International Science and Technology Journal
المجلة الدولية للعلوم والتقنية

Volume 37 العدد
Part 1 المجلد

http://www.doi.org/10.62341/trzj3390

Received	2025/09/05	تم استلام الورقة العلمية في
Accepted	2025/09/28	تم قبول الورقة العلمية في
Published	2025/09/30	تم نشر الورقة العلمية في

Advances in Quantum Dot Solar Cells: Materials Innovation, Device Engineering, and Performance Evolution

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Abstract
Quantum Dot Solar Cells (QDSCs) represent an advanced class of photovoltaic devices that utilize quantum dots as their primary photoactive materials. Their unique ability to tune the bandgap enables broad-spectrum light absorption, forming the foundation for multi-junction architectures capable of surpassing traditional efficiency limits. Recent developments have achieved power conversion efficiencies up to 18.1%, with theoretical potential reaching 66%. Despite these impressive milestones, QDSCs still face significant challenges related to material toxicity and scalability in large-scale production. Current research is therefore focused on developing non-toxic quantum dot materials and hybrid designs that integrate QDSCs with emerging technologies such as perovskite systems to enhance both performance and operational stability. By combining cost-effective fabrication, tunable optoelectronic properties, and mechanical flexibility, QDSCs stand as a promising candidate for next-generation photovoltaic technologies poised to revolutionize the solar energy landscape.

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ISTJ

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Keywords: Quantum Dots; Solar Cells; Bandgap Tuning; Perovskites; Non-toxic Materials

التطورات في الخلايا الشمسية ذات النقاط الكمومية: ابتكارات المواد، هندسة الأجهزة، وتطور الأداء

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ملخص

تمثل الخلايا الشمسية ذات النقاط الكمومية (QDSCs) فئة متقدمة من الأجهزة الكهروضوئية التي تستخدم النقاط الكمومية كمواد أساسية نشطة ضوئيًا. تتيح قدرتها الفريدة على ضبط فجوة النطاق امتصاصًا واسع النطاق للضوء، مما يشكل أساسًا لهياكل متعددة الوصلات قادرة على تجاوز حدود الكفاءة التقليدية وقد حققت التطورات الحديثة كفاءة تحويل طاقة تصل إلى18.1% ، مع إمكانات نظرية تصل إلى .66% على الرغم من هذه الإنجازات المذهلة، لا تزال الخلايا الشمسية ذات النقاط الكمومية تواجه تحديات كبيرة تتعلق بسمية المواد وقابلية التوسع في الإنتاج واسع النطاق. لذلك، يركز البحث الحالي على تطوير مواد نقاط كمومية غير سامة وتصميمات هجينة تدمج الخلايا الشمسية ذات النقاط الكمومية مع التقنيات الناشئة مثل أنظمة البيروفسكايت لتحسين الأداء والاستقرار التشغيلي .من خلال الجمع بين التصنيع الفعال من حيث التكلفة، والخصائص البصرية الإلكترونية القابلة للضبط، والمرونة الميكانيكية، تُعتبر الخلايا

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الشمسية ذات النقاط الكمومية مرشحًا واعدًا للجيل القادم من تقنيات الطاقة الكهروضوئية، والتي من المتوقع أن تُحدث ثورة في مجال الطاقة الشمسية.

الكلمات المفتاحية :النقاط الكمومية؛ الخلايا الشمسية؛ ضبط فجوة النطاق؛ البيروفسكايت؛ المواد غير السامة.

Introduction

The global transition toward renewable energy places solar power at the forefront as a vital alternative to fossil fuels in achieving sustainable energy goals. Although conventional photovoltaic (PV) technologies have proven effective, they are constrained by efficiency limits, high material costs, and limited adaptability. Recent advances such as multi-junction solar cells achieving efficiencies of around 40% under concentrated sunlight, and bifacial panels delivering up to 30% higher energy yield illustrate the rapid evolution of solar technologies [1]. Ongoing efforts to achieve higher performance, cost-effective fabrication, and flexible device architecture continue to drive intensive research in materials science and solar cell design optimization [1].

Solar power technology gets its most significant advancement from quantum dot cells which utilize nanoscale semiconductor particles to address conventional cellular restrictions. The size tuning ability of quantum dots makes QDSCs suitable for different applications because the wider solar spectrum absorption extends from ultraviolet to infrared wavelengths. QDSCs outperform conventional cells because each photon can create multiple excitons rather than single electron-hole pairs which boosts their energy conversion efficiency towards three times beyond Shockley-Queisser theoretical limit [2]. The combination of inexpensive fabrication methods such as spin-coating together with scalable production methods lowers the manufacturing expenses for QDSCs beyond those of silicon-based cells. The development of organic perovskite quantum dots (PQDs) at 18.1% efficiency is possible through advanced ligand exchange techniques that solve stability and defect issues as shown in **figure 1** [3, 4].

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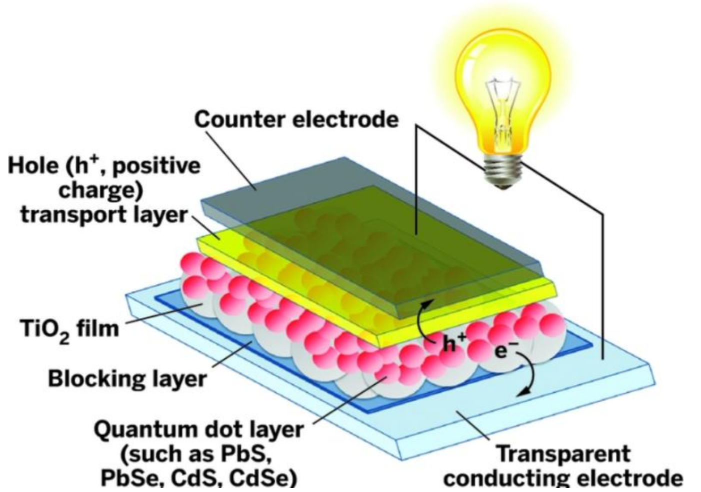

Figure 1. Anatomy of QDSC depicting different layers [3]

QDSCs represent a substantial solar power option because recent discoveries provide strong evidence for their commercial success as high-performance solar solutions. The analysis includes both multi-junction solar cell architecture designs as well as bifacial panels together with perovskite and organic PQD materials. The evaluation of emerging quantum dot materials follows their effects on power generation and stability performance as well as scalability potential. The review examines TBDQs for enhancing solar building elements through solar window usage and rooftop tile integration together with dual energy storage solutions. The proposed research should address stability challenges together with environmental concerns and commercialization restrictions to develop practical guidelines for upcoming scientific research. The review combines these findings to create a recommended path for both resolving existing solar technology challenges and speeding up the market adoption of future solar technology systems [1]. The QDSCs technology shows outstanding potential in photovoltaics because it delivers distinct benefits beyond typical solar cells. A short presents significant results and future perspectives about QDSCs for additional photovoltaic technology generations.
QDSCs function as advanced photovoltaic technology because they give solutions to traditional silicon-based solar cell restrictions. The cells implement quantum dots (QDs) as their light-absorbing core component that exploits quantum confinement effects for their specific optoelectronic properties [5]. Due to their nanometer-level dimensions of 2-10 nm quantum dots appear as semiconductor

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nanocrystals that exhibit quantum mechanical behavior [6]. Quantum confinement creates a set of advantageous features applicable to the system. Quantum dot bandgaps become adjustable for photon energy absorption through size modifications of QD structures. Solar cells with expanded spectrum absorption capabilities become possible through this feature. QD absorbents functions at high rates even with thin layer coverage because of their strong light absorption properties. Quantum dots show the ability to produce multiple exciton generation through single high-energy photon absorption which allows them to surpass the Shockley-Queisser limit [7].

