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Article

A COMPREHENSIVE SYSTEMATIC LITERATURE REVIEW ON PEROVSKITE SOLAR CELLS: ADVANCEMENTS, EFFICIENCY OPTIMIZATION, AND COMMERCIALIZATION POTENTIAL FOR NEXT-GENERATION PHOTOVOLTAICS

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ABSTRACT

This systematic literature review investigates the recent advancements, efficiency optimization strategies, and commercialization potential of perovskite solar cells (PSCs), with an emphasis on the integration of scalable fabrication, environmental sustainability, and techno-economic viability. Utilizing the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines, a total of 609 peer-reviewed articles published between 2013 and 2022 were critically analyzed across multiple scientific databases, including Scopus, Web of Science, IEEE Xplore, and ScienceDirect. The review synthesizes thematic insights from compositional engineering, device architecture optimization, long-term stability enhancement, and environmental impact assessments. Findings reveal that mixed-cation and mixed-halide perovskite formulations have significantly improved power conversion efficiency and operational durability, with planar and inverted device architectures emerging as dominant configurations due to their scalability and reduced hysteresis. Encapsulation and interface passivation techniques have notably extended T80 lifetimes, while scalable manufacturing methods such as slot-die coating and hybrid vapor-phase deposition have been validated for large-area module production. Techno-economic analyses indicate that PSCs offer competitive cost-per-watt and levelized cost of electricity (LCOE) values relative to silicon-based photovoltaics, supported by shorter energy payback times and lower embodied energy. However, the review also highlights critical research gaps, including inconsistent long-term stability testing protocols, limited outdoor performance data, and inadequate degradation modeling frameworks. Lifecycle assessment studies confirm the environmental promise of PSCs, though concerns about lead toxicity and end-of-life recyclability persist. Industrial partnerships, technology readiness level (TRL) assessments, and early-stage commercialization efforts suggest growing confidence in PSC deployment, though standardization and regulatory alignment remain uneven. This review provides a consolidated, multi-dimensional understanding of the perovskite photovoltaic landscape and offers direction for future research, policy formulation, and sustainable market integration.

KEYWORDS

National Resilience; AI-Driven Data Analytics; Cybersecurity; Crisis Response; Critical Infrastructure Protection;

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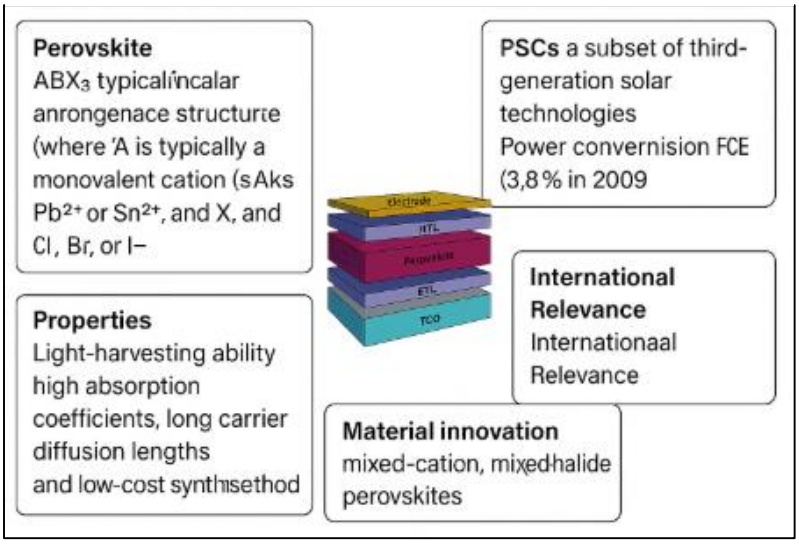
INTRODUCTION

The term "perovskite" refers to a class of materials with a specific ABX_3 crystal structure, where 'A' is typically a monovalent cation (such as methylammonium, MA^+), 'B' is a divalent metal cation (such as Pb^{2+} or Sn^{2+}), and 'X' represents a halide anion (Cl^-, Br^-, or I^-) ((Yang et al., 2020). Perovskite materials have attracted immense interest in photovoltaic research due to their exceptional light-harvesting ability, high absorption coefficients, long carrier diffusion lengths, and low-cost synthesis methods (Cao et al., 2015). Perovskite solar cells (PSCs) are a subset of third-generation solar technologies, demonstrating rapid improvements in power conversion efficiency (PCE), growing from 3.8% in 2009 to over 25% in recent laboratory-scale prototypes (Wu et al., 2021). This unprecedented leap in performance positions PSCs as strong contenders in the global energy transition toward sustainable electricity generation (Qiu et al., 2019). The evolution of PSCs highlights not only material innovation but also the intricate interplay between chemistry, physics, and engineering (Ma et al., 2018; Qiu et al., 2019). The international relevance of PSCs stems from their potential to democratize energy access through low-cost, lightweight, and semi-transparent modules that can be deployed in a wide range of climatic conditions (Chen et al., 2017). Many countries with solar-rich geographies face barriers such as limited grid infrastructure and high capital costs associated with conventional silicon photovoltaics (PV) (Wang et al., 2018). In this context, PSCs are viewed as promising alternatives capable of facilitating decentralized energy systems and energy autonomy (Im et al., 2011).

Figure 1: ross-Sectional Structure of a Perovskite Solar Cell with Interface Engineering Layers



Furthermore, PSCs can be integrated into building-integrated photovoltaics (BIPV), wearables, and indoor energy harvesting applications (Mahmood et al., 2015). Governments and international organizations have begun to invest in research and development (R&D) programs focusing on scalable PSC technologies, particularly in Asia, Europe, and North America (Tao et al., 2015). This global research momentum has led to interdisciplinary collaborations across materials science, environmental engineering, nanotechnology, and policy domains (Bush et al., 2017).Moreover, material innovation lies at the heart of PSC development. The incorporation of various organic and inorganic cations has led to mixed-cation and mixed-halide perovskites that demonstrate improved thermal and phase stability (Borriello et al., 2008). Research on double perovskites and low-dimensional perovskites has introduced alternative pathways to reduce ion migration and increase resistance to moisture-induced degradation (Rajagopal et al., 2016). Furthermore, additive engineering, such as the introduction of alkali metal ions or passivating agents like fullerene derivatives, has resulted in enhanced film uniformity and defect passivation (Anaya et al., 2017). The choice of transport layers—such as TiO_2, SnO_2, Spiro-OMeTAD, or CuSCN—also significantly influences device performance, hysteresis behavior, and long-term durability (Wang et al., 2016). The synergistic interaction between perovskite compositions and interfacial layers continues to drive efficiency gains and operational stability under ambient conditions (Wan et al., 2018).

