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A Comprehensive Review of CdTe and PbSe-Based Photovoltaic Materials: Synthesis Strategies, Processing Techniques, and Performance Optimization

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Abstract

The increasing demand for sustainable and cost-effective energy solutions has intensified research into advanced photovoltaic materials beyond conventional silicon-based systems. Among emerging thin-film technologies, cadmium telluride (CdTe) has established itself as a commercially viable material, while lead selenide (PbSe) has gained attention for its unique optoelectronic properties and potential in next-generation photovoltaic applications. This review presents a comprehensive and critical analysis of CdTe and PbSe-based photovoltaic materials, focusing on their fundamental properties, synthesis techniques, processing strategies, and performance characteristics. The study highlights that CdTe exhibits a near-optimal bandgap, high absorption coefficient, and well-developed fabrication processes, enabling efficiencies exceeding 22% at the laboratory scale. In contrast, PbSe, particularly in quantum dot form, offers bandgap tunability and extended infrared absorption, with the potential for multiple exciton generation. However, its performance is currently limited by surface defects, charge transport constraints, and stability issues. A comparative evaluation reveals that while CdTe has reached a stage of performance optimization with incremental improvements, PbSe remains an emerging system requiring significant advancements in material engineering and device design. The review further emphasizes the critical role of synthesis and post-deposition processing, including doping, annealing, interface engineering, and defect passivation, in determining device efficiency and stability. Key challenges such as recombination losses, environmental concerns, and scalability limitations are discussed, along with future research directions. The integration of CdTe and PbSe in tandem and hybrid photovoltaic architectures is identified as a promising approach to enhance spectral utilization and surpass conventional efficiency limits. Overall, this review provides a comprehensive understanding of the current status, challenges, and future potential of CdTe and PbSe-based photovoltaic systems, offering valuable insights for the development of high-efficiency, stable, and sustainable solar energy technologies.

Introduction

The increasing global demand for sustainable and renewable energy has significantly accelerated research in photovoltaic (PV) technologies [1,2]. Conventional silicon-based solar cells have long dominated the PV market due to their high efficiency and technological maturity. However, their limitations, including high fabrication costs, energy-intensive manufacturing processes, and material constraints, have prompted the exploration of alternative semiconductor materials, particularly within thin-film photovoltaic technologies [3]. Thin-film solar cells offer advantages such as reduced material consumption, lower production costs, and compatibility with large-area fabrication [4]. Among these materials, cadmium telluride (CdTe) has emerged as one of the most successful and commercially viable thin-film photovoltaic technologies [5]. CdTe possesses a direct bandgap of approximately 1.45 eV, which closely matches the optimal value predicted for maximum solar energy conversion [6]. Its high absorption coefficient enables efficient light absorption within a few micrometers of thickness, making it highly suitable for cost-effective thin-film applications [7]. As a result, CdTe-based solar cells have achieved laboratory efficiencies exceeding 22%, demonstrating their strong potential for large-scale deployment [8]. In contrast, lead selenide (PbSe), a narrow bandgap IV–VI semiconductor, has attracted considerable attention due to its unique optoelectronic properties, particularly in the infrared region [9]. PbSe exhibits tunable bandgap characteristics in its nanostructured form, along with high carrier mobility and the potential for multiple exciton generation (MEG), which may enable efficiencies beyond the Shockley–Queisser limit [10,11]. These properties make PbSe a promising candidate for next-generation photovoltaic systems, including quantum dot and tandem solar cells [12]. However, PbSe-based technologies remain largely at the research stage, facing challenges related to stability, surface defects, and device integration [13]. The performance of CdTe and PbSe photovoltaic devices is strongly influenced by synthesis techniques, processing conditions, and microstructural properties. Various fabrication methods, including close-spaced sublimation, vapor transport deposition, electrodeposition, and solution-based techniques, have been employed to optimize film quality and device efficiency [14,15]. In addition, post-deposition processing strategies such as doping, annealing, and interface engineering play a critical role in enhancing carrier transport and minimizing recombination losses [16]. Despite significant progress, several challenges remain, including toxicity concerns, long-term stability issues, and limitations in scalable fabrication [17]. Furthermore, most existing studies focus on CdTe and PbSe independently, with limited efforts toward their comparative analysis or integration into hybrid photovoltaic systems [18]. Therefore, this review aims to provide a comprehensive and critical evaluation of CdTe and PbSe-based photovoltaic materials, focusing on synthesis methods, processing strategies, and performance optimization. The study also identifies key research gaps and outlines future directions for the development of high-efficiency and sustainable photovoltaic technologies.