Multiple solar cells utilize quantum dots as an integration component. A similar function to dye-sensitized solar cells (DSSCs) occurs when QDs work as light-absorbing sensitizer. The scaffold arrangement requires placement of QD materials onto mesoporous metal oxide such as TiO2 where the electrolyte solution with redox couple performs charge transport [8]. The bulk heterojunction formed through QD blending with organic polymers or other semiconductors enhances both charge separation and transport processes [9]. Semiconductor materials become more efficient because QDs introduce an intermediate bandgap through which sub-bandgap photons can be absorbed [10]. The creation of QD materials for solar cell production requires multiple types of materials, which include. PbS QDs have become popular for study since they feature strong photoabsorption properties in near-infrared wavelengths. These II-VI semiconductor QDs operate in the visible range with adjustable bandgaps in the visible region [11]. The optical qualities and non-toxic properties of CuInS2 QDs make them suitable for solar cell applications. Perovskite QDs represent materials with great potential for solar cell applications because they possess outstanding optoelectronic capabilities alongside user-friendly synthetic methods [12]. GQDs establish themselves as zero-dimensional carbon nanomaterial's, which possess distinct characteristics. The application of Si nanoparticles occurs in quantum dot-sensitized solar cells [7]. Rational control of precise size and shape and compound properties in QDs happens through colloidal synthesis processes. Ligand modification combined with surface engineering stands as essential for both protecting QD surface defects while boosting their solar cell stability and performance [13]. The implementation of QDSCs provides numerous important benefits above conventional solar cell

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technologies. A combination of adjustable bandgap and MEG properties in QDs presents pathways to outperform the Shockley-Queisser limit in solar cells. Mass production through solution-based synthesis allows the cost-effective production of QDs along with high manufacturing speed [14]. The capablity of QDSCs to function on flexible structures expands their application potential for flexible electronics and building-integrated photovoltaics systems. QDs have the unique ability to accept energy from a broad section of the solar spectrum which results in optimized light capturing [6]. Despite their promise, QDSCs still face several challenges. Perovskite QDs along with other QDs experience degradation due to environmental factors which diminishes their operational capability [15]. QDs containing lead and cadmium as elements pose environment-related threats because these materials prove toxic to ecosystems. QD layer and its electrode interface require better charge transport to achieve efficient operation [8]. The research-based efficiencies have shown progress but they remain behind the efficiency rates of both silicon cells and perovskite solar cell technology [16]. Future research directions include. Scientists need to advance QD technology toward stable and non-hazardous designs. Improving charge transport and collection [13]. Scientists investigate fresh arrangements of devices combined with new materials. Surface engineering and passivation approaches hold promise to enhance the performance capabilities of quantum dots according to research references [12]. The specifications of polymer solar cells benefit from metallic nanoparticles according to research findings [17]. Quantum dot solar cells need proper solutions to their problems to become an effective renewable energy technology that is both affordable and efficient [18]. The diagram in figure 2 illustrates how quantum dots deliver diverse and notable utilization throughout many technological fields in addition to scientific areas.

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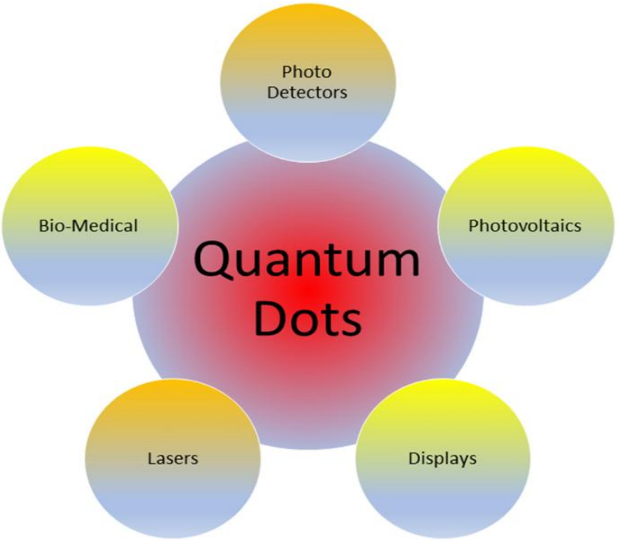

Figure 2. Applications of Quantum Dots[19]

QDSCs use quantum dot particles to make electricity from sunlight with a high rate of efficiency. With these quantum dots, we can achieve unusual benefits, including variable bandgaps, MEG and broad light absorption which theoretically allows an efficiency of 66% but is currently 18.1%. Their flexibility, light weight and low cost allow QDSCs to be used in wearable electronics and systems that use solar panels in buildings. Although there is much potential for them, these materials can be harmful to the environment, may rust and become brittle with moisture or heat and are difficult to manufacture in large quantities. Now, researchers are combining perovskites, making core-shell designs, improving surface passivation and using AI to boost both efficiency and toughness. Because of new advances in safe and sustainable materials, smarter structures and mass manufacturing, QDSCs could become a top choice in the market for solar energy.

1. Fundamentals of Quantum Dot Solar Cells

QDSCs present an evolutionary photovoltaics solution which uses nanometer-scale semiconductor particles to make solar energy transformation more efficient. The three areas of innovation in QDSCs reverse significant weak points within conventional solar technologies through quantum effects with adjustable properties and advanced design capabilities. The standard QDSC design follows an optimally designed layered structure which supports efficient light absorption while enabling proper charge transport. The structure

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functions both as a support element and light-entry channel. Acts as a transparent conductive electrode. TEM evidence shows that PEDOT: PSS is commonly used as such electrodes because they inhibit electron recombination. The compound of cadmium selenide (CdSe) or lead sulfide (PbS) exists within a P3HT polymer matrix which functions as photon absorber. Collects electrons to complete the circuit [20]. QDSCs function in a four-step process where quantum dots absorb multiple wavelengths because of their adjustable bandgap properties. A photon entering the system produces electron-hole pairs known as excitons and enables multiple photon-generated excitons through multiple exciton generation (MEG). Inner electric voltages split electron-hole pairs from one another. The external circuit allows electron movement and holes migrate toward the anode. The spatial restrictions created by quantum confinement improve energy conversion efficiency in respect to bulk materials [21, 22]. Their bandgap adjusts according to size and enables them to harvest ivory and ultraviolet wavelengths of sunlight which delivers 30% additional energy relative to silicon bands [23]. Through MEG process one photon at high energy level transforms into 2 to 3 electron-hole pairs to achieve possible efficiencies greater than 66% [24]. Electron energy retention benefits through delayed thermal processes in the conversion process. Unsupported theoretical computations show that the QD bandgap energy exhibits an opposite relationship to the quantum dot size (direct correlation) hence smaller $CuInS_2$ QDs with 2.7 – 6.1 nm dimensions demonstrate noticeable energy shifts [25]. The nanoparticle diameter serves as a parameter to achieve specific spectral responsibilities. When electrons experience increased interactions as a result of quantum confinement a single photon can produce multiple pairs of charge carriers. Experimental cells delivered up to 35% better photocurrent performance when applying the technology. The synthesis process using wet chemistry enables QD production followed by ink deposition for single-step low-cost roll-to-roll industrial production. Quantum dots obtain 10-100 times higher light absorption capability than ordinary bulk semiconductors when considering unit mass [26, 27].
Computer modeling shows that optimized tandem MEG cells have the potential to reach a solar cell efficiency of over 66% while current QDSC implementations in laboratories reach >18% efficiency. The technology stands out as a front-running option for photovoltaic innovations thanks to its adjustable optics properties

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and affordable production approach although scalability and stability issues need resolution [2].