Device architecture has evolved from mesoporous to planar and inverted configurations, each offering distinct advantages in terms of fabrication simplicity, flexibility, and compatibility with different substrates (Cheng et al., 2016). Innovations in tandem solar cells, particularly

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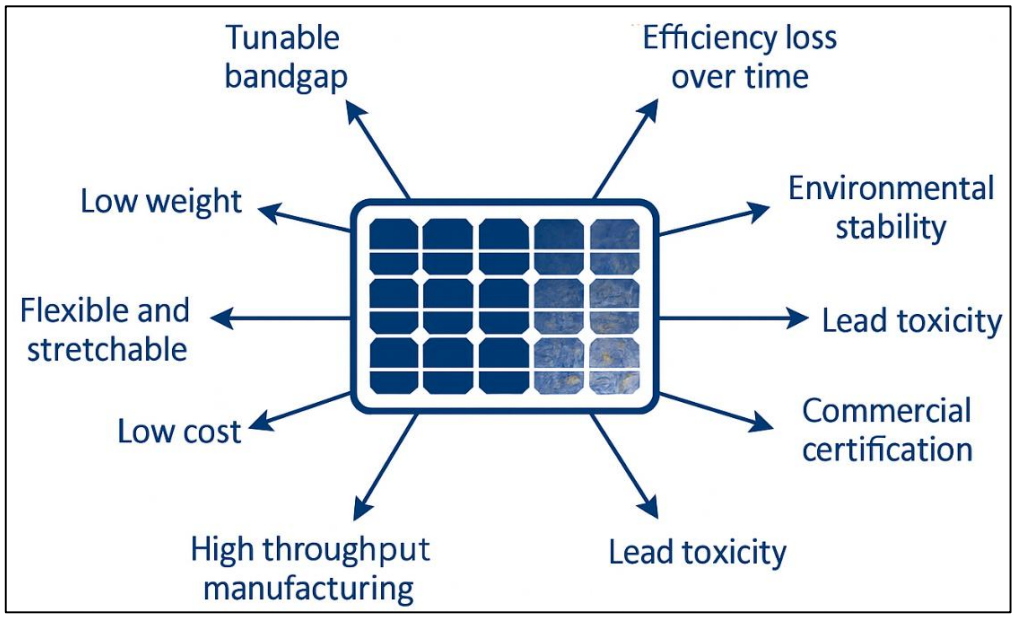
perovskite/silicon and perovskite/perovskite tandems, have enabled efficiency improvements beyond the Shockley-Queisser limit of single-junction cells (Lee et al., 2017). These architectures leverage the wide bandgap tunability of perovskites to optimize spectral utilization and minimize thermalization losses (Back et al., 2016). Flexible and stretchable PSCs, made using polymeric substrates and roll-to-roll printing methods, have further diversified potential applications beyond conventional rooftops and power plants (Li, et al., 2016). Interface engineering, anti-reflective coatings, and light-trapping structures have also been incorporated to enhance photon absorption and carrier transport mechanisms (Zhang & Zhu, 2019).

Figure 2: Advantages and Challenges in Advancing Perovskite Solar Cell Technologies



While rapid performance enhancements characterize PSC research, challenges related to environmental stability remain critical. Exposure to moisture, oxygen, heat, and ultraviolet (UV) radiation can induce ion migration, phase segregation, and interfacial degradation, leading to loss of efficiency over time (Li et al., 2017). Encapsulation technologies using barrier films, glass-glass modules, and novel polymer layers have been developed to extend device lifetimes (Lyu et al., 2017). Moreover, replacing toxic lead with less hazardous alternatives such as tin (Sn), bismuth (Bi), or antimony (Sb) is an area of active investigation (Bakr et al., 2017). However, these substitutes often suffer from lower efficiency and stability, indicating the trade-off between performance and environmental compliance (Zhang et al., 2020). Lifecycle assessment (LCA) and techno-economic analyses have emerged to evaluate the sustainability and feasibility of PSC deployment at scale (Fei & Wang, 2019). Moreover, Commercialization efforts for PSCs have accelerated, with pilot manufacturing facilities emerging in countries such as China, Germany, and the United States (Wu et al., 2019). Key strategies include inkjet printing, blade coating, and vapor deposition to fabricate large-area modules while maintaining high throughput and uniformity (Wang et al., 2016). Techno-economic modeling has shown promising results, suggesting that PSCs could achieve competitive levelized cost of electricity (LCOE) in comparison to conventional PV technologies (Zhao et al., 2017). Certification and bankability assessments—governed by international standards such as IEC 61215 and IEC 61730—are necessary for commercial success and investor confidence (Adnan & Lee, 2018). Moreover, venture capital interest and strategic partnerships between academia and industry are providing financial momentum to accelerate commercialization roadmaps (Liu et al., 2018).

Interdisciplinary approaches are increasingly shaping PSC research, combining advances in computational modeling, machine learning, and high-throughput screening to accelerate material discovery and process optimization (Ogomi et al., 2014). Data-driven insights have

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enabled the prediction of defect tolerance, stability profiles, and optoelectronic properties across perovskite compositions (Chen et al., 2017). Simultaneously, environmental and economic modeling has provided a framework for integrating PSCs into distributed energy networks and net-zero energy systems (Yang et al., 2015). Collaboration across sectors—including energy policy, chemical engineering, and industrial ecology—underscores the systemic nature of transitioning PSCs from laboratory prototypes to commercially viable, scalable solutions (Shih et al., 2017). The global landscape of PSC innovation is characterized by robust academic output, increasing patent activity, and diverse application domains, forming a dynamic research frontier within the renewable energy ecosystem (Sun et al., 2015).

The primary objective of this systematic literature review is to critically evaluate the body of scholarly work surrounding perovskite solar cells (PSCs) in order to identify, synthesize, and contextualize key advancements, performance optimization strategies, and commercialization frameworks within the field of next-generation photovoltaics. Given the exponential growth in research output related to PSCs, the study aims to establish a structured and evidence-based understanding of how material innovations, device architectures, and stabilization methods have contributed to the significant gains in power conversion efficiency and operational viability over the past decade. This objective is pursued through the rigorous application of the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) methodology to ensure replicability, transparency, and thematic consistency. Another core objective is to explore how interdisciplinary research across materials science, energy economics, and environmental engineering is converging to address the challenges hindering the large-scale deployment of PSCs, such as environmental instability, lead toxicity, and scale-up complexity. By systematically analyzing the findings from peer-reviewed journal articles, this review seeks to highlight the specific technical approaches that have enabled efficiency records to surpass 25% and uncover gaps where further empirical investigation is required. Additionally, the study aims to assess the current status and prospects for the commercialization of PSCs by examining market readiness indicators, manufacturing scalability, lifecycle sustainability metrics, and regulatory compliance requirements. Understanding the complex interdependencies among these factors is essential for informing both academic research agendas and industrial investment decisions. Thus, this review serves not only as a repository of validated knowledge but also as a strategic guide for accelerating the translation of PSC technology from experimental success to practical energy solutions. The synthesis of results also contributes to establishing a foundational benchmark for evaluating subsequent innovation trajectories and industry-led standardization practices.

