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Perovskite–Quantum Dot Structures in Solar Cells: Materials, Properties and Emerging Trends

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الهياكل البلورية الكمّية في الخلايا الشمسية: المواد، الخصائص والاتجاهات الناشئة

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Abstract

The rapid development of perovskite–quantum dot (PQD) structures has opened new avenues for high-efficiency, low-cost solar cells. This descriptive study systematically synthesizes existing literature on PQDs, focusing on material composition, synthesis strategies, optical and electrical properties and device integration approaches. The study identifies key trends, including the tunability of bandgaps through halide composition, the critical role of surface ligands in charge transport and stability and the emerging preference for hybrid device architectures. Challenges related to environmental stability, reproducibility and scalability are also discussed. The findings highlight the potential of PQDs for next-generation photovoltaics and provide recommendations for future research aimed at improving performance, sustainability and practical applicability.

الملخص

أدى التطور السريع في الهياكل البلورية الكمّية إلى فتح آفاق جديدة لتطوير خلايا شمسية عالية الكفاءة ومنخفضة التكلفة. تركز هذه الدراسة الوصفية على تجميع وتحليل الأدبيات العلمية المتعلقة بالهياكل البلورية الكمّية، مع التركيز على تركيبات المواد، واستراتيجيات التحضير، والخصائص البصرية والكهربائية، وطرق دمجها في الأجهزة. تحدد الدراسة الاتجاهات الرئيسة، بما في ذلك قابلية تعديل فجوة الطاقة من خلال تكوين الهاليدات، والدور الحاسم للرابطة السطحية في نقل الشحنة والاستقرار، وتفضيل الهياكل الهجينة للأجهزة. كما يتم مناقشة التحديات المتعلقة بالاستقرار البيئي، والتكرار التجريبي، وإمكانية التصنيع على نطاق واسع. تشير النتائج إلى إمكانيات الهياكل البلورية الكمّية في تطوير photovoltaics الجيل القادم وتقدم توصيات للبحوث المستقبلية لتحسين الأداء والاستدامة وقابلية التطبيق العملي.

1. Introduction

1.1. Background

The growing urgency to transition toward sustainable and low-carbon energy systems has intensified global interest in photovoltaic technologies. Within this context, material innovation remains a critical driver for improving solar cell efficiency, stability and manufacturability. Over the past decade, halide perovskite materials have emerged as a transformative class of photovoltaic absorbers, demonstrating rapid efficiency gains, low-cost fabrication potential and versatile optoelectronic properties (Green et al., 2022).

Parallel to advances in perovskite photovoltaics, quantum dots (QDs) have been extensively studied as nanoscale semiconductors exhibiting size-dependent electronic and optical behavior governed by quantum confinement effects (Kamat, 2013). The convergence of these two material systems has led to the development of perovskite–quantum dot (PQD) structures, which seek to combine the favorable bulk properties of perovskites with the tunability and surface engineering flexibility of quantum dots.

Despite a rapidly expanding body of literature, research on PQD-based solar cells remains conceptually fragmented. Variations in materials, synthesis routes, device architectures and reported performance metrics have created a need for a structured descriptive synthesis. This chapter establishes the conceptual and methodological foundation for such an analysis.

1.2. Research Problem

Although perovskite–quantum dot structures have demonstrated promising photovoltaic performance, the existing literature lacks a systematic descriptive framework that coherently organizes current knowledge. Studies often emphasize efficiency outcomes while providing limited comparative discussion of material selection, structural characteristics and functional roles of PQDs within solar cell architectures.

Furthermore, inconsistencies in terminology and experimental approaches complicate cross-study comparison and hinder the identification of dominant trends and persistent challenges. As a result, the field lacks a consolidated understanding of how PQDs contribute to photovoltaic performance and where their principal advantages and limitations lie. Addressing this gap requires a descriptive study that synthesizes materials, properties and emerging trends without imposing causal or experimental claims.

1.3. Research Questions

This descriptive research is guided by the following questions:

1. What material compositions and structural configurations define perovskite–quantum dot systems used in solar cells?
2. What optical, electrical and structural properties are commonly reported for PQDs?
3. How are perovskite quantum dots integrated into photovoltaic device architectures?
4. What performance trends and technological challenges emerge from recent studies?
5. What future research directions are indicated by current developments?