2. Working of Quantum dot solar cell

The photovoltaic sector shows great promise through Quantum dot solar cells (QDSCs) since they bring benefits beyond silicon-based solar cells. The exclusive optoelectronic characteristics of quantum dots (QDs) create two benefits through quantum confinement bandgap tunability and efficient multiple exciton generation [28]. An explanation regarding QDSC operation follows below. QDs act as the primary light-absorbing material in QDSCs. A QD creates an exciton when it absorbs a photon having energy greater than or equal to its bandgap energy. The binding of an electron with a hole produces an exciton which functions as an excited state within the QD. QD bandgap tunability based on size generates broad light absorption which leads to improved cell efficiency [29]. The succeeding stage requires separate and transference of exciton-generated electrons and holes toward their dedicated electrodes [30]. The cell requires the creation of charge separation to produce a photocurrent. Various mechanisms enable charge separation within QDSC devices. Direct electron transfer from the QD occurs into the electron-transporting material (ETM) which includes TiO2 or ZnO. The transfer of holes takes place to hole-transporting materials (HTM) according to the literature [31]. QD-based cell efficiency can be increased by using non-radiative energy transfer to move energy between QDs and semiconductor nanostructures. The process of constructing cells with powerful electric fields in their active regions facilitates electron-hole pair separation.

Transit layers transfer separated electrons and holes from their source to reach the electrodes. The transport of charges needs to be efficient enough to prevent recombination losses and boost the photocurrent production. The quantum dot-sensitized solar cell (QDSSC) stands as one main architecture design for QDSCs. The quantum dots in QDSSC devices are usually applied on top of TiO2 mesoporous oxide surfaces. The steps are as follows. After photon absorption QDs create pairs of electrons and holes. The TiO2 material accepts electrons that enter its conduction band [32]. The TiO2 network allows electron transfer to the FTO transparent conducting electrode as shown in figure 3.

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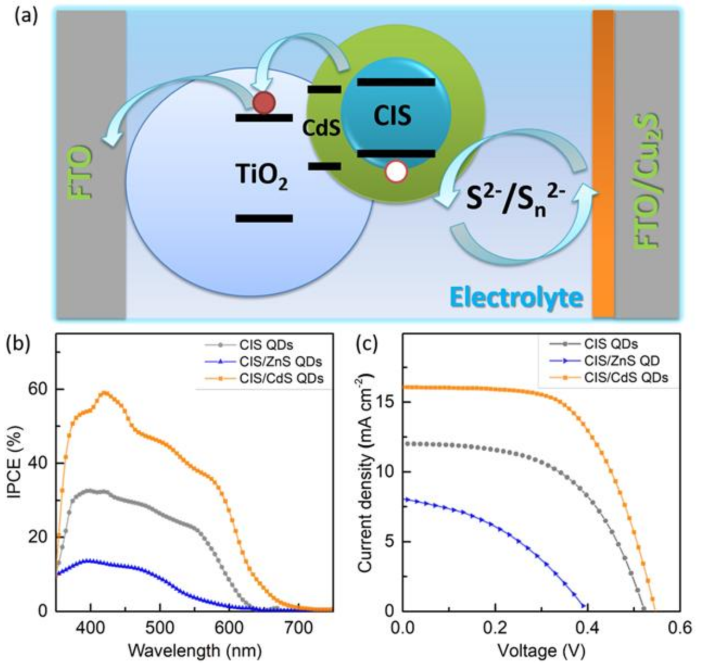

Figure 3. a) Schematic illustration of structures and the electronic processes of the QDSSCs assembled using CIS/CdS core/shell QDs, b) IPCE spectra and c) Current density versus voltage of the fabricated QDSSCs assembled using CIS QDs and CIS/XS (X=Zn, Cd) core/shell QDs under simulated AM 1.5 Sunlight [33]

Holes find their scavenging path through a redox electrolyte (for instance polysulfide). The electrolyte participates in two processes: first by restoring QD functions with electrons then transferring the resulting oxidized electrolyte to the counter electrode. Reduction of oxidized electrolyte takes place at the counter electrode which completes the electronic flow [19]. Multiple variables control the working efficiency of QDSCs. These determine the bandgap and absorption spectrum of the QDs. The existence of surface imperfections on QDs results in recombination losses. Efficiencies of QD-based photovoltaic systems can increase through surface passivation techniques which include using inorganic coatings together with ligand exchange operations. HTM combined with ETM determines how effectively solar cell charges can be collected. Fabry-Perot resonators function as light-trapping elements that maximize solar cell absorption potential in their active area [33]. The amount of QD deposition on top of the TiO2 film serves to boost both light absorption and charge formation abilities [34]. Solar cells based on Perovskite quantum dots (PQDs) stand out as

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prospective materials because they show high defect tolerance besides extended exciton lifetimes and adjustable characteristics. The optoelectronic properties and phase stability of PQDs have been upgraded through studies in surface stress engineering. Researchers use QDs together with perovskites or organic polymers to produce hybrid solar cells according to literature [35]. The addition of graphene quantum dots (GQDs) across different solar cell layers enhances the process of solar energy conversion [36].

Current QDSC efficiency levels remain behind traditional solar cell performance metrics [37]. Exposure to moisture combined with oxygen leads QDs to become sensitive to their environment. Research shows that QDs which incorporate cadmium and lead components create environmental concerns because these toxic elements require special attention [38]. Research investigating QD materials must concentrate on discovery of improved stable QD compositions as well as seeking better device designs and alternative charge carriers [28].

3. PV Generations

PV generation technologies have undergone major advancements throughout history since they began important contributions to electricity generation systems. This evolution encompasses different generations of solar cells, each with its own materials, techniques, and levels of efficiency. QDSCs demonstrate great potential as a breakthrough in modern solar cell development [39]. PV technology development follows multiple generations based on different time periods. Solar cell technology uses crystalline silicon (Si) as its base material since this material dominates the photovoltaic industry. The PV industry relies on monocrystalline as well as multi crystalline silicon cells for its operations. Due to their superior performance capabilities monocrystalline silicon cells cost more to manufacture than other types. The production costs of multi crystalline silicon cells remain lower than their performance capacity [40]. Two thin-film solar cells based on CdTe and CIGS materials operate within this generation. Thin-film cells provide reduced production expenses and adjustable characteristics which make them ideal for multiple application areas. Each of the emerging technologies from this generation includes dye-sensitized solar cells (DSSCs), organic solar cells (OSCs), perovskite solar cells and quantum dot solar cells (QDSCs). The goal behind these technologies is to establish efficient systems at reduced prices while

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enabling solar cells that maintain flexibility and transparency [41]. The emerging advanced solar cells incorporate solar materials comprising 2D materials together with quantum dots along with perovskites and organic materials and dye-sensitized solar cells [19]. These leverage exceptional electronic properties for enhanced performance.