LITERATURE REVIEW

The evolution of perovskite solar cells (PSCs) represents one of the most dynamic frontiers in photovoltaic research, marked by a rapid escalation in power conversion efficiencies, low-cost fabrication techniques, and versatile applications. Since their introduction in 2009, PSCs have been the subject of intense scientific scrutiny and engineering development, attracting contributions from disciplines including materials chemistry, electrical engineering, nanotechnology, and environmental science. The breadth and depth of research necessitate a systematic synthesis of the available literature to understand the transformative advancements and persisting barriers within the PSC landscape. This literature review aims to organize and evaluate existing empirical, theoretical, and experimental studies across multiple domains to provide a comprehensive account of the factors influencing PSC efficiency, stability, and commercial viability. Emphasis is placed on identifying critical innovations in perovskite material compositions, novel device structures, stability engineering, toxicity mitigation, and industrial scalability. Furthermore, the review highlights the interrelation of academic advancements and industrial demands in shaping the commercialization trajectory of PSC technologies. This section is divided into focused subsections that dissect each aspect of PSC development in detail, reflecting the interdisciplinary nature of the topic and offering thematic clarity to the systematic review process.

Perovskite Solar Cells (PSCs)

Perovskite solar cells (PSCs) have undergone a remarkable evolution since their inception in 2009, when Kojima et al. first demonstrated the photovoltaic capabilities of methylammonium lead

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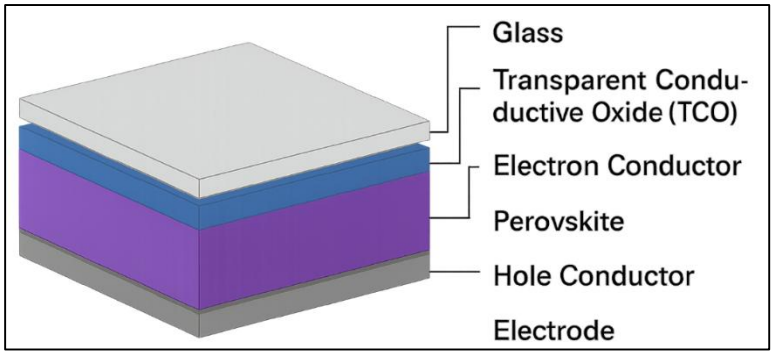
halide ($CH_3NH_3PbX_3$) materials (Wang, Shi, et al., 2015). The archetypal perovskite crystal structure—ABX_3—has become central to understanding the physicochemical properties that govern optoelectronic performance in solar energy conversion (De Giorgi et al., 2017). Research has consistently highlighted the relevance of the Goldschmidt tolerance factor and octahedral factor in predicting structural stability, crystallinity, and dimensionality ((Vallés-Pelarda et al., 2016). Hybrid organic-inorganic compositions, such as methylammonium lead iodide ($MAPbI_3$), rapidly became a benchmark material due to their balanced bandgap (~1.55 eV), strong absorption, and low exciton binding energy (Marronnier et al., 2018). Subsequent exploration into formamidinium (FA^+) and cesium (Cs^+) substitutions helped to enhance thermal stability and mitigate phase segregation, enabling improved device performance and reproducibility (Maughan et al., 2017). All-inorganic perovskites such as $CsPbBr_3$ have also been studied for their moisture resistance and thermal endurance, though they typically exhibit wider bandgaps (Zhao et al., 2016). Furthermore, dimensional engineering—via two-dimensional (2D) or quasi-2D perovskites—has been proposed to overcome ion migration and improve environmental resilience (Hao, Stoumpos, Chang, et al., 2014). These structural variants have expanded the PSC landscape, offering researchers a versatile platform to manipulate optical and electronic properties while simultaneously addressing stability limitations.

Figure 3: Perovskite Solar Cell Architecture with Integrated Material and Stability Enhancements



Efficiency improvements in PSCs have been largely driven by meticulous material engineering and interface optimization strategies. Mixed-cation and mixed-halide formulations—such as FA-Cs-MA lead iodide-bromide blends—have demonstrated improved crystallinity, grain boundary passivation, and reduced phase separation, leading to devices with efficiencies exceeding 24% (Snaith et al., 2014). Incorporating alkali metal ions (e.g., Rb^+, K^+) into perovskite precursors has further enhanced carrier lifetimes and device uniformity (Im et al., 2015). Concurrently, additive engineering using fullerene derivatives, polymer stabilizers, and Lewis base molecules has significantly suppressed defect densities and ion migration, contributing to higher open-circuit voltages and fill factors (Konstantakou et al., 2017). Interface engineering between perovskite layers and charge transport layers (CTLs) has also been a focal point, with materials like SnO_2, NiO, and PTAA offering improved energy alignment, reduced recombination, and enhanced thermal durability (Subhani et al., 2019). Passivation layers, such as phenethylammonium iodide (PEAI) and various self-assembled monolayers (SAMs), have been shown to suppress non-radiative recombination and stabilize interfacial contacts (Eperon et al., 2016). Several studies confirm that interfacial defects, rather than bulk defects, are the dominant recombination sites in PSCs, highlighting the need for surface control (Adonin et al., 2017). Moreover, vapor-assisted solution processes and antisolvent techniques have been developed to control film morphology and reduce pinholes (Stewart et al., 2016). These refinements in material and interface design collectively form the foundation of modern PSCs, allowing them to achieve competitive power conversion efficiencies on par with traditional silicon photovoltaics (Stolterfoht et al., 2017).