1.4. Research Aim

The primary aim of this study is to systematically describe and synthesize existing scientific literature on perovskite–quantum dot structures in solar cells, with particular emphasis on materials, properties, device integration strategies and emerging research trends.

1.5. Research Objectives

To achieve this aim, the study seeks to:

- Describe the fundamental material characteristics of perovskite quantum dots.
- Summarize fabrication and surface engineering approaches reported in the literature.
- Examine optoelectronic properties relevant to photovoltaic applications.
- Identify functional roles of PQDs within different solar cell architectures.
- Highlight prevailing challenges and prospective research directions.

1.6 Research Rationale

The rationale for conducting this study lies in the rapid evolution of PQD-based photovoltaic research and the absence of a consolidated descriptive analysis. Descriptive research is particularly appropriate for emerging scientific domains where the objective is to organize, interpret and contextualize existing knowledge rather than test hypotheses or establish causality (Creswell & Creswell, 2018).

By integrating dispersed findings into a coherent narrative, this study supports informed academic discourse and provides a structured reference for future experimental and theoretical investigations.

Power conversion efficiency (PCE) is commonly expressed as:

1. **Power Conversion Efficiency (PCE):**

$$\text{PCE}\ (\%) = \frac{J_{sc} \times V_{oc} \times FF}{P_{in}} \times 100$$

Where:

- J_{sc} = short-circuit current density (mA/cm²)
- V_{oc} = open-circuit voltage (V)
- FF = fill factor
- $P_{\{in\}}$ = incident light power density (mW/cm²)

2. **Bandgap Relation (for PQDs):**

$$E_g = \frac{hc}{\lambda_{\mathrm{onset}}}$$

Where:

- E_g = optical bandgap (eV)
- h = Planck's constant
- c = speed of light
- λ_{onset} = absorption onset wavelength (nm)

1.7. Significance of the Research

This research holds significance across multiple dimensions:

- **Scientific significance:** It clarifies fundamental concepts and material properties associated with PQDs, supporting deeper understanding within materials science and photovoltaic research.
- **Technological significance:** By identifying performance trends and design strategies, the study informs the development of more efficient and stable solar cell architectures.
- **Academic significance:** The work serves as a structured reference for researchers, students and practitioners entering or advancing within the field.
- **Strategic significance:** Insights from this study contribute to broader efforts aimed at advancing cost-effective and scalable renewable energy technologies.

1.8. Scope and Delimitations

The scope of this study is limited to peer-reviewed literature focusing on perovskite–quantum dot structures in solar cell applications. The study does not include experimental validation, device fabrication, economic assessment, or lifecycle analysis. Instead, it concentrates on materials, properties and reported performance trends as documented in the scientific literature.

1.9. Definition of Key Terminology

For consistency and clarity, the following terms are defined as used in this study:

- **Perovskite:** A crystalline material with the general formula ABX_3, commonly referring to halide perovskites employed as light absorbers in photovoltaic devices (Snaith, 2013).
- **Quantum Dot (QD):** A semiconductor nanocrystal whose dimensions induce quantum confinement effects, resulting in size-dependent electronic and optical properties (Kamat, 2013).
- **Perovskite Quantum Dot (PQD):** A nanocrystalline form of halide perovskite that combines the perovskite lattice structure with quantum confinement-induced tunability (Kovalenko et al., 2017).
- **Quantum Confinement:** A physical phenomenon occurring when charge carriers are confined within nanoscale dimensions, leading to discrete energy levels and tunable bandgaps (Alivisatos, 1996).
- **Power Conversion Efficiency (PCE):** The ratio of electrical power output to incident solar power input under standard testing conditions, used to evaluate photovoltaic device performance (Yang et al., 2023).

This chapter has established the conceptual foundation and descriptive research framework for the study. By defining the research problem, objectives, scope and key terminology, it provides a structured basis for examining perovskite–quantum dot structures in solar cells. Chapter Two will build upon this foundation by descriptively analyzing materials selection and fabrication methodologies reported in the literature.