Photovoltaic cells create electricity from sunlight through the photovoltaic effect. Solar cell semiconductor materials generate an electric current through electron excitation triggered by sunlight photon energy. Solar cell conversion efficiency depends both on technological factors and external weather elements. Solar irradiance and temperature and shading create substantial impact on the operational effectiveness of PV systems [42]. Different deployment methods of PV systems become possible. Solar systems send power straight to the power grid which increases the total electrical production [43]. These systems deliver electricity to off-grid areas through storage capabilities of batteries for upcoming power needs [44]. The systems incorporate solar cells throughout materials that build structures and unite electricity generation with structural capabilities [45]. QDSCs represent a third-generation solar technology which outperforms traditional cells through multiple benefits. Quantum dots (QDs) display quantum mechanical behavior because they are semiconductor nanocrystals which allows size variations to tune their bandgaps and achieve high light absorption efficiency [46]. The bandgap of QDs stays adjustable through size adjustments which enables effective solar spectrum absorption [39]. QDSCs show promising results for surpassing the fundamental efficiencies established by the Shockley-Queisser limit in traditional solar cell technology. Solution-based methods allow for the synthesis of QDs while being potentially more affordable than standard semiconductor manufacturing processes [47]. Integrated QDSCs offer flexibility for these devices which paves new possibilities in solar energy generation. Silicon solar cells maintain their status as well-established high-performance devices but these benefits come with high cost and rigid construction. The quantum dot solar cells serve as an appealing affordable and lightweight alternative solution [48]. The prices of CdTe and CIGS solar cells lie below those of silicon but demonstrate lower efficiency rates and utilize toxic materials. The prospective cost effectiveness of QDSCs comes with superior environmental performance [49]. The efficiency of perovskite solar cells

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experienced significant growth during recent years which caused scientists to view them as potent silicon substitutes [50]. The cells present stability challenges mainly when operating within humid climate zones. Research is being conducted on perovskite quantum dots as QDSCs to unite the strengths of both silicon solar cells and perovskite solar cells.

The popularity of QDSCs encounters obstacles which researchers must overcome. The efficiency levels demonstrated by QDSCs remain lower than those achieved by traditional silicon solar cells as well as several thin-film technologies. More scientific investigation is required to enhance light absorption and charge movement and collection in QDSCs [51]. The performance stability of quantum dots is reduced because they react negatively to atmospheric influences including moisture and oxygen exposure. Mandatory development of effective encapsulation techniques along with stable quantum dot materials constitutes an essential necessity. The environmental challenges stem from toxic materials including cadmium and lead that exist within certain QDs. The current research aims to create new QD materials which are less toxic by developing zinc oxide and copper indium sulfide [52].

Various techniques to boost QDSC operation performance have been studied recently. The surface modification of QDs creates two benefits by decreasing defects and enhancing charge conduction. The replacement of organic ligands on QDs with inorganic ligands enables better electronic connection between QDs [50]. Light-trapping structures ought to be included for maximizing light absorption within the QD layer. Solar cells gain enhanced performance when QD technology combines with perovskites and graphene materials [53]. The field of PV generation has experienced substantial progress as QDSCs have been identified as an appealing technology for future power generation applications. Ongoing developmental research brings QDSCs closer to becoming competitively viable sustainable energy technology [54].

4. Architectures of Quantum Dot Solar Cells

The architectural designs of QDSCs are diverse because they serve to enhance light absorption and charge separation along with carrier collection. This section evaluates principal QDSC arrangements together with their fundamental components and working principles. Mercury sulfite (PbS or CdSe/ZnS) quantum dots receive direct application onto aluminum or gold metal cathodes [55]. No

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additional semiconductor layers; relies on the Schottky barrier at the QD-metal interface. The QD material forms electron-hole pairs when photons strike the structure. A built-in electric field across the metal-QD junction leads electrons to the cathode and holes to migrate to a transparent conductive oxide anode [55]. Simplified fabrication, low-cost processing, and suitability for flexible substrates. The scaffold configuration uses a mesoporous oxide substance such as TiO_2 or ZnO which supports QD layers including CdS and CdSe. A solid-state electrolyte known as spiro-OMeTAD builds up the electrical circuit together with the electrolyte. QDs absorb light, creating excitons. The oxide scaffold accepts electrons at the same time the electrolyte/hole transporter obtains holes. External circuit collects charges, generating current [56]. Table 1 shows the comparison of QDSSCs and DSSCs.

Table 1: Comparison of QDSSCs and DSSCs

Feature	QDSSCs	DSSCs (Dye-Sensitized)
Light Absorber	Quantum dots (tunable bandgap)	Organic dyes (fixed bandgap)
Efficiency	Up to 13.4%	~12%
MEG Utilization	Yes (enhanced current)	No

The interpenetrating structure developed by QD (e.g., PbS, CdTe) with polymer (e.g., P3HT). Application between the Transparent Conductive Oxide anode and metallic cathode components. The incoming photons lead to exciton activity simultaneously in QD and polymer structures. Photons generate excitons in QD-polymer interfaces where separation between electrons and holes occurs. Electron flow occurs through QDs although hole transport uses the polymer networks. High absorbance from quantum dots and flexible behavior of polymers allow solution-processing for economical manufacturing. The optically resonant system of PbS QD heterojunctions reached 19.5% improved absorption with the addition of nanopillar arrays [57, 58]. Solar cells based on silicon Indirect Back Junction and QD material layers operate together as an integrated system. Example: $CdSe_{1-x}S_x$/ZnS QDs on silicon with AlO_x passivation. QDs transfer energy to silicon via near-field interactions. QDs break up powerful UV photons for photons of lower visible light frequencies which minimizes heat dissipation. By adding QD layers to solar devices light reflection decreases thus enhancing broadband absorption of photons. Hybrid IBC cells

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achieved a 39.5% enhancement in short-circuit current and delivered a 40% increase in PCE performance according to research findings [59]. Table 2 depicts the efficiency, challenges and key strength of Schottky, QDSSCs, bulk heterojunction and hybrid solar cells

Table 2: The efficiency, challenges and key strength of Schottky, QDSSCs, bulk heterojunction and hybrid solar cells

Architecture	Efficiency Range	Key Strength	Challenge
Schottky	5–8%	Simple structure	Low carrier mobility
QDSSCs	8–13.4%	Tunable absorption	Electrolyte stability
Bulk Heterojunction	6–10%	Solution-processable	Morphology control
Hybrid	Up to 18.1%	Synergy with existing PV tech	Interface engineering

QDs and photovoltaic materials used together in hybrid designs provide the current highest efficiency through their overlap of QD spectral properties and photovoltaic capabilities. QDSSCs outperform other designs in theoretical conversion because of MEG but their scalability depends on bulk heterojunction technology.