Stability remains one of the most pressing concerns in PSC research, as environmental degradation impedes long-term device reliability. Moisture, thermal stress, UV exposure, and oxygen infiltration are key degradation factors that induce ion migration, lattice distortion, and interfacial delamination (Tian & Scheblykin, 2015). Humidity is especially detrimental to organic cation-based perovskites like $MAPbI_3$, which readily decompose into PbI_2 under ambient conditions (Babayigit et al., 2016). Researchers have responded by replacing volatile MA^+ with more stable FA^+ and Cs^+ cations, improving lattice cohesion and thermal tolerance (Alharbi et

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al., 2019; Babayigit et al., 2016). Additionally, the formation of 2D perovskite capping layers over 3D perovskite films has been effective in blocking moisture infiltration and retarding ion diffusion (Frost et al., 2014). UV-induced degradation, often exacerbated by TiO_2 as an electron transport layer, has prompted the exploration of alternative materials like SnO_2, ZnO, and PCBM, which exhibit lower photocatalytic activity (Urbina, 2020). Thermal stability has been improved through both compositional tuning and encapsulation techniques, such as the use of UV-curable resins and glass-glass packaging (Prasanna et al., 2017). Furthermore, surface defects and ion migration pathways have been addressed through grain boundary passivation using thiocyanates, quaternary ammonium salts, and cross-linking polymers (Filip et al., 2016). Encapsulation methods have matured, allowing some PSCs to retain 80–90% of their initial efficiency over 1,000 hours under continuous illumination and elevated temperatures (Kulkarni et al., 2014). These multifaceted approaches to stability have led to significant, albeit incremental, progress in extending the operational lifetimes of PSCs under real-world conditions.

The scalability and commercialization of PSCs depend on the feasibility of transitioning from laboratory-scale devices to large-area modules while maintaining performance and stability. Various deposition techniques—such as blade coating, inkjet printing, slot-die coating, and vapor deposition—have been developed to support scalable, low-cost manufacturing compatible with roll-to-roll processing (Du et al., 2017). Among these, slot-die coating and vacuum-assisted deposition have shown promise for fabricating uniform, pinhole-free films on flexible and rigid substrates (Yun et al., 2015). Several start-ups and consortiums, including Oxford PV, Saule Technologies, and Microquanta, have begun piloting commercial-scale production facilities (Zhou et al., 2017). Efforts to optimize module interconnection schemes, such as laser scribing and monolithic integration, have improved voltage matching and reduced series resistance losses in multi-cell configurations (Christians et al., 2015). Another essential consideration for commercialization is device encapsulation, which must maintain barrier properties while allowing flexibility for non-standard form factors (Rong et al., 2015). In parallel, techno-economic assessments have indicated that PSCs could achieve competitive levelized costs of electricity (LCOE) below $0.03/kWh under ideal conditions, positioning them favorably against silicon photovoltaics (Zhang et al., 2017). Industrial standards such as IEC 61215 and IEC 61730 have begun to be adapted to PSCs, allowing pre-certification testing under damp heat, thermal cycling, and light soaking conditions (Pan et al., 2018). Financial support from governments, private investors, and public-private partnerships has further incentivized technology transfer and market penetration (Wang et al., 2019). These developments suggest that the technical readiness of PSCs for commercial integration is growing more robust across global photovoltaic markets.

The environmental sustainability of PSCs is increasingly scrutinized due to the presence of lead (Pb) in the absorber layer, which poses ecological and health risks during production, operation, and end-of-life stages (Wang et al., 2018). Lead leakage during module disposal or accidental breakage raises concerns about groundwater contamination and regulatory compliance (Ran, Xi, et al., 2018). Consequently, researchers have explored lead-free alternatives, such as tin (Sn), bismuth (Bi), antimony (Sb), and silver-bismuth halides, though these often suffer from poor film formation, increased defect states, and reduced efficiency (Hu et al., 2017). Sn-based perovskites, such as $MASnI_3$ and $FASnI_3$, offer similar electronic structures to Pb-based systems but are highly prone to oxidation and p-type self-doping, resulting in rapid performance degradation (Slavney et al., 2016). Hybrid approaches using trace Pb doping or double perovskite configurations like $Cs_2AgBiBr_6$ have been proposed to balance performance and sustainability (Gatti et al., 2016). Encapsulation and recycling protocols are also being developed to contain and recover lead from used modules (Lee et al., 2017). Additionally, life-cycle assessments (LCAs) and environmental product declarations (EPDs) are being employed to quantify the carbon footprint, energy payback time (EPBT), and end-of-life recyclability of PSCs in comparison to silicon and CdTe solar technologies (Malinauskas et al., 2016). These assessments inform regulatory frameworks and help establish environmental benchmarks necessary for large-scale deployment. Overall, while Pb toxicity presents a significant hurdle, current mitigation efforts demonstrate a growing alignment between technological advancement and environmental stewardship in PSC development.

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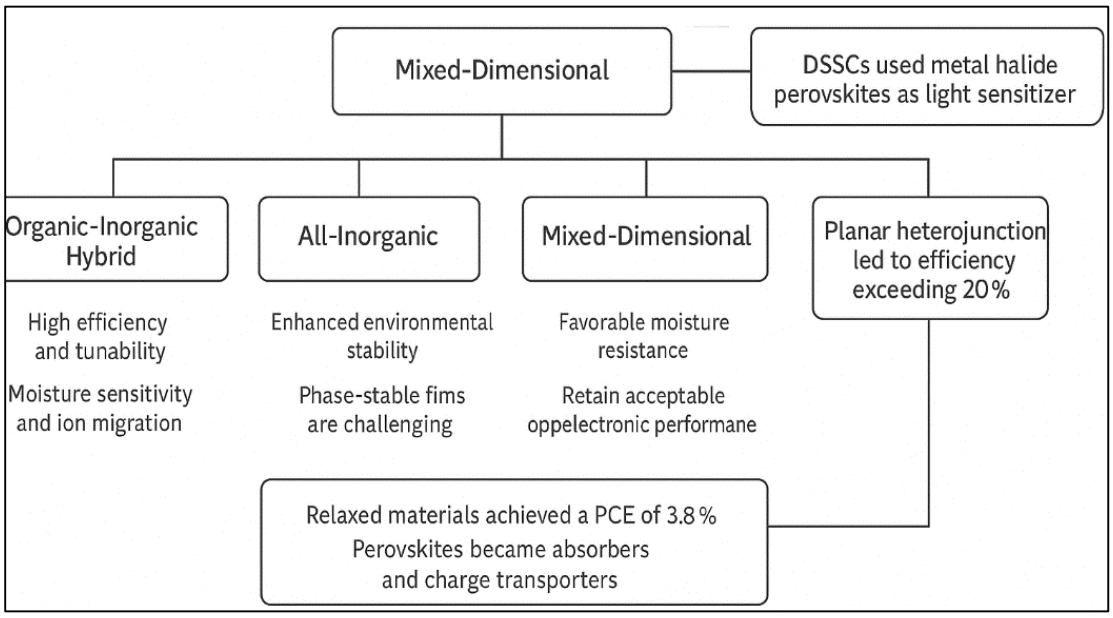
Evolution and Classification of Perovskite Materials