Review of Literature

A substantial body of research has investigated CdTe and PbSe as promising semiconductor materials for photovoltaic applications, reflecting a clear transition from early material feasibility studies to advanced device-level optimization. The evolution of this field highlights a strong emphasis on improving efficiency, controlling defects, and enhancing long-term stability. The foundational work of Bonnet and Rabenhorst (1972) first demonstrated the viability of CdTe as an absorber material, reporting conversion efficiencies of approximately 6%, thereby establishing the basis for subsequent thin-film photovoltaic research. This early demonstration was followed by significant advancements by Ferekides et al. (1993), who optimized the CdS/CdTe heterojunction using close-spaced sublimation techniques. Their work highlighted the critical role of $CdCl_2$ activation treatment in promoting grain growth and reducing recombination losses, which remains a cornerstone in CdTe device fabrication. Further technological progress was reported by Green et al. (2015), who documented CdTe solar cell efficiencies exceeding 21%, emphasizing the importance of interface engineering and defect passivation in achieving high performance. In parallel, Burst et al. (2016) introduced group-V doping strategies, demonstrating improved carrier concentration and enhanced device efficiency. Subsequent investigations by McCandless and Sites (2017) provided deeper insights into defect physics, identifying grain boundary passivation as a key factor in minimizing non-radiative recombination and improving carrier lifetime. In contrast, research on PbSe has followed a different trajectory, primarily driven by developments in nanostructured and quantum dot-based systems. The seminal work of Murray et al. (1993) established reliable methods for synthesizing semiconductor nanocrystals, enabling size-dependent bandgap tunability through quantum confinement effects. Building on this foundation, Nozik (2002) introduced the concept of multiple exciton generation (MEG), which suggested the possibility of surpassing conventional efficiency limits in photovoltaic devices. Subsequent studies by Sargent et al. (2011) demonstrated the potential of solution-processed PbSe quantum dot solar cells, highlighting the importance of surface passivation and ligand engineering in improving charge transport. Kramer and Sargent (2014) further emphasized the role of interface engineering and energy level alignment in enhancing device efficiency. More recent work by Luther et al. (2016) identified surface chemistry as a critical limiting factor, showing that trap states and improper passivation significantly reduce carrier lifetime and overall device performance. Despite these advancements, a critical gap remains in the literature. Most studies treat CdTe and PbSe as independent material systems, with limited efforts toward their comparative evaluation or integration within a unified photovoltaic framework. In particular, research on hybrid or tandem architectures combining CdTe and PbSe is still underdeveloped. This lack of integrative analysis restricts the ability to fully exploit their complementary properties, especially in terms of spectral utilization and efficiency enhancement.

Review Methodology

The present study is based on a structured and systematic review of existing literature on CdTe and PbSe-based photovoltaic materials. Rather than conducting experimental work, this research critically synthesizes previously published findings to identify key developments, trends, and research gaps in the field. Relevant literature was collected from established academic databases, including Scopus, Web of Science, ScienceDirect, SpringerLink, and Google Scholar. These sources were selected to ensure access to high-quality, peer-reviewed research articles, review papers, and authoritative publications in materials science and photovoltaic technology. The search process was guided by specific keywords such as *"CdTe solar cells," "PbSe quantum dots," "thin-film photovoltaics," "photovoltaic efficiency,"* and *"semiconductor synthesis and processing."* Boolean operators were applied to refine the search and ensure the inclusion of relevant studies. The review primarily focuses on publications from 2000 to 2024, while also incorporating seminal earlier works to provide historical context. Inclusion criteria were defined to ensure the reliability and relevance of the selected studies. Only peer-reviewed journal articles and well-cited review papers directly related to the synthesis, processing, and performance of CdTe and PbSe materials were considered. Studies lacking clear experimental validation, incomplete data, or weak methodological grounding were excluded. Duplicate and non-academic sources were also omitted to maintain the integrity of the review. The selected literature was systematically analyzed and organized into key thematic areas, including material properties, synthesis techniques, processing strategies, and photovoltaic performance. A comparative approach was adopted to evaluate differences and similarities between CdTe and PbSe systems, with particular emphasis on how fabrication methods influence device efficiency and stability. This methodology enables a critical and integrative understanding of the current state of research, rather than a mere descriptive summary. By synthesizing findings across multiple studies, the review aims to highlight consistent patterns, identify limitations in existing approaches, and establish a clear direction for future research in advanced photovoltaic materials.