4.1. Materials Used in QDSCs

Solar cells built with quantum dots (QDSCs) use specific materials to enhance both absorptions of light and charge transport and device durability characteristics. The components are shown in table 3 [60].

Table 3: QDs serve as the core component in which composition together with dimensions define performance levels.

Material	Bandgap Range	Efficiency	Key Properties
PbS	0.4–1.5 eV	11.3%	Near-IR absorption, solution-processable, oleic acid ligands enhance stability
CdSe	1.7–2.7 eV	-	Visible spectrum tuning, high MEG potential
Sn:InP	~1.3 eV	3.54%	Eco-friendly, Sn doping improves band alignment

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Research on QDSCs predominantly investigates QDs because they absorb light from visible spectrum through infrared with dependent stability characteristics. QD cell performance remains stable through decreased interdot coupling after capping with oleic acid. The nontoxic doping method with Sn provides TiO_2 scaffolds superior charge injection which results in a 35% increase in efficiency relative to unmodified TiO_2 [60].

Table 4: Light-captured QD electrons can be extracted by Electron transport material (ETMs) through which recombination is minimization.

Material	Electron Mobility (cm^2/Vs)	Role	Performance Impact
TiO_2	0.1–4	Mesoporous scaffold for QD loading	Baseline for QDSSCs
ZnO	200–300	High-transparency layer	Hybrid TiO_2/ZnO boosts PCE to 18.24%
TiO_2/ZnO	-	Composite for enhanced alignment	Reduces recombination losses

The hybrid TiO_2/ZnO mesoporous structure creates better band matching between perovskite layers which results in higher electron injection rates according to literature as shown in **Table 4** [61].

Table 5: Through hole transport materials (HTMs) the extraction of holes becomes efficient while maintaining low interfacial energy losses.

Material	Hole Mobility (cm^2/Vs)	Key Feature	Efficiency Boost
Spiro-OMeTAD	2×10^{-4}	Energy-level matching with perovskites	Up to 23.14%
Graphene Oxide	-	Accelerates hole transfer 4.7×	13.84% PCE
PEDOT	10^{-3}–10^{-2}	Low-cost, flexible	2.79% PCE
Cu_2S	-	High catalytic activity	4.06% PCE

The high HOMO level of (−5.0 eV) in Spiro-OMeTAD matches perovskite valence bands so holes are efficiently extracted.

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Photocurrent efficiency gets improved through graphene oxide which minimizes charge recombination between QDs and electrolyte interfaces as shown in table 5 [62, 63]. Table 6 depicts the components, materials and functionality for charge collection and structural integrity:

Table 6: Critical for charge collection and structural integrity

Component	Material Examples	Functionality
Transparent Anode	ITO, FTO-coated glass	Conducts electrons, 85–90% transparency
Metal Cathode	Au, Al	High conductivity, Schottky barrier
Counter Electrode	C-Fabric/$WO_3^-{}_x$ composite	Synergistic catalysis, 4.6% PCE

The combination of carbon fabric with $WO_3^-{}_x$ counter electrodes leads to both low sheet resistance from C-Fabric and high catalytic activity of $WO_3^-{}_x$ and creates new record performance levels. Use of PDTPBT polymers on ITO anodes improves hole extraction in PbS QDSCs which results in a Voc increase of 15% [64]. The change of oleic acid to MPA during ligand exchange affects both inter-diet coupling performance as well as device operational stability. The high-temperature stability of Spiro-OMeTAD is improved by adding fluorinated graphene as an additive. Research in materials development leads QDSC efficiency levels toward their theoretical 66% limit through the use of both hybrid structures along with environmentally friendly QD materials like InP [63]. Figure 4 shows the schematic illustration of photo induced charge-transfer processes following a laser pulse excitation.

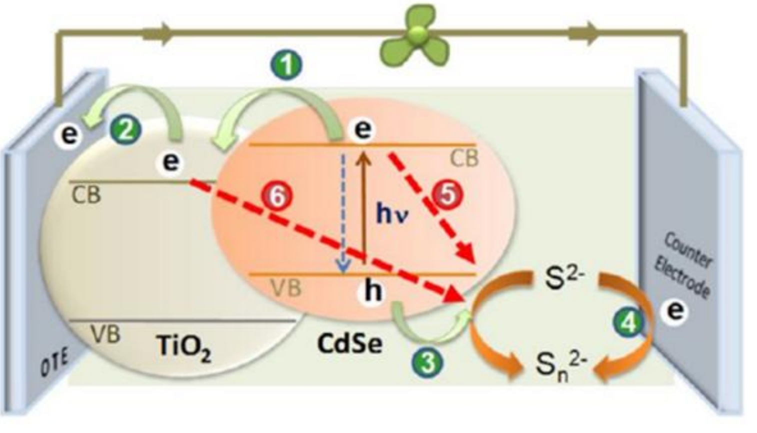

Figure 4. Schematic illustration of photo induced charge-transfer processes following a laser pulse excitation [3].

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5. Performance and efficiency of quantum dot solar cell

QDSCs serve as a potential solution among third-generation photovoltaic technologies because they function as an alternative to silicon-based solar cells. QDSCs work by using quantum dots as main light-absorbing components because their unique quantum confinement properties enable these functions. The light absorbing quantum dots exhibit three defining properties: bandgap tunability with high extinction coefficient and capability of creating multiple excitons [30]. QDSC performance and efficiency depend on three major elements namely materials selection, surface passivation methods and device structural design.

Laboratories have previously investigated QD solutions that contain no toxic heavy metals such as Pb or Cd. The implementation of effective surface passivation techniques on CIS QDs leads to the development of high-photovoltaic-quality CIS/ZnS core/shell structures improving solar cell efficiency. The high efficiency of all-inorganic $CsPbI_3$ perovskite QDs combined with their perovskite features enables them to receive substantial scientific interest. The photovoltaic performance can reach higher levels when $CsPbI_3$ PQDs undergo surface stress engineering for both enhanced optoelectronic properties and improved phase stability. PbS QDs serve as the primary material choice for QDSC devices. Surface passivation through the implementation of triple-cation perovskites produces superior photovoltaic outcomes than regular ligand passivation mechanisms do. Ag-doped CdS QDs created through SILAR have shown potential in photovoltaic cells using iodide/triiodide and polysulfide electrolytes when synthesized through the SILAR method. QD performance heavily relies on the existence of both surface defects as well as the ligand molecules. The process of surface engineering leads to major changes in optoelectronic behavior along with performance improvement of $CsPbX_3$ QDs [65]. Surface stress issues can be treated by implementing onium cations into surface lattice regularizations that enhance stability.