The emergence of perovskite solar cells (PSCs) can be traced back to the innovation within dye-sensitized solar cells (DSSCs), where metal halide perovskites were initially used as light-absorbing sensitizers. Ye et al.(2017) were the first to demonstrate the photovoltaic capabilities of methylammonium lead halide ($CH_3NH_3PbX_3$), achieving a modest power conversion efficiency (PCE) of 3.8% by incorporating it into a DSSC structure. This breakthrough, although limited by rapid degradation in liquid electrolytes, opened a new avenue for hybrid organic-inorganic halide materials (Wang, Liu, et al., 2015). The critical transition from DSSCs to solid-state PSCs occurred with the replacement of the liquid electrolyte by hole transport materials like spiro-OMeTAD, drastically improving device stability and pushing PCEs above 10% within a few years (Chiang & Wu, 2016). This development was further supported by the discovery that perovskite layers could serve both as absorbers and charge transporters, eliminating the need for separate dye molecules (Zuo & Ding, 2015). The planar heterojunction configuration became dominant as it allowed for simplified device architecture and greater control over thin-film morphology (Liu et al., 2017). By 2015, PSCs surpassed 20% efficiency, outperforming other third-generation photovoltaics like organic solar cells and quantum dot solar cells (Frost, 2017). The rapid improvement was fueled by advancements in perovskite composition, film deposition techniques, and interface engineering (Almora et al., 2015). The evolution of PSCs from DSSCs exemplifies the paradigm shift in photovoltaic research, wherein the absorber material not only harvests photons but also facilitates efficient charge separation and transport.

Figure 4: Classification and Evolution of Perovskite Materials in Solar Cell Development



Organic-inorganic hybrid perovskites have formed the foundation of early PSC research due to their favorable optoelectronic properties and processability. The prototypical structure, methylammonium lead iodide ($MAPbI_3$), remains one of the most studied materials owing to its optimal bandgap (~1.55 eV), high absorption coefficient, and long charge carrier diffusion lengths (Petrus et al., 2017). However, issues with moisture sensitivity and thermal instability led to the development of more complex cation combinations. Formamidinium (FA^+), when substituted for methylammonium (MA^+), enhanced the thermal stability and phase purity of the perovskite layer (Luo et al., 2017). The inclusion of cesium (Cs^+) in triple-cation perovskites (CsFA-MA) has shown to reduce hysteresis and improve overall device reproducibility (Aitola et al., 2016). Hybrid compositions also allow for tuning of the bandgap via halide substitution (Br^-, Cl^-, I^-), enabling broader spectral absorption and compatibility with tandem architectures (Habisreutinger et al.,

2014). In addition to absorber layers, hybrid perovskites facilitate defect passivation at grain boundaries, a critical feature for suppressing recombination losses (Li et al., 2017). Their compatibility with low-temperature solution processing further supports scalability on flexible substrates, allowing roll-to-roll production and integration into portable electronics (Chen & Yang, 2017). However, challenges with ion migration, phase segregation under illumination, and volatile organic components have spurred continued research to refine hybrid systems (Ma et al., 2016). These hybrid perovskites, while central to the success of PSCs, highlight the complex balance between device performance, longevity, and environmental durability (Chen et al., 2018).

All-inorganic perovskites, particularly cesium lead halides ($CsPbX_3$), have garnered significant attention as candidates for enhanced thermal and photochemical stability compared to their hybrid counterparts. Unlike organic cation-based perovskites, inorganic variants are devoid of volatile components, making them inherently more robust under heat and UV exposure (Kulbak et al., 2015; Eperon et al., 2015). $CsPbI_3$, with its ideal bandgap of ~1.73 eV, offers efficient light absorption, but its high-temperature cubic phase (α-$CsPbI_3$) is metastable at room temperature and tends to transition into a non-perovskite orthorhombic phase (δ-$CsPbI_3$) that is optically inactive (Leijtens et al., 2016). To address this, researchers have employed strain engineering, polymer encapsulation, and additive incorporation to stabilize the cubic phase (Zhu et al., 2017). $CsPbBr_3$, another popular variant, exhibits superior phase stability and UV resistance, although its wide bandgap (~2.3 eV) limits solar spectrum utilization (Amat et al., 2014). The lower processing temperature requirements and absence of organic decomposition pathways make all-inorganic perovskites suitable for tandem applications and harsh operational environments (Saliba et al., 2016). Furthermore, they exhibit reduced hysteresis and superior environmental resilience under prolonged operation (Zhang et al., 2017). However, achieving large-area uniform films with high crystallinity remains a challenge, as grain boundaries and pinholes affect reproducibility (Nagarjuna et al., 2015). Additionally, the high lead content remains an environmental concern, prompting further investigation into lead-free all-inorganic alternatives such as $Cs_2AgBiBr_6$ and $CsSnI_3$ (Jeng et al., 2013). All-inorganic perovskites represent a trade-off between enhanced operational stability and limitations in optoelectronic tunability.

Mixed-dimensional perovskites have emerged as a novel class of materials that combine the stability of low-dimensional structures with the high efficiency of 3D perovskites. These materials are often composed of alternating layers of organic and inorganic components, forming Ruddlesden–Popper (RP) phases with the general formula $(RNH_3)_2(A)n-1BnX_3n+1$, where n denotes the number of perovskite layers between the organic spacers (Weber, 1978a). Two-dimensional (2D) perovskites, especially those with n = 1–4, exhibit excellent moisture resistance due to the hydrophobic nature of the organic cations, often derived from phenethylammonium (PEA^+) or butylammonium (BA^+) (Weber, 1978b). While pure 2D perovskites suffer from limited carrier mobility and exciton dissociation, quasi-2D structures (n > 1) bridge this performance gap by retaining efficient charge transport pathways (Shalan, 2020). These mixed-dimensional systems have been successfully employed as capping layers or bulk heterojunctions to suppress ion migration, passivate surface defects, and mitigate phase segregation in mixed-halide systems (Shrestha et al., 2019). Notably, they exhibit increased photostability under continuous illumination, reduced thermal degradation, and enhanced resistance to humidity and oxygen (Handa et al., 2017). The self-assembly of layered structures allows precise control over film morphology and orientation, which directly influences charge extraction and hysteresis behavior (Yang et al., 2018; Liu et al., 2021). However, the synthesis of highly crystalline, large-area mixed-dimensional films remains technically complex, with issues such as phase purity and anisotropic conductivity limiting scalability (Brauer et al., 2015). Mixed-dimensional perovskites thus represent a strategically balanced approach to address the trade-offs between device longevity and performance metrics in PSCs.