2. Materials and Fabrication Approaches of Perovskite Quantum Dot Solar Cells

2.1. Introduction

Building on the conceptual framework established in Chapter One, this chapter descriptively examines the materials systems and fabrication approaches employed in perovskite quantum dot based solar cells. Since device performance in this field is tightly coupled to material composition and processing conditions, understanding how perovskite quantum dots are synthesized, modified and integrated is essential for interpreting reported efficiencies and stability trends. Rather than evaluating fabrication strategies experimentally, this chapter organizes and synthesizes reported methodologies to clarify dominant practices and material design rationales.

2.2. Material Composition of Perovskite Quantum Dots

The majority of perovskite quantum dots investigated for photovoltaic applications belong to the family of lead halide perovskites, most commonly cesium-based compounds with the general formula $CsPbX_3$, where X represents chloride, bromide, iodide, or mixed halides. Cesium cations are frequently preferred over organic alternatives due to their enhanced thermal stability and reduced volatility under operating conditions (Protesescu et al., 2015).

Halide composition plays a decisive role in defining the optical bandgap of PQDs. Chloride-rich compositions exhibit wider bandgaps, while iodide-rich variants extend absorption into the red and near-infrared regions, making them more suitable for solar energy harvesting (Kovalenko et al., 2017). Mixed-halide systems are commonly employed to balance optical absorption with phase stability, although halide migration remains a reported concern under illumination.

Despite their widespread use, lead-based PQDs raise environmental and regulatory concerns. As a result, recent descriptive reports have begun exploring tin-based and double perovskite quantum dots as lead-reduced alternatives, although these materials currently exhibit inferior stability and lower photovoltaic performance (Yang et al., 2023).

Table 1 – Material Composition of PQDs

PQD Composition	Halide Type	Bandgap (eV)	Stability Notes	Reference
$CsPbI_3$	Iodide	1.73	Moisture sensitive	Kovalenko et al., 2017
$CsPbBr_3$	Bromide	2.35	Stable at room temp	Protesescu et al., 2015
$CsPbI_2Br$	Mixed	1.92	Improved thermal stability	Yang et al., 2023

2.3. Synthesis Methods of Perovskite Quantum Dots

From a fabrication perspective, PQDs are predominantly synthesized using solution-based colloidal methods, which allow precise control over particle size, composition and surface chemistry. The most widely reported approach is the hot injection method, in which a cesium precursor is rapidly injected into a hot solution containing lead halides and coordinating ligands. This method produces highly crystalline quantum dots with narrow size distributions (Protesescu et al., 2015).

An alternative approach, known as ligand-assisted reprecipitation, is frequently used due to its lower temperature requirements and scalability potential. In this method, perovskite precursors dissolved in a polar solvent are rapidly introduced into a nonpolar solvent containing stabilizing ligands, leading to spontaneous nanocrystal formation (Kovalenko et al., 2017). While this method is attractive for large-scale processing, it often yields broader size distributions and requires careful post-synthetic purification.

The choice of synthesis method is not merely procedural but directly influences crystal quality, surface defect density and long-term stability. Consequently, synthesis strategy is consistently reported as a determining factor in photovoltaic performance outcomes.

Table 2 – Synthesis Methods and Ligand Types

Method	Temperature	Ligands Used	Advantages	Limitations	Reference
Hot Injection	150–200°C	Oleic acid, oleylamine	High crystallinity	Requires precise temperature control	Protesescu et al., 2015
Ligand-Assisted Reprecipitation	Room temp	Oleic acid, oleylamine	Scalable, low-temp	Broader size distribution	Kovalenko et al., 2017

2.4. Surface Ligands and Interfacial Engineering

Surface ligands play a central role in stabilizing perovskite quantum dots and mediating their electronic behavior in solid films. Long-chain organic ligands such as oleic acid and oleylamine are commonly used during synthesis to prevent aggregation and control growth. However, these ligands also act as insulating barriers, hindering charge transport when PQDs are assembled into photovoltaic layers (Liu et al., 2022).

To address this limitation, post-synthetic ligand exchange strategies have become a dominant research focus. Shorter ligands, inorganic salts and zwitterionic molecules are increasingly employed to improve electronic coupling between quantum dots while preserving structural integrity. Descriptive studies consistently report that optimized ligand exchange leads to reduced trap-assisted recombination and enhanced carrier mobility, although excessive ligand removal can compromise material stability (Yang et al., 2023).