Fundamental Properties of CdTe and PbSe

A clear understanding of the fundamental physical and electronic properties of cadmium telluride (CdTe) and lead selenide (PbSe) is essential for evaluating their suitability as photovoltaic absorber materials. Parameters such as crystal structure, bandgap energy, optical absorption, charge transport, and defect behavior directly determine device efficiency and operational stability. CdTe is a II–VI semiconductor that crystallizes in the zinc blende (cubic) structure, characterized by a symmetric lattice that supports uniform electronic properties and efficient charge transport. The strong covalent bonding within the Cd–Te network contributes to structural stability and makes CdTe highly suitable for thin-film deposition. In contrast, PbSe belongs to the IV–VI group and adopts a rock-salt crystal structure. This distinct arrangement leads to isotropic electronic behavior and facilitates its use in both bulk and nanostructured forms, particularly in quantum dot systems. These structural differences significantly influence defect formation and carrier dynamics in the two materials. Bandgap energy plays a central role in determining photovoltaic performance. CdTe possesses a direct bandgap of approximately 1.45 eV, which closely aligns with the optimal value for single-junction solar cells, enabling efficient absorption of visible light and high conversion efficiency. PbSe, however, has a much narrower bandgap (~0.27 eV at room temperature), corresponding to infrared absorption. While this limits its use as a standalone absorber, PbSe becomes highly advantageous in advanced systems, especially in quantum dot form where bandgap tunability can be achieved through quantum confinement. This allows extension of absorption into longer wavelengths, complementing conventional materials like CdTe. In terms of optical properties, CdTe exhibits a very high absorption coefficient ($\sim 10^5$ cm^{-1}), allowing efficient light harvesting within a thin absorber layer. This reduces material usage while maintaining performance. PbSe also demonstrates strong absorption, particularly in the infrared region. Additionally, quantum-confined PbSe structures enable multiple exciton generation, where a single photon can generate more than one electron–hole pair, offering the possibility of enhanced efficiency beyond conventional limits. Charge transport characteristics further distinguish these materials. CdTe typically shows moderate electron mobility and relatively lower hole mobility, which can affect carrier collection. However, advancements in doping and grain boundary passivation have significantly improved carrier lifetime and transport efficiency. PbSe, in bulk form, exhibits high carrier mobility, but in quantum dot assemblies, transport is often hindered by surface ligands and interparticle barriers. Therefore, surface engineering and ligand exchange become essential to improve conductivity in PbSe-based devices. Defect behavior is another critical factor influencing device performance. In CdTe, intrinsic defects such as cadmium vacancies and tellurium antisites act as recombination centers. However, treatments such as chlorine activation have proven effective in passivating these defects and enhancing carrier lifetime. In PbSe, particularly in nanostructured systems, surface defects dominate due to the high surface-to-volume ratio, leading to significant non-radiative recombination. Effective surface passivation is therefore crucial to improving device efficiency. Thermal and chemical stability also play a key role in practical applications. CdTe exhibits relatively high stability under operational conditions, which has supported its commercial success. In contrast, PbSe is more prone to degradation, especially in nanostructured forms where oxidation and environmental exposure can deteriorate material properties. This necessitates advanced encapsulation strategies for long-term device stability. Overall, CdTe represents a mature and well-optimized photovoltaic material with properties closely aligned to efficient solar energy conversion. PbSe, on the other hand, offers unique advantages such as bandgap tunability and infrared absorption but requires further development in terms of stability and device integration. The complementary nature of these materials highlights their potential for tandem or hybrid photovoltaic architectures, where broader spectral utilization can be achieved.