The classification of perovskite materials into organic-inorganic hybrids, all-inorganic, and mixed-dimensional structures has significant implications for device design, stability, and manufacturability. Organic-inorganic hybrids offer the advantage of high efficiency and tunability but are hindered by moisture sensitivity and ion migration (Hutter et al., 2017). All-inorganic perovskites exhibit enhanced environmental stability but face challenges in achieving

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phase-stable films at ambient temperatures (Herz, 2016). Mixed-dimensional perovskites integrate favorable aspects of both classes by enhancing moisture resistance while retaining acceptable optoelectronic performance (Wehrenfennig et al., 2014). The choice of perovskite structure directly impacts the selection of charge transport layers, encapsulation strategies, and thermal management protocols (Buizza et al., 2019). Research demonstrates that triple-cation hybrid systems (Cs^+, FA^+, MA^+) offer superior tolerance to environmental stress compared to single-cation formulations (Takahashi et al., 2011). Conversely, $CsPbBr_3$-based inorganic PSCs are favored in tandem cell designs due to their stability under UV-rich conditions, though their wide bandgap limits standalone efficiency (Frolova et al., 2015). Mixed-dimensional perovskites, particularly quasi-2D variants, show promise for flexible and wearable electronics owing to their mechanical compliance and reduced ionic conductivity (Liu et al., 2017). However, each classification entails unique fabrication techniques, degradation pathways, and stability considerations, necessitating material-specific processing and testing protocols (Laurita et al., 2017). Comparative analyses underscore the importance of tailoring perovskite composition to application-specific performance criteria, providing a structured framework for advancing the commercial and scientific development of PSCs (Li et al., 2017).

Material Engineering for Performance Enhancement

Cation substitution has played a pivotal role in enhancing the structural and optoelectronic properties of perovskite materials used in solar cells. The original methylammonium (MA^+) cation, while offering good light absorption and an optimal bandgap (~1.55 eV), suffers from poor thermal and moisture stability. Formamidinium (FA^+), with a slightly larger ionic radius, has been used to replace MA^+ to form $FAPbI_3$, which presents a narrower bandgap (~1.47 eV) and better thermal stability (Qing et al., 2015) However, FA^+-based perovskites are prone to forming non-perovskite δ-phases under ambient conditions, requiring further compositional engineering to stabilize the black α-phase (Feng et al., 2021). Cesium (Cs^+), an inorganic cation, is often incorporated as a secondary or tertiary cation in mixed systems to improve crystallinity and reduce phase instability, as demonstrated in triple-cation systems such as Cs^+-FA^+-MA^+ perovskites (Wang et al., 2020). Cation engineering not only impacts phase stability but also influences carrier lifetimes, grain size, and trap state densities (Zhang et al., 2019). Studies show that incorporating Rb^+ and K^+ as minor additives can further passivate defects and enhance photovoltage (Shin et al., 2017). These substitutions enable fine-tuning of the bandgap across a range from 1.47 eV to over 2.0 eV, making them suitable for tandem cell configurations and light-harvesting optimization (Tang et al., 2017). Cation mixing strategies thus provide a versatile approach to controlling film morphology, stability, and energy alignment, laying the foundation for further performance enhancement in PSCs (Tian et al., 2020).

In addition to cation engineering, anion substitution has emerged as a fundamental strategy to tailor the optical properties and stability of perovskite absorbers. The most commonly used halides—iodide (I^-), bromide (Br^-), and chloride (Cl^-)—directly influence the bandgap of the perovskite material, with iodide-based perovskites typically providing optimal absorption in the near-infrared region (~1.55 eV) and bromide-based materials exhibiting wider bandgaps (~2.3 eV) suitable for top-cell tandem applications (Igbari et al., 2019). Mixing I^- and Br^- enables continuous bandgap tuning across the visible spectrum, allowing for spectral matching in tandem solar cells (Matsui et al., 2019). However, the introduction of mixed halides often leads to photo-induced halide segregation, where iodide- and bromide-rich domains form under illumination, leading to performance degradation and photoinstability (Jeon et al., 2015). Researchers have mitigated this issue through compositional balancing and interface passivation techniques that stabilize halide distributions. Moreover, Cl^- incorporation has been explored to enhance crystallization kinetics and film morphology, although Cl^- does not typically remain in the final crystal lattice. Halide engineering also affects carrier recombination rates and mobility, making it a critical factor in device performance. The careful selection and mixing of halides, combined with appropriate annealing conditions and solvent treatments, allow for precise control over perovskite bandgaps and layer uniformity (Zhang et al., 2021). Thus, anion substitution remains a powerful lever for modulating light absorption, enhancing efficiency, and adapting PSCs for multi-junction configurations.