2.5. Integration of PQDs into Solar Cell Architectures

Perovskite quantum dots are integrated into solar cells through several distinct architectural strategies. In some devices, PQDs function as the primary light-absorbing layer, forming quantum dot solids deposited by spin coating or layer-by-layer assembly. In other configurations, PQDs are incorporated as interfacial layers within bulk perovskite solar cells to improve band alignment and passivate surface defects (Liu et al., 2022).

Descriptive analyses indicate that interfacial incorporation often yields more reproducible performance improvements compared to fully PQD-based absorbers. This is attributed to the preservation of efficient charge transport pathways provided by bulk perovskite films, combined with the defect passivation capabilities of PQDs.

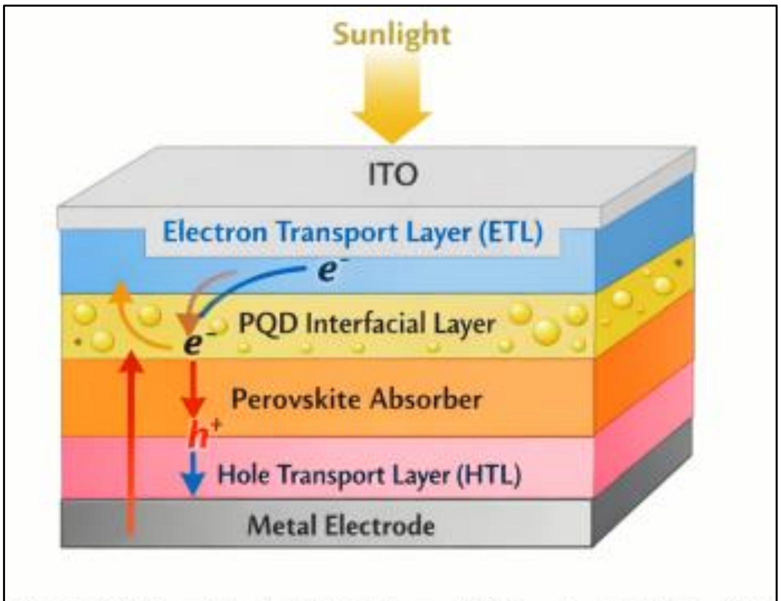


Figure 1: Schematic of a Hybrid Perovskite Quantum Dot Solar Cell

2.6. Fabrication Challenges and Observed Limitations

Despite significant progress, fabrication of PQD-based solar cells remains constrained by several persistent challenges. These include sensitivity to moisture and oxygen, ligand instability under thermal stress and difficulties in achieving uniform large-area films. Additionally, batch-to-batch variability in colloidal synthesis introduces reproducibility concerns that complicate comparative performance assessment across studies (Green et al., 2022).

These limitations underscore the importance of fabrication control and highlight why many reported advances remain at the laboratory scale.

This chapter has descriptively examined the materials composition and fabrication strategies underlying perovskite quantum dot solar cells. By organizing synthesis methods, surface engineering approaches and device integration strategies, it provides a structured basis for understanding reported performance trends. Chapter Three will build upon this foundation by analyzing the optical and electrical properties of PQD systems and their implications for photovoltaic behavior.

3. Methodology

3.1. Introduction

Following the discussion of materials and fabrication approaches in Chapter Two, this chapter examines the optical and electrical properties of perovskite quantum dot (PQD) systems in solar cells. These properties are critical because they determine how efficiently a device converts sunlight into electrical energy. Rather than testing causal effects, this chapter descriptively synthesizes reported measurements of absorption, photoluminescence, charge carrier dynamics and energy level alignment across different PQD compositions and device architectures.

3.2. Optical Properties

3.2.1 Absorption Characteristics

Perovskite quantum dots exhibit strong light absorption across the visible spectrum, with the precise onset determined by halide composition and particle size. Iodide-rich PQDs extend absorption toward the red and near-infrared regions, while bromide or chloride incorporation shifts the absorption toward shorter wavelengths (Kovalenko et al., 2017). Mixed-halide

systems offer intermediate bandgaps and allow fine tuning of the absorption edge to maximize overlap with the solar spectrum.