Synthesis Techniques of CdTe and PbSe

The synthesis route critically governs the structural quality, defect density, and electronic properties of semiconductor materials, thereby determining photovoltaic performance. CdTe and PbSe follow distinct fabrication pathways reflecting their technological maturity: CdTe is primarily developed through scalable thin-film deposition, whereas PbSe is largely explored in nanostructured and quantum dot forms. CdTe thin films are predominantly fabricated using high-temperature vapor-phase techniques such as close-spaced sublimation (CSS) and vapor transport deposition (VTD). These methods enable rapid deposition, promote large grain formation, and reduce grain boundary recombination, leading to efficient charge transport. Their compatibility with large-area substrates makes them suitable for industrial-scale production, although precise control of processing conditions is essential to minimize defects. In contrast, solution-based methods such as electrodeposition offer cost advantages and thickness control but typically yield films with inferior crystallinity, requiring post-deposition treatments like annealing and $CdCl_2$ activation to enhance performance. Techniques such as sputtering and thermal evaporation provide compositional control but remain less viable for large-scale manufacturing.

PbSe synthesis is dominated by colloidal quantum dot approaches, which allow precise control over particle size and bandgap through quantum confinement. This enables tunable optical absorption, including the infrared region, and supports low-cost, solution-based processing. However, performance is limited by surface trap states and insulating ligands, necessitating ligand exchange to improve charge transport. Thin-film techniques such as chemical vapor deposition, thermal evaporation, and molecular beam epitaxy produce high-quality films with better transport properties, but their complexity and cost restrict scalability.

Overall, synthesis–performance relationships highlight that CdTe benefits from established, scalable methods yielding stable and efficient devices, whereas PbSe offers tunability and advanced optoelectronic properties but requires significant improvement in charge transport and stability. Key challenges include achieving uniform defect control in CdTe, developing scalable PbSe thin-film fabrication, and integrating both materials for tandem architectures.

Table 1: Comparative Summary of Synthesis Approaches

Parameter	**CdTe**	**PbSe**
Dominant Approach	Thin-film (CSS, VTD)	Quantum dots (colloidal)
Processing Temperature	High	Low (QD) / High (films)
Structure	Polycrystalline (large grains)	Nanocrystals / thin films
Defect Control	Moderate (post-treatment needed)	Challenging (surface traps)
Charge Transport	Efficient	Limited (QD systems)
Scalability	High	Limited
Strength	Stability and maturity	Tunability and IR absorption
Limitation	Process sensitivity	Stability and transport issues

Processing and Fabrication Strategies

Post-deposition processing plays a critical role in determining the electrical performance and long-term stability of CdTe and PbSe-based photovoltaic devices. While synthesis establishes the initial material quality, subsequent treatments control defect passivation, carrier concentration, interface properties, and charge extraction efficiency. In CdTe systems, achieving stable p-type conductivity remains essential. Copper is widely used to enhance hole concentration; however, its tendency to diffuse can compromise device stability. As a result, alternative dopants such as group V elements (As, Sb, P) have been explored, offering improved carrier lifetime and reduced degradation. In PbSe, particularly in quantum dot systems, carrier concentration is not governed by conventional doping but by stoichiometry and surface chemistry, making ligand engineering a key factor in device optimization. Thermal annealing is a fundamental step for improving crystallinity and minimizing defect density. In CdTe, $CdCl_2$ activation promotes grain growth, enhances junction quality, and reduces recombination losses. For PbSe quantum dot films, annealing improves interparticle coupling and facilitates ligand removal; however, excessive treatment can induce oxidation and structural degradation, limiting its effectiveness. Interface engineering is equally important for efficient charge separation and transport. CdTe devices typically employ a CdS/CdTe heterojunction, where proper band alignment reduces interfacial recombination. Strategies such as bandgap grading and interface passivation have further enhanced device performance. In PbSe systems, interface optimization focuses on energy level alignment and suppression of trap states, as interfacial defects remain a dominant loss mechanism. Defect passivation is central to performance improvement in both materials. In CdTe, chlorine treatment effectively passivates grain boundaries, leading to enhanced carrier lifetime. In PbSe, the high surface-to-volume ratio of quantum dots results in a large density of surface traps, necessitating rigorous passivation. Ligand exchange processes are particularly important in improving electronic coupling and charge transport. Charge extraction efficiency is strongly influenced by contact engineering. CdTe devices face challenges in forming stable ohmic back contacts due to their electronic properties, often requiring buffer layers or engineered contact materials. In PbSe-based devices, contact design focuses on minimizing resistance and achieving proper energy alignment to improve the fill factor. Device stability is further governed by encapsulation strategies. CdTe modules exhibit relatively high environmental stability, contributing to their commercial success. In contrast, PbSe systems are more vulnerable to degradation from oxygen and moisture, making protective encapsulation essential for long-term operation. Overall, processing strategies serve as a critical link between material synthesis and device performance. While advances in doping, interface engineering, and defect passivation have enabled significant efficiency improvements in CdTe, PbSe systems still require substantial progress in surface chemistry control and stability to achieve comparable performance.