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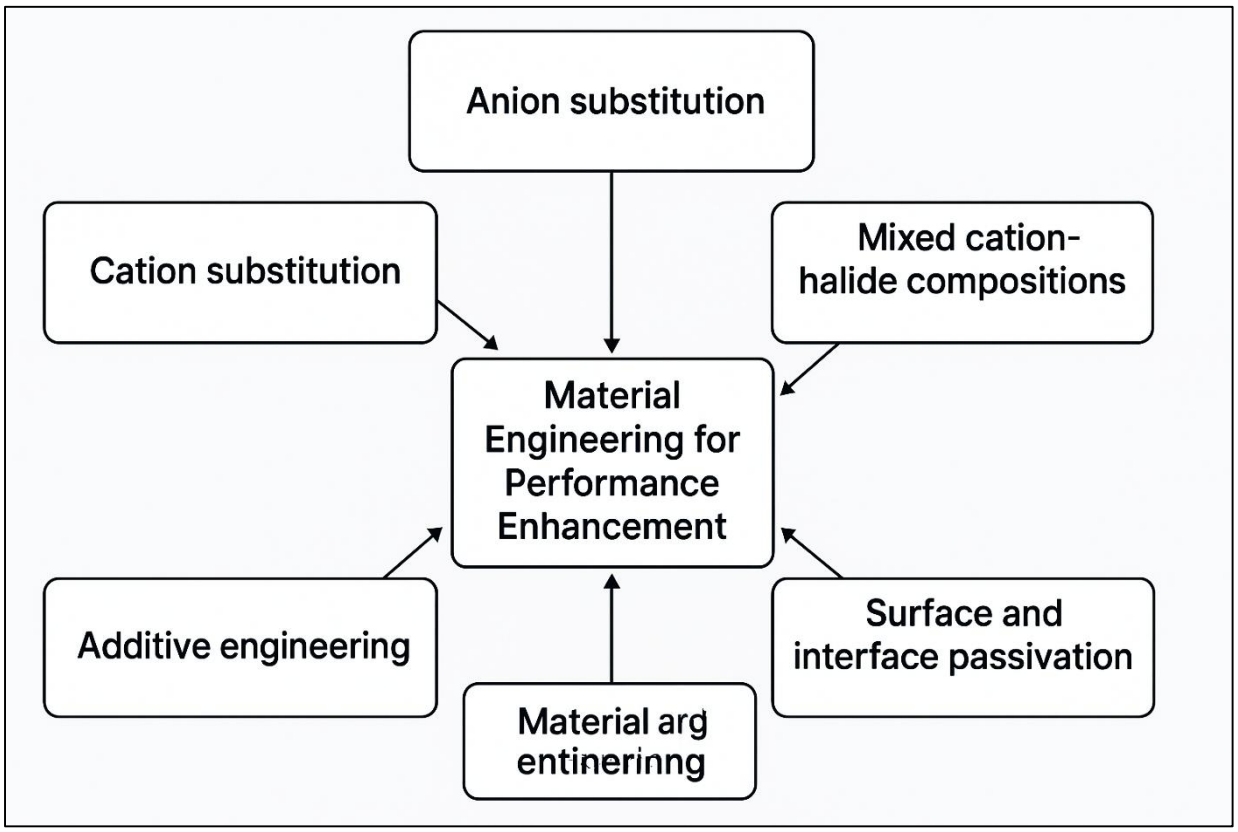
Figure 5: Comprehensive Framework of Material Engineering Approaches for Enhancing Perovskite Solar Cell Performance



The co-engineering of mixed cation and mixed halide compositions has produced some of the most efficient and stable perovskite formulations to date. By integrating organic (e.g., MA^+, FA^+) and inorganic (e.g., Cs^+, Rb^+) cations, researchers have created perovskite structures with improved lattice stability, reduced defect densities, and enhanced tolerance to thermal and humidity stress (Mitzi et al., 1995). When combined with mixed halides (I^-/Br^-), these systems can achieve bandgap tunability in the range of 1.5 to 1.8 eV, ideal for tandem cell integration and color-specific applications. Triple- and quadruple-cation systems have demonstrated superior phase stability under operational conditions, suppressing the formation of yellow δ-phases and enabling long-term photo-stability (Mitzi et al., 1994). Studies also suggest that the interplay between cation radius and halide size contributes to the stabilization of the perovskite cubic phase, thereby promoting better crystallinity and charge transport. Furthermore, halide mixing allows perovskite layers to absorb over a broader range of the solar spectrum, improving short-circuit current (Jsc) and enhancing overall PCE (Yang et al., 2017). While photo-induced phase segregation remains a challenge, interface and surface passivation have been successful in mitigating its effects (Xiao et al., 2017). These synergistic compositions also display better reproducibility during scale-up processes, making them favorable for industrial application (Kim et al., 2015). As a result, mixed cation-halide systems represent a finely tuned class of materials with balanced efficiency, stability, and processing benefits that dominate current PSC research (Wang et al., 2021).

Additive engineering has been central to the control of crystallization kinetics, film morphology, and defect passivation in PSCs. The inclusion of small quantities of chemical additives into the perovskite precursor solution has been shown to significantly impact the nucleation process, resulting in uniform grain growth and high film coverage (Gong et al., 2015). One of the most frequently used additives is methylammonium chloride (MACl), which facilitates larger grain formation and smoother surfaces without remaining in the final crystal structure (Chen et al., 2014). Lewis base additives such as thiourea, urea, and DMSO act as coordination agents with lead

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precursors, slowing down crystal formation and yielding dense, pinhole-free films (Fu et al., 2016). Fullerene derivatives, particularly [6,6]-phenyl-C61-butyric acid methyl ester (PCBM), have been used to passivate electron traps at grain boundaries and interfaces (Han et al., 2020). Other functional additives, including alkali metal ions (Rb^+, K^+), have been reported to increase open-circuit voltage and suppress ion migration (Giuri et al., 2016). Furthermore, additives like guanidinium iodide (GAI) have been explored for their ability to enhance lattice stability and eliminate deep-level traps (Yao et al., 2017). Passivation of undercoordinated lead and halide ions is also achieved using quaternary ammonium halides, which stabilize the film's electronic structure (Hwang et al., 2015). These strategies collectively improve the photovoltage, reduce hysteresis, and extend device lifetime under operational conditions (Zhao et al., 2016). Additive engineering thus provides a cost-effective and scalable route to high-quality perovskite films with superior optoelectronic properties and reproducibility (Zongqi Li et al., 2018).

Surface and interface passivation are critical for suppressing non-radiative recombination losses, which significantly impact the open-circuit voltage and overall efficiency of PSCs. The majority of recombination events occur at grain boundaries and interfaces between the perovskite layer and charge transport layers (Cai et al., 2016). Organic molecules such as phenethylammonium iodide (PEAI) and 2-thiopheneethylammonium iodide (TEAI) have been widely employed to form quasi-2D passivation layers that reduce trap states and enhance film stability (Castro et al., 2017). Inorganic passivation agents such as Al_2O_3, MgF_2, and LiF have also been introduced to improve interface energy alignment and minimize carrier recombination at the electrode interface (Konstantakou & Stergiopoulos, 2017). The use of self-assembled monolayers (SAMs) like MeO-2PACz on metal oxide surfaces has demonstrated improved charge extraction and reduced interface defects (Wojciechowski et al., 2016). Interfacial engineering also includes the application of buffer layers such as PCBM or SnO_2 to bridge lattice mismatches and improve carrier mobility (Watson et al., 2016). Surface defects caused by halide vacancies or under-coordinated Pb^{2+} ions have been addressed with ammonium halides and post-treatment techniques using MAI, FAI, or $Pb(SCN)_2$ (Xu et al., 2016). Studies confirm that passivated devices consistently show higher photoluminescence quantum yields, indicating fewer non-radiative pathways (Dong et al., 2020). These techniques have enabled PSCs to reach efficiency levels exceeding 25%, with reduced hysteresis and improved operational lifetimes (Castro et al., 2017). Therefore, surface and interface passivation represent indispensable aspects of material engineering for PSC performance enhancement and device reliability.