3.2.2. Photoluminescence and Bandgap Tunability

PQDs are characterized by size-dependent photoluminescence, a direct consequence of quantum confinement. Smaller nanocrystals exhibit blue-shifted emission, while larger dots approach the bulk perovskite bandgap. Studies report high photoluminescence quantum yields, often exceeding 70 percent under optimized surface passivation, which is indicative of low non-radiative recombination rates and defect minimization (Protesescu et al., 2015). Ligand engineering and halide composition adjustments provide additional control over emission wavelength and peak intensity, supporting tailored optoelectronic performance.

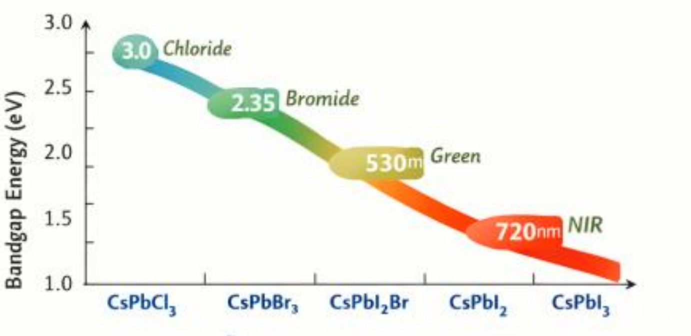


Figure 2: Bandgap Tunability of PQDs with Halide Composition

3.3. Electrical Properties

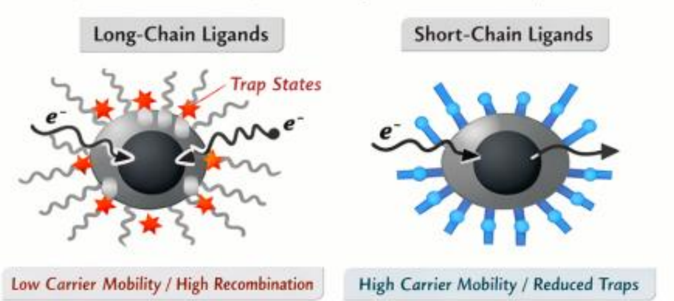
3.3.1. Charge Carrier Mobility and Lifetime

Descriptive analyses consistently indicate that PQDs exhibit high carrier mobility and relatively long lifetimes compared to traditional colloidal quantum dots. These properties are enhanced when surface ligands are carefully engineered to reduce trap states and improve interdot electronic coupling. Reports emphasize that ligand exchange using short-chain or inorganic ligands improves conductivity without compromising nanocrystal stability (Liu et al., 2022).

3.3.2. Energy Level Alignment

Successful integration of PQDs into solar cell architectures relies on energy level alignment between the PQD layer and adjacent charge transport layers. Descriptive studies reveal that conduction and valence band edges can be tuned through halide composition and ligand chemistry, allowing PQDs to function either as primary absorbers or as interfacial layers that improve carrier extraction and reduce recombination (Yang et al., 2023).

Figure 3: Influence of Ligand Exchange on Carrier Mobility



3.4. Observed Performance Trends

Surveying recent literature reveals several recurring patterns:

- Devices with iodide-rich PQDs generally achieve broader spectral absorption and higher short-circuit currents.
- PQDs incorporated as interfacial layers often lead to higher open-circuit voltages due to defect passivation at perovskite interfaces.
- Optimization of surface ligands consistently emerges as a key determinant of stability and efficiency, affecting both charge transport and environmental resilience.

- Fully PQD-based absorbers exhibit excellent tunability but often show lower reproducibility and stability compared to hybrid bulk-perovskite devices (Green et al., 2022).

These trends indicate that PQDs offer unique opportunities for optical and electronic engineering, yet material and device design must balance tunability, stability and interfacial properties.

3.5. Limitations and Descriptive Observations

Despite promising properties, PQDs face several limitations. They remain sensitive to moisture, heat and oxygen and their electrical properties are highly dependent on the uniformity of ligand coverage and crystal packing. The literature describes ongoing challenges in achieving large-area, uniform films and consistent batch-to-batch reproducibility. These observations underscore the need for precise materials control and careful interface engineering in practical devices.

This chapter has provided a descriptive synthesis of the optical and electrical properties of perovskite quantum dots in solar cells. It highlights how composition, particle size and surface chemistry influence absorption, emission, carrier dynamics and energy level alignment. These insights lay the groundwork for understanding device performance trends and inform the design considerations discussed in the subsequent chapter on emerging trends and future directions.