Type II QDs deliver enhanced Voc together with improved efficiency for QDSCs by benefiting from superior Auger recombination in such QDs. The combination of backside mirrors with thin-film QDSCs becomes more efficient due to resonances in FP intensity peaks between the QD layers thus improving near-infrared photon absorption [66]. Core shell nanowire array structures composed of perovskite materials and QDs enable

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extended light absorption throughout the spectrum which boosts solar cell performance. The production of electrodes with three-dimensional nanostructured characteristics yields substantial improvements in QDSSC functionality.
Researchers currently concentrate on different ways to enhance QDSCs. The use of alkyl ammonium iodides in ligand exchange methods has resulted in superior performance of organic-cation perovskite QD solar cells [29]. The application of perovskite materials to passivate PbS QDs leads to improved efficiency together with enhanced stability. The use of hydroiodic acid (HI) in $CsPbI_3$ perovskite QD production improves the photoluminescence quantum yield through better crystallinity and reduced defects which boosts solar cell efficiency levels. Quantum dot-sensitized solar cells (QDSSCs) have improved their efficiency to exceed 15% during recent years because researchers paid more attention to surface chemistry, quantum confinement and electron transport studies [67].
Quantum dot solar cells maintain progress but they still face present difficulties. QDSCs demonstrate theoretical power conversion efficiencies that reach 66% but their actual maximum efficiency remains lower than this value. Future investigations need to address this existing gap. The current performance level for quantum dot solar cells stands at 18.1% as of 2024 [8]. The stability of Perovskite solar cells which includes QD-based devices remains a challenge for researchers today. The improvement of moisture and heat resistance in perovskite solar cells depends on combined strategies like capping layers and size control modifications. The incorporation of lead-based QDs together with cadmium-based QDs creates environmental issues because these materials are toxic to the environment. Sustainable alternative quantum dots presently undergo research development [68]. Researchers must concentrate on surface passivation methods and ligand exchange techniques since these improvements help minimize defects while strengthening charge transport processes [33]. Scientists investigate innovative compositions of QD materials to enhance both light absorption and charge generation processes [69]. QD materials work together with perovskite and silicon photovoltaic technologies when used as components in tandem solar cells which develop both a larger absorption range and enhanced overall efficiency [70]. Researchers need to study QD optoelectronic behavior in applications with solar cells to achieve better device designs [71].

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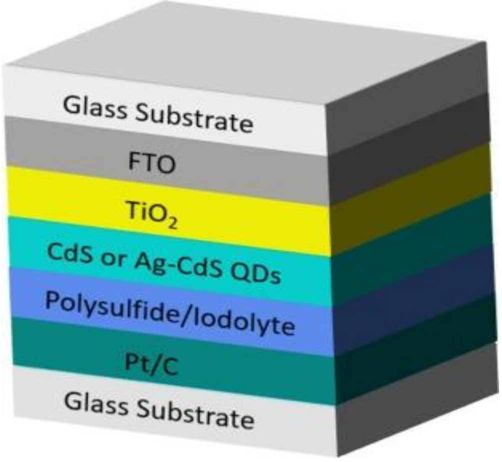

Figure 5. A multilayer device structure from cross-section represents an active thin-film technology like thin-film devices or quantum dot solar cells [9]

Figure 5 reveals the sequential placement of glass substrate, FTO, TiO_2, CdS or Ag-CdS QDs, polysulfide/iodolyte electrolyte and Pt/C counter electrode to show how device layers work together [9].

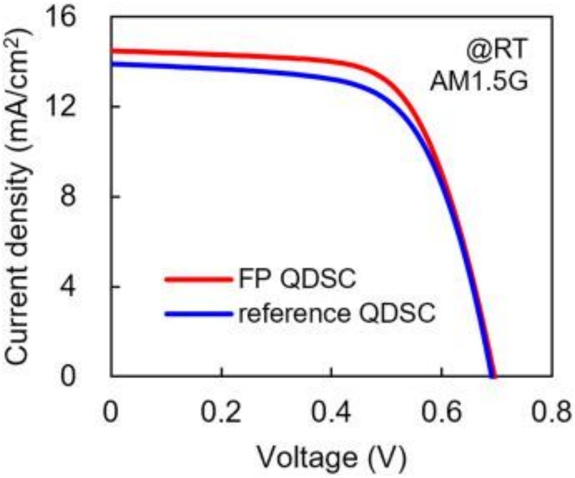

Figure 6. The current-voltage (I-V) characteristic curve graph in compares "FP QDSC" and "reference QDSC" under AM1.5G illumination [51]

The graphical presentation of **Figure 6** shows the electrical behavior of produced QDSCs through its display of light trapping effects on device performance [51].

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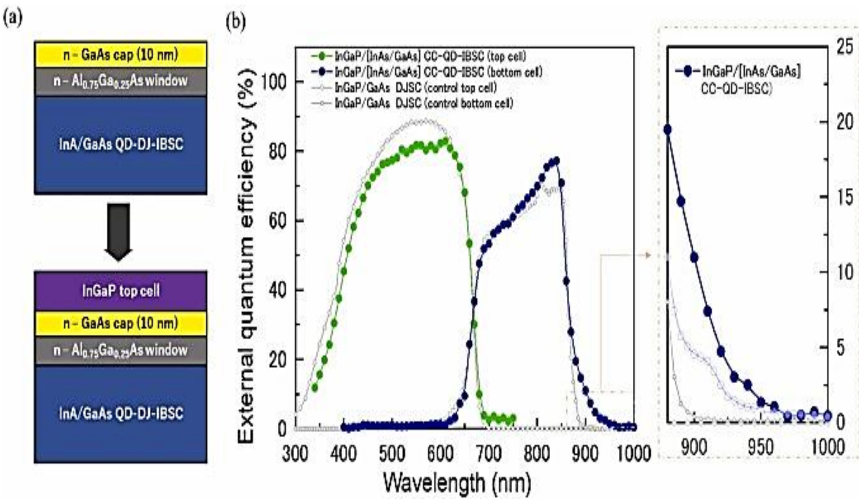

Figure 7. Detailed information about quantum-dot-based photovoltaic cell structure while performing an extensive analysis of their operational features relative to control cells which evaluates wavelength-dependent efficiency of QD-based devices and shows their improved EQE performance [11].

Quantum dot solar cells in figure 7 achieve their renewable energy technology potential as a low-cost high-efficiency solution by overcoming current challenges and pursuing specific research directions.

6. Efficiency Enhancements in QDSCs

The successful future utilization of quantum dots solar cells (QDSCs) depends heavily on boosting their efficiency rates. The enhancement of Power Conversion Efficiency (PCE) occurs through quantum dot loading optimization as well as plasmonic enhancements and ligand engineering and through multiple exciton generation (MEG) and hot carrier effects. The efficiency of light absorption and charge generation increases when more QDs are placed on the photoanode structure. Two methods for enhancing loading efficiency known as capping ligand-induced self-assembly (CLIS) together with secondary deposition have proven effective [72]. Research has shown that PCE performance increases when black phosphorus QDs are integrated with ZCISSe QD-sensitized TiO_2 [20]. Light absorption in PbS QDSCs increased to 11.0% through implementation of V-groove structures or compound parabolic trappers (VCPT) which decrease photon escape probabilities [73]. The integration of metal particles (such as Ag or

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Au) near QD layers enhances absorption through surface plasmon resonance (SPR) effects although this technique is more frequently used in different PV technologies. Device performance improves when researchers substitute native ligands with MPA while replacing oleic acid because this change enhances QD-photoanode charge transfer. Surface defects become less prominent after passivation making QD surfaces more stable and reducing non-radiative recombination thus increasing efficiency. Quantum dots have the ability to produce several excitons from solitary photons thus enabling photocurrent levels to surpass Shockley-Queisser limitations [74]. Efficient control of this phenomenon remains difficult to achieve. Hot carriers in QDSCs require energy preservation before thermalization to boost voltage output yet practical implementation remains complicated. Achieving environmental longevity for QDSCs and implementing large-scale manufacturing systems which maintain high efficiency represent critical barriers to overcome. The process of improving QD-transport layer interfaces remains crucial to cut down recombination while boosting charge transport efficiency [75]. The combined resolution of technical obstacles through quantum dot characteristics can turn QDSCs into highly efficient photovoltaic technology that exceeds conventional boundaries.