Device Architecture and Structural Design

Planar device architecture has emerged as one of the dominant structural designs for perovskite solar cells due to its fabrication simplicity and compatibility with low-temperature processes. Unlike traditional dye-sensitized solar cells that rely on mesoporous scaffolds, planar architectures consist of a compact layer that serves as the electron transport layer (ETL) or hole transport layer (HTL) depending on the configuration (Ahmed et al., 2022; Konstantakou & Stergiopoulos, 2017). The planar configuration facilitates uniform perovskite deposition and is suitable for both rigid and flexible substrates, enhancing its potential for commercial scalability (Aklima et al., 2022; Wojciechowski et al., 2016). These devices can be constructed in either the regular (n–i–p) or inverted (p–i–n) configurations, each offering distinct charge dynamics and interface characteristics (Helal, 2022; Watson et al., 2016). Planar devices with TiO_2 as the ETL initially gained popularity, but performance losses due to hysteresis and UV degradation necessitated alternative materials. With SnO_2 and PCBM as replacements, planar architectures now display reduced recombination rates and increased stability (Mahfuj et al., 2022; Xu et al., 2016). Moreover, surface passivation and interfacial engineering in planar PSCs have enabled power conversion efficiencies (PCEs) exceeding 25% in small-area devices (Dong et al., 2020; Majharul et al., 2022). The smooth and pinhole-free perovskite layers grown in this structure reduce trap densities and promote efficient charge separation and extraction (Hossen & Atiqur, 2022; Park, 2016). Planar PSCs therefore represent an optimal blend of high efficiency, scalable processing, and simplified layer design, which has contributed to their widespread adoption in laboratory and pilot-scale research (Mohiul et al., 2022; Xu et al., 2020).

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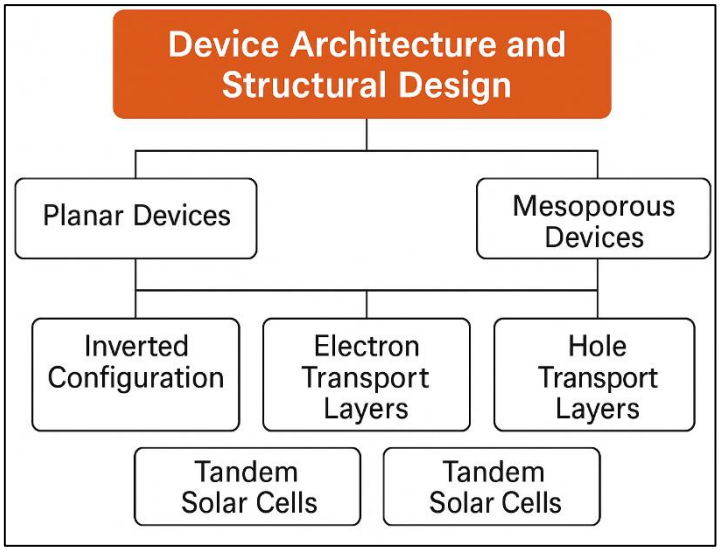
Figure 6: Device Architecture and Structural Design Strategies for High-Performance Perovskite Solar Cells



Mesoporous PSC architectures were among the earliest forms of solid-state devices that demonstrated high photovoltaic efficiency using perovskite absorbers. This structure consists of a mesoporous scaffold, typically made of TiO_2 or Al_2O_3, that facilitates electron or ion transport and supports uniform crystal growth (Moore et al., 2015; Kumar et al., 2022). In mesoporous devices, the perovskite infiltrates the scaffold pores, leading to large interfacial contact areas and efficient charge separation at the perovskite–ETL interface (McClure et al., 2016; Sohel et al., 2022). The use of mesoporous TiO_2 has been instrumental in achieving early PCE breakthroughs above 15%, as it enabled fast electron extraction and minimized bulk recombination (Gupta et al., 2016; Tonoy, 2022). However, the high-temperature sintering process required to prepare the mesoporous layer, typically around 500°C, limits compatibility with flexible substrates and scale-up techniques (Chung et al., 2012; Younus, 2022). Furthermore, TiO_2 has been linked to UV-induced degradation due to its photocatalytic nature, which compromises long-term device stability (Sutton et al., 2018). To overcome these limitations, alternative low-temperature mesoporous materials such as SnO_2, ZrO_2, and Nb_2O_5 have been explored for their improved chemical stability and electron mobility (Zhang et al., 2016). Studies have also investigated the incorporation of insulating Al_2O_3 scaffolds to decouple the electronic function from the scaffold and highlight the intrinsic ambipolar charge transport in perovskites (Cui et al., 2015). Although planar devices have surpassed mesoporous structures in most performance metrics, mesoporous PSCs remain a useful model system to study charge extraction dynamics and structural stability (Williams et al., 2016).

The inverted (p–i–n) configuration has gained prominence in PSC research due to its low-temperature processing capability and superior compatibility with flexible substrates. In this architecture, the HTL is deposited first (typically PEDOT:PSS, NiOx, or PTAA), followed by the perovskite layer and an ETL such as PCBM, C_{60}, or ZnO (Mahmood et al., 2017). The absence of sintered mesoporous layers enables fabrication below 150°C, making inverted PSCs ideal for roll-to-roll production and tandem integration (Braly et al., 2017). Additionally, inverted structures often exhibit reduced hysteresis and enhanced reproducibility, attributed to the more balanced charge carrier mobility and improved interfacial contact (Ye et al., 2015). One of the key limitations of early inverted devices was the lower PCE, primarily due to inefficient hole transport and poor energy level alignment (Zhang et al., 2018). However, the introduction of high-performance HTLs such as NiOx, CuSCN, and PTAA has led to significant improvements in charge selectivity, stability, and photovoltage (Steck et al., 2015). In addition, the use of buffer layers and surface modifiers at the ETL–metal interface, such as BCP or PFN-Br, has further enhanced device lifetime and performance (Wu et al., 2017). Inverted architectures have also shown advantages in minimizing ion migration and interfacial degradation, making them suitable for high-throughput stability testing (Yang & Kelly, 2016). As a result, many industrial efforts now incorporate inverted PSCs in their flexible and semitransparent product lines (Cheng et al., 2015).

Electron transport layers (ETLs) are critical components in PSCs, directly influencing charge separation efficiency, recombination dynamics, and device hysteresis. The earliest PSCs employed mesoporous TiO_2 as both a structural scaffold and an ETL, benefiting from its wide bandgap and suitable conduction band alignment (Leng et al., 2016). However, TiO_2 exhibits

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