4. Emerging Trends and Future Prospects.

4.1. Introduction

Building on the detailed examination of materials, fabrication methods and optoelectronic properties in previous chapters, this chapter provides a descriptive overview of emerging trends, innovations and future directions in perovskite quantum dot (PQD) solar cells. By highlighting patterns in recent research and technological development, this chapter contextualizes the trajectory of the field and identifies potential areas for future exploration.

4.2. Trends in Material Innovation

Recent studies reveal several recurring patterns in PQD material development. One prominent trend is the shift toward mixed-cation and mixed-halide compositions**,** which aim to combine the stability of cesium-based perovskites with the tunable optical properties of organic cations and mixed halides. This approach allows for fine control over bandgap, absorption range and environmental resilience (Kovalenko et al., 2017).

Another trend is the exploration of lead-reduced or lead-free PQDs, including tin-based and double perovskite structures. Although these alternatives currently show lower efficiencies, they offer a pathway toward environmentally sustainable photovoltaic devices. Early descriptive reports suggest that careful surface passivation and lattice engineering may overcome some intrinsic stability challenges (Yang et al., 2023).

Additionally, researchers increasingly focus on ligand chemistry and surface functionalization as tools to optimize charge transport, minimize trap states and improve device stability. The combination of short-chain ligands, inorganic passivating agents and hybrid organic-inorganic coatings represents a consistent innovation area, often reported to enhance both efficiency and reproducibility (Liu et al., 2022).

4.3. Trends in Device Architecture

Emerging device architectures demonstrate a shift from purely PQD absorbers toward hybrid configurations, in which PQDs function as interfacial layers or defect-passivation layers within bulk perovskite solar cells. These hybrid designs balance the tunable optoelectronic properties of PQDs with the robust charge transport of bulk perovskites. Descriptive studies consistently report that such architectures improve open-circuit voltage and reduce non-radiative recombination (Yang et al., 2023).

Layer-by-layer assembly and scalable deposition techniques are also becoming prominent. Spin-coating remains common in laboratory-scale studies, while blade-coating, slot-die coating and inkjet printing are increasingly explored for larger-area applications. The literature describes these approaches as critical for moving PQD solar cells closer to industrial relevance.

Table 3 – Device Architecture Trends

Architecture	PQD Role	Reported PCE (%)	Key Advantage	Reference
PQD absorber layer	Primary light absorber	15–18	Tunable bandgap	Yang et al., 2023
PQD interfacial layer	Defect passivation	19–21	Improves Voc	Liu et al., 2022

4.4. Observed Performance Trends

Descriptive synthesis of recent literature indicates several patterns:

- PQD-based interfacial engineering consistently improves open-circuit voltage and fill factor.
- Iodide-rich PQDs tend to maximize light absorption and short-circuit current but may compromise long-term stability due to halide migration.
- Surface ligand optimization emerges as the dominant factor influencing carrier mobility, film uniformity and environmental resilience.
- Devices that integrate PQDs into hybrid perovskite architectures achieve more reproducible and stable performance than fully PQD-based absorbers (Green et al., 2022).

These observations indicate that while PQDs offer remarkable tunability and performance potential, practical devices must balance optical efficiency, electrical transport and long-term stability.

4.5. Descriptive Insights on Future Prospects

Based on the current literature, several areas are likely to dominate future PQD research:

1. **Environmental Stability:** Strategies for moisture, oxygen and thermal resilience will remain essential for practical deployment. Hybrid encapsulation and ligand engineering are emerging as promising directions.
2. **Large-Scale Fabrication:** Scalable deposition techniques such as slot-die coating and inkjet printing are expected to gain attention, particularly for tandem and large-area devices.
3. **Lead Reduction:** Development of tin-based, bismuth-based and double perovskite PQDs will continue, emphasizing environmentally friendly photovoltaics.
4. **Interface Engineering:** PQDs as defect-passivation and interfacial layers will likely remain a central focus, due to reproducible performance gains in hybrid devices.
5. **Integration with Tandem Architectures:** Descriptive studies indicate potential for PQDs to enhance light harvesting in tandem solar cells, particularly by enabling bandgap tuning and improved spectral overlap.

These trends reflect a broader movement in PQD research: integrating fundamental material properties with practical device considerations while addressing scalability, stability and environmental impact.