Table 2: Impact of Processing Strategies on Device Performance

Processing Step	**CdTe Impact**	**PbSe Impact**
Doping	Enhances p-type conductivity and Voc	Controlled via surface chemistry
Annealing	Improves grain growth and reduces defects	Enhances coupling; risk of degradation
Interface Engineering	Reduces recombination, improves Jsc	Critical for energy alignment
Passivation	Grain boundary passivation (Cl treatment)	Surface trap reduction
Contact Formation	Improves FF, but challenging	Reduces resistance
Encapsulation	Ensures long-term stability	Essential due to instability

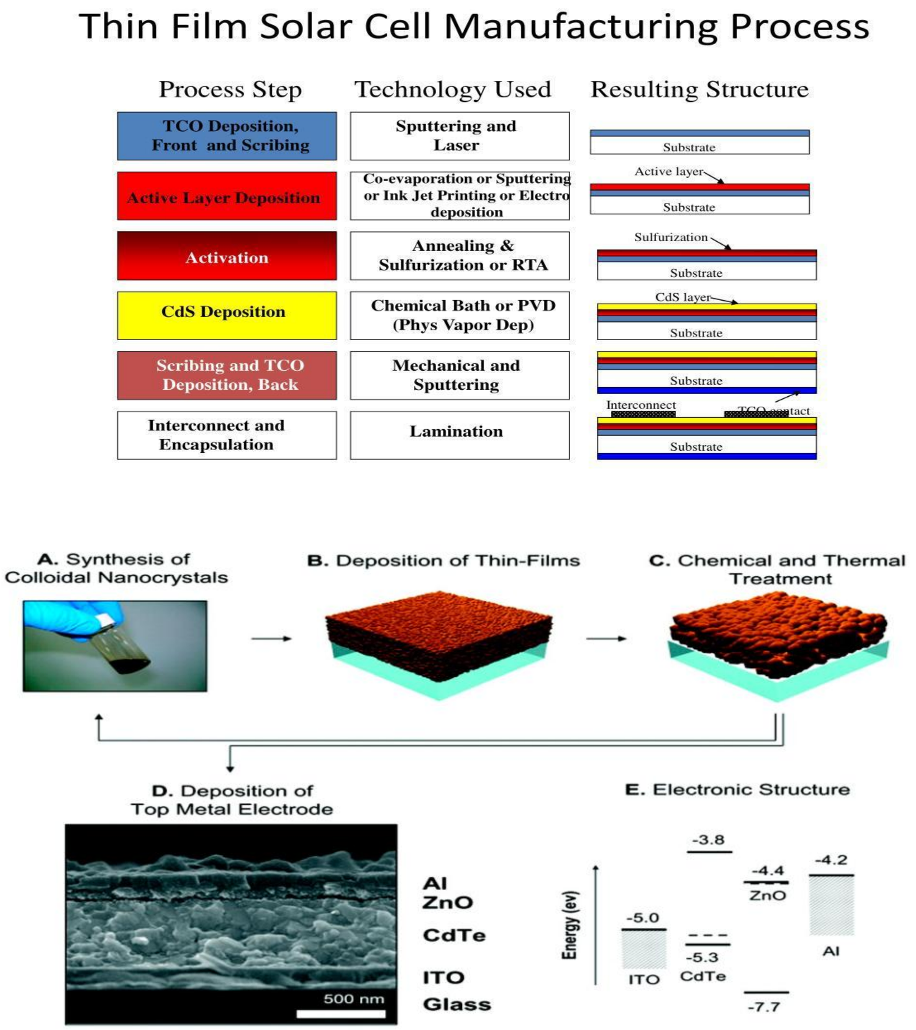

Figure 1: Schematic representation of processing and fabrication strategies influencing the performance of CdTe and PbSe-based photovoltaic devices.

Photovoltaic Performance Analysis

The performance of CdTe and PbSe-based photovoltaic devices is fundamentally determined by their ability to convert incident solar energy into electrical power, typically evaluated through parameters such as power conversion efficiency (PCE), open-circuit voltage (Voc), short-circuit current density (Jsc), and fill factor (FF). These parameters are closely interdependent and are governed by material quality, defect states, interface characteristics, and charge transport behavior established during synthesis and processing. CdTe solar cells represent one of the most mature thin-film technologies, with laboratory efficiencies exceeding 22%. This level of performance arises from its near-optimal bandgap, high absorption coefficient, and well-developed fabrication processes. Improvements in grain structure, defect passivation, and back-contact engineering have significantly enhanced carrier collection while suppressing recombination losses. Nevertheless, a persistent voltage deficit remains relative to theoretical limits, primarily due to non-radiative recombination at grain boundaries and interfaces, indicating that further gains depend on precise control of defect chemistry and interface quality. In contrast, PbSe-based photovoltaic systems—particularly those based on quantum dot architectures—are still in an early stage of development, with efficiencies typically in the range of 8–13%. Their key advantage lies in quantum confinement, which enables bandgap tunability and extends absorption into the infrared region, thereby enhancing current generation. However, these benefits are counterbalanced by high trap-state densities, limited charge transport, and instability associated with surface chemistry. Consequently, PbSe devices often exhibit lower