7. Stability and Degradation Mechanisms

The operational lifespan of QDSCs is reduced by both environmental elements and inherent material characteristics that negatively impact device durability. The fundamental comprehension of these degradation processes leads to better development of durability enhancement strategies. Lead-chalcogenide and lead-halide perovskites show sensitivity to oxidation as well as degradation under exposure to ambient air moisture and high temperatures [76]. The performance gradually declines over time when no protection is used. QD-based degradation occurs when they react with other cell layers. The band alignment of MoO_2 interfacial layers evolves over time which leads to degraded stability of the device [77]. QD stability depends heavily on the ligands chosen for the material. Ligands made from organic substances easily undergo oxidation whereas inorganic ligands such as iodide protect against air deterioration. Surface binding of both chemical entities results in QD deterioration. The process of degradation becomes quicker when humidity exists

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because water molecules tend to bind to a specific surface. The operational lifespan of QDSCs decreases when exposed to high illumination levels because it both induces thermal stress and causes light-based oxidation processes [78, 79].

Glass and polymer films function as environmental protection barriers for devices when applied as sealing materials. Engineering protective materials works efficiently yet introduces obstacles and expense to the system. Molecular coatings together with self-healing materials provide protection against oxidation by fixing QD surface defects [80]. The essential stability features of devices emerge from applying stable ligands and optimal thicknesses and low-reactivity materials selection. Standardized testing protocols that follow perovskite solar cell testing norms provide steady performance metrics for different devices across different conditions [81]. QDSCs require effective encapsulation methods and solutions to overcome stability issues that ensure their commercial success.

8. Recent Advances in QDSCs

The field of QDSCs shows substantial progress in producing materials while advancing device making and architectural improvements. Scientists have created new technologies which address power efficiency barriers while resolving problems with long-term stability and scaling up of operations. Core shell Quantum Dot solar cells (CSQDSCs) represent a promising technology platform because they provide adjustable bandgaps together with better charge carrier dynamics while enabling increased stability according to research by [82]. This core-shell design both fixes surface flaws and cuts down non-radiative recombination which leads to better efficiency outcomes [83]. Quests about material toxicity and scalability alongside long-term stability stop this technology from reaching commercial success. Scientists explore new lead-free materials as well as advanced passivation methods for current research. The utilization of multiple layers which unite quantum dot core-shell structures and silicon-based components or perovskite materials enables the broad spectrum quantum dot absorption while gaining the higher efficiency characteristics of additional materials. Such combination of approaches shows promise to outperform the efficiency capabilities of independent quantum dot solar units. Artificial intelligence and machine learning processes huge experimental and simulation data to determine the

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best material mixtures together with synthesizing methods and device architectures. Efficient device development along with enhanced operational capability occurs because of this advanced process [84]. QDSCs reach 18.1% efficiency as the highest record but theoretical models indicate 44.7% maximum efficiency through MEG properties[85]. QDSCs gain efficiency improvements when they operate in tandem with other solar cell technologies because they capture light through quantum dots across a wide range of wavelengths. Solar cell efficiency can surpass single-junction cells when quantum dots are integrated with other solar cell technologies through this approach. Advanced solar energy solutions will include the use of CSQDSC integrated with perovskite or silicon-based layers which presents a promising technology framework according to research findings [86, 87].
Quantum dot solar cells (QDSCs) constitute a major photovoltaic breakthrough that supplies new solutions to better traditional silicon-based solar cells [19]. Sunlight harvesting benefits from QD optoelectronic features that include bandgap adjustability and extra exciton production capabilities [33]. The fundamental parts make up the complete structure of QDSCs. The structure receives physical support because of this component. Different QDSC structures utilize glass together with flexible polymers or glass. The front electrode allows light passage with simultaneous electron collection and transportation functions. The two common TCO materials used for solar cells consist of fluorine-doped tin oxide (FTO) and indium tin oxide (ITO) [88]. Facilitates the transport of electrons from the QDs to the TCO. The high electron mobility of titanium dioxide (TiO_2) makes it the popular choice for solar cell applications because of its suitable energy level alignment [89]. The active light-absorbing material in the solar cell. The process of excitation in quantum dots creates electron-hole pairs through photon absorption. The active materials within solar cells utilize cadmium sulfide (CdS) together with cadmium selenide (CdSe) as well as lead sulfide (PbS) and copper indium gallium selenide (CIGSe) [17]. The QD material uses transport holes through its connection to the back electrode. Sprio-OMeTAD as well as PEDOT:PSS serve as widely used materials in this application. The hole collector serves as a finishing point of the electrical circuit. Depending on the application scientists choose between Au, Ag or Pt as metals for the absorber layers. The electrolyte system in quantum dot-sensitized solar cells (QDSSCs) enables both the movement of charges and QD recovery

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through mechanisms such as polysulfide or iodide/triiodide medium acts as the electrolyte [89]. The development of QDSCs has focused on stability and efficiency improvement using innovative materials and device systems. Key areas of advancement include lead halide perovskites alongside other PQD materials demonstrate great potential as photoactive materials because their combination of superior optoelectronic features accompanies basic fabrication protocols. The operational performance of PQDs for solar cells needs surface engineering techniques including ligand exchange to optimize functionality as shown in figure 8. Alkyl ammonium iodide-based ligand exchange methods produce CDs for PQDSCs that exhibit significantly improved efficiency than their traditional inorganic variations [90].

