convergence of materials science breakthroughs, device engineering innovations, and systems-level integration strategies positions nano-engineered quantum dots as cornerstone technologies for building more sustainable, efficient, and intelligent urban environments [30,84].

Conclusion and Future Perspectives

The science of nano-engineered quantum dots and low-dimensional semiconductors has already attained an extraordinarily high level of maturity, with commercial applications that establish the feasibility of these materials in real-world optoelectronics uses. The basic knowledge of quantum confinement effects, combined with advanced synthesis and processing methods, has produced quantum dots that possess near-optimal optical characteristics as well as enhanced device functionality in an array of applications.

Further improvements in the performance and variety of applications of quantum dot technologies are assured by the continued growth in new material compositions and heterostructure designs. Specifically, perovskite quantum dots offer interesting prospects to affordable, high-performance devices, while 2D materials and van der Waals heterostructures provide new opportunities to design band structures and new architectures.

The next wave of innovation in this direction is expected to be the integration of quantum dots with other emerging technologies, including artificial intelligence, the Internet of Things, and quantum computing. Another promising area of future research is the creation of smart quantum dots that have the ability to change their properties depending on environmental conditions or the nature of their applications.

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Conflict of Interest

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