Voc and fill factors, reflecting recombination-dominated transport and inefficient charge extraction. The differences between these systems are further evident in their current–voltage characteristics. CdTe devices typically display well-defined diode behavior with higher fill factors, indicating lower resistive losses and efficient carrier extraction. In contrast, PbSe devices frequently show reduced slopes near open-circuit conditions, a signature of recombination losses and suboptimal interface quality. These electrical characteristics highlight the gap between theoretical potential and practical device realization, particularly in PbSe systems. Spectral response analysis reinforces the complementary nature of these materials. CdTe exhibits strong quantum efficiency in the visible range, while PbSe extends absorption into the infrared region. This distinction is significant, as it enables the design of tandem architectures where CdTe acts as the primary absorber and PbSe contributes to harvesting low-energy photons, thereby improving overall spectral utilization. From a performance perspective, CdTe has reached a stage of incremental improvement, where further efficiency gains require advanced strategies such as interface engineering, bandgap grading, and improved defect control. In contrast, PbSe offers a fundamentally different pathway for performance enhancement through mechanisms such as multiple exciton generation, although its practical implementation remains limited. Thus, CdTe represents a benchmark for stability and efficiency, whereas PbSe reflects emerging potential that is yet to be fully realized in high-performance devices.

Table 3: Comparative Photovoltaic Performance of CdTe and PbSe

Parameter	**CdTe**	**PbSe**
Efficiency (PCE)	>22% (lab scale)	~8–13%
Voc	High	Lower (recombination-limited)
Jsc	Moderate–High	High (infrared contribution)
Fill Factor (FF)	High	Moderate
Charge Transport	Efficient	Limited (QD barriers)
Stability	High	Moderate to low
Technological Status	Commercially mature	Emerging

CdTe has reached a stage of performance optimization, where efficiency gains are incremental and dependent on fine control of defects and interfaces. In contrast, PbSe remains a high-potential but under-optimized system, where fundamental limitations in charge transport and stability continue to restrict its performance. The real opportunity lies not in comparing these materials as alternatives, but in strategically integrating them, particularly in tandem architectures that exploit their complementary spectral responses.