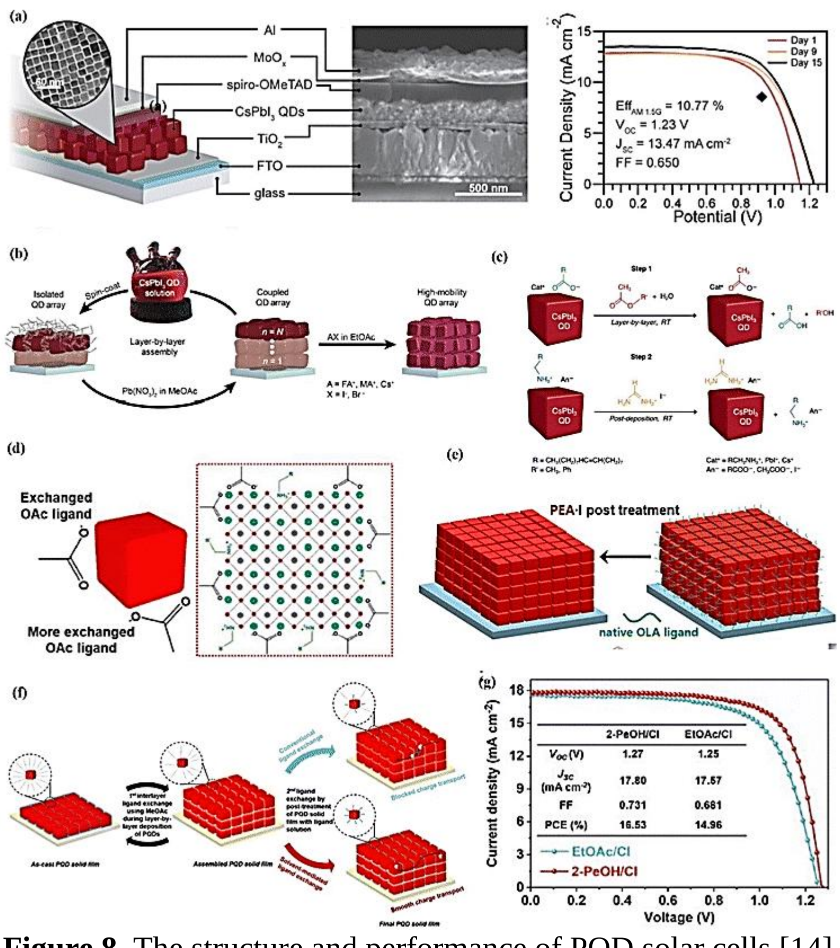

Figure 8. The structure and performance of PQD solar cells [14]

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Due to their zero-dimensional carbon nanomaterial design GQDs exhibit adjustable band gaps coupled with high conductive properties. Solar energy harvesting benefits from the addition of GQDs to different solar cell layers [88]. Semiconductor structures comprise of central nano-quantum dot materials which are enveloped by another semiconductor shell. Core-shell QDs offer enhanced stability features along with improved quantum yield capabilities in addition to decreased surface defects presence [91]. Surface modification of QDs using appropriate ligands and treatments enables reduction of non-radiative recombination phenomena and better charge transport functions. The attachment of diamines to tin atoms within mixed Sn-Pb perovskite thin films diminishes both oxidation processes and recombination frequencies which leads to increased stability. QDSSCs function as solar cells through the use of QDs as light absorbing sensitizers like typical dye-sensitized solar cells. The utilization of three-dimensional electrodes in QDSSCs leads to higher operational efficiency because it creates greater QD absorption sites and superior charge transport mechanisms [92]. The theoretical QD-IBSCs concept builds a framework to surpass standard single-gap solar cell limitations regarding efficiency.
The cells create an intermediate band through QD implementation within semiconductor materials to absorb photons that have energies below the bandgap. A layer comprised of perovskite quantum dot composite film acts as a luminescence downshifting (LDS) element that enhances the UV-blue spectral response of silicon solar cells to increase their power conversion efficiency[93]. Despite the significant progress, QDSCs still face challenges. Theoretical models demonstrate high efficiency but solar cell technologies using other methods maintain better actual efficiency levels. Scientists require additional research to perfect QD structural components and surface treatments alongside device structural designs [33]. Exposure to moisture and oxygen tends to deteriorate QD materials by causing degradation. Long-term stability of solar cells depends heavily on encapsulation and surface passivation techniques since they serve as fundamental stability enhancements [94]. Several QD materials include toxic compounds such as cadmium and lead. Search and development of environmentally friendly quantum dot alternatives represents a key requirement for sustainable solar cell technology development. Research in the field should focus on discovering new quantum dot materials along with advancing

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tandem solar cell device designs while enhancing quantum dot solar cell manufacturing stability and scalability [95].QDSC development pursues a vital role in solar power generation technologies as they progress into the future [96].

9. Challenges and Future Prospects

QDSCs require attention to multiple obstacles before becoming sustainable and commercially viable at a large scale. Due to their heavy metal composition of lead and cadmium many quantum dots present notable risks to the environment and human health. Scientists work to create lead-free and cadmium-free alternatives through perovskite quantum dots and carbon-based quantum dots and other non-toxic materials as reported in research literature [84]. The appropriate management of QDSC disposal along with recycling programs must be implemented because it prevents environmental dangers. A recycling system that can efficiently manage QD materials will reduce their environmental hazards. The current mass-production scaling of quantum dots suffers from limitations posed by spin-coating coupled with layer-by-layer deposition fabricating methods. Moving forward the commercial application requires the development of price-efficient scalable approaches which include roll-to-roll printing and inkjet printing systems [97]. The market capability of QDSCs is restricted by high precursor material prices alongside complex manufacturing processes which surpass silicon-based photovoltaic cell costs. The market entry of QDSCs will depend heavily on optimizing both their synthesis processes and manufacturing infrastructure to decrease production expenses. The fields of non-toxic alternatives are expanding through research on both perovskite quantum dots and carbon-based quantum dots [98]. The materials show potential to develop efficient sustainable devices. The integration of quantum dot with perovskite materials in tandem devices allows both technologies to benefit from their respective advantages toward producing higher efficiency than solitary QDSCs. The fusion of these approaches presents an effective solution to current performance restrictions and environmental problems [99]. Through data assessment AI speeds up development cycles by finding the best device construction and material combination patterns [100]. The employment of this approach would decrease experimental trial-and-error efforts coupled with their related timescales and expenses. QDSCs will become commercially viable green solar

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energy systems through the integration of emerging materials and technologies to solve their current difficulties [48].

Conclusion

Quantum Dot Solar Cells (QDSCs) exhibit exceptional promise as next-generation photovoltaic technologies, offering distinctive advantages that extend beyond conventional solar cells. Their tunable quantum confinement enables broad spectral absorption, hot-carrier extraction, and multiple exciton generation, allowing them to potentially surpass the Shockley-Queisser efficiency limit, with theoretical efficiencies approaching 66% and experimental records exceeding 18.1%. The ability to tailor the optical and electronic properties of quantum dots through size and composition engineering makes QDSCs strong contenders against multi-junction devices in terms of light-harvesting capability and power conversion potential. Current review is increasingly directed toward developing lead- and cadmium-free quantum dots, addressing environmental and health concerns while enhancing device stability through core shell architectures and perovskite-quantum dot hybrid systems. Low-temperature and solution-based fabrication methods further support cost-effective, scalable production, providing a sustainable alternative to conventional silicon-based photovoltaics. Despite persistent challenges related to large-scale manufacturing, long-term stability, and material toxicity, the synergistic integration of quantum dots with perovskites and tandem architecture offers a pathway toward higher performance and reliability. Environmentally benign QDSCs, supported by efficient recycling strategies, align with the global vision for green and circular energy technologies. Driven by rapid technological progress and growing demand for renewable energy, the QDSC market is projected to expand at an estimated annual rate of ~20% between 2032 and 2033. Their inherent flexibility and high efficiency under diverse lighting conditions make them attractive for wearable electronics, building-integrated photovoltaics, and automotive applications. Continued advances in materials science, interface engineering, and device architecture are expected to solidify QDSCs as frontline candidates in the future photovoltaic landscape, combining environmental sustainability with high performance and economic viability.

Data Availability

No primary research results, software or code have been included and no new data were generated or analyzed as part of this review.

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Conflicts of interest

There are no conflicts to declare.

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