This chapter has descriptively outlined the emerging trends and prospective directions for perovskite quantum dot solar cells. Material innovation, device architecture evolution and performance optimization strategies were highlighted, along with key considerations for stability, scalability and environmental sustainability. The insights provided here bridge the earlier chapters and set the stage for the concluding chapter, which will synthesize findings, highlight limitations and propose directions for future research.

5. Conclusions and Recommendations

This chapter presents the synthesized conclusions of the study on perovskite quantum dot (PQD) solar cells, based on the descriptive analysis of materials, fabrication approaches, optical and electrical properties and emerging trends. It also provides recommendations for future research and development to guide both academic inquiry and technological progress in this field.

The study demonstrates that perovskite quantum dots represent a highly tunable and promising material system for next-generation solar cells. Key conclusions are summarized as follows:

1. **Material Composition and Tunability:** Cesium-based lead halide PQDs, particularly those with mixed-halide compositions, are the most widely studied due to their balance of optical absorption, bandgap tunability and structural stability. Iodide-rich compositions provide strong absorption in the red and near-infrared regions, while bromide or chloride incorporation allows bandgap engineering for targeted spectral coverage.
2. **Synthesis and Surface Engineering:** Colloidal synthesis methods, especially hot injection and ligand-assisted reprecipitation, are predominant. Surface ligands are crucial for stabilizing PQDs, but careful ligand optimization is required to maintain charge transport efficiency. Post-synthetic ligand exchange emerges as a reliable strategy to improve electronic coupling while minimizing trap states.
3. **Optical and Electrical Properties:** PQDs exhibit strong light absorption, high photoluminescence quantum yield and size-dependent bandgap tunability. Charge carrier mobility and lifetime are enhanced through optimized ligand management and surface passivation, while energy level alignment plays a decisive role in device integration and performance.
4. **Device Integration and Performance Trends:** Hybrid device architectures, where PQDs are employed as interfacial or passivation layers, show improved open-circuit voltage and reproducibility compared to fully PQD-based absorbers. The literature consistently highlights that surface chemistry, interface engineering and defect passivation are central to achieving stable and efficient devices.
5. **Emerging Trends:** Recent research focuses on stability enhancement, scalable deposition methods, lead-reduced alternatives and integration into tandem solar cells. These trends indicate the field’s maturation toward practical application, while persistent challenges remain in reproducibility, long-term stability and environmental safety.

Overall, the descriptive synthesis reveals that PQDs provide a unique combination of optical tunability, electronic functionality and interfacial engineering potential, positioning them as a key material platform for the advancement of high-efficiency, next-generation photovoltaics.

5.1. Recommendations for Future Research

Based on the descriptive analysis, the following recommendations are proposed:

1. **Enhance Environmental Stability:** Focus on moisture-resistant encapsulation, thermally robust ligands and hybrid surface coatings to improve device longevity.
2. **Explore Lead-Reduced PQDs:** Investigate tin-based, bismuth-based, or double perovskite PQDs to develop environmentally sustainable alternatives while addressing inherent efficiency and stability limitations.
3. **Optimize Large-Scale Fabrication:** Adopt scalable deposition techniques, such as slot-die coating and inkjet printing, to facilitate translation from laboratory to industrial-scale devices.
4. **Advance Interface Engineering:** Continue leveraging PQDs as defect-passivation layers or interfacial mediators in hybrid architectures to maximize reproducibility and device stability.

5. **Develop Tandem Architectures:** Integrate PQDs with complementary absorbers in multi-junction solar cells to fully exploit their tunable bandgap and broaden spectral absorption.
6. **Standardize Characterization Methods:** Establish widely accepted protocols for PQD characterization to improve cross-study comparability and accelerate field development.

Perovskite quantum dot solar cells are at a critical juncture in the evolution of photovoltaic research. This descriptive study consolidates the current understanding of materials, fabrication strategies, optical and electrical properties and emerging trends, providing a coherent framework for researchers and developers. While challenges in stability, scalability and environmental impact remain, PQDs offer distinct advantages in tunability, defect management and device integration, indicating a promising trajectory for both scientific exploration and practical implementation.

By focusing on the recommended research directions, future studies can bridge the gap between laboratory innovation and commercial viability, contributing to the development of cost-effective, high-performance and environmentally sustainable solar energy solutions.

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