Challenges and Limitations

Despite significant progress in CdTe and PbSe-based photovoltaic technologies, several challenges continue to restrict their full potential and large-scale deployment. These limitations extend beyond device performance to include material sustainability, stability, and scalability. In CdTe systems, a persistent issue is the voltage deficit, where the achieved open-circuit voltage remains below the theoretical limit. This is primarily attributed to non-radiative recombination at grain boundaries and interfaces. Although defect passivation strategies have improved performance, complete suppression of recombination losses remains challenging. In addition, the formation of stable, low-resistance back contacts continues to limit long-term device reliability. Material-related concerns also play a significant role. The presence of cadmium raises environmental and regulatory issues, requiring strict control over handling, recycling, and lifecycle management. Furthermore, achieving uniform film quality over large-area modules remains a challenge under industrial fabrication conditions. For PbSe, the limitations are more fundamental. Device performance is strongly affected by high surface trap densities, which lead to severe recombination losses and reduced carrier lifetime. The use of organic ligands in quantum dot systems further introduces barriers to charge transport, limiting overall efficiency. In addition, PbSe materials exhibit poor environmental stability, particularly due to oxidation under ambient conditions. Another critical issue is the lack of scalable fabrication methods for PbSe thin films. While laboratory-scale results are promising, translating these into reproducible and large-area devices remains difficult. Moreover, advanced concepts such as multiple exciton generation have not yet resulted in significant efficiency improvements in practical devices. Overall, these challenges highlight a clear contrast: CdTe primarily requires incremental optimization, whereas PbSe demands more fundamental advancements in material design and device engineering.

Future Perspectives

Future progress in CdTe and PbSe-based photovoltaic technologies will depend on addressing existing limitations while leveraging their complementary properties for advanced energy systems. For CdTe, further improvements are expected through enhanced defect engineering and interface optimization to reduce the voltage deficit. Approaches such as bandgap grading, improved doping strategies, and advanced back-contact materials offer promising pathways toward higher efficiencies. At the same time, the development of environmentally sustainable processing and efficient recycling systems will be essential for long-term scalability. In PbSe systems, the focus must shift toward improving charge transport and environmental stability. This includes the development of robust surface passivation methods, inorganic ligand systems, and effective encapsulation strategies. In addition, scalable thin-film fabrication techniques are required to bridge the gap between laboratory research and practical applications. A key direction for future research is the development of tandem and hybrid photovoltaic architectures. By combining CdTe and PbSe, it becomes possible to utilize a broader portion of the solar spectrum, with CdTe absorbing visible light and PbSe extending into the infrared region. Such integration offers a viable pathway toward exceeding the efficiency limits of single-junction devices. Emerging approaches, including nanostructure engineering and data-driven material design, are also expected to accelerate progress. These strategies can enable more efficient optimization of synthesis conditions and device configurations, reducing experimental limitations. Ultimately, the transition from material-level innovation to scalable device integration will determine the future success of these technologies. Achieving this will require coordinated efforts across materials science, device engineering, and sustainability research.

Conclusion

This review presents a comprehensive analysis of CdTe and PbSe-based photovoltaic materials, focusing on their synthesis, processing, and performance characteristics. CdTe has emerged as a mature and commercially viable technology, offering high efficiency, stability, and scalability. In contrast, PbSe represents an emerging system with unique advantages such as bandgap tunability and infrared absorption, but it remains limited by challenges in stability, charge transport, and large-scale fabrication. The findings indicate that while CdTe is approaching its performance limits through incremental improvements, PbSe provides a fundamentally different pathway for next-generation photovoltaic development. However, realizing its full potential requires significant advances in material control and device engineering. A key conclusion of this study is that CdTe and PbSe should be viewed as complementary rather than competing materials. Their integration, particularly in tandem configurations, offers a promising route toward enhanced efficiency and improved spectral utilization. In summary, the future of photovoltaic technology will depend on the effective combination of material innovation and scalable engineering. Continued research in defect control, interface optimization, and hybrid device design will be essential for developing efficient, stable, and sustainable solar energy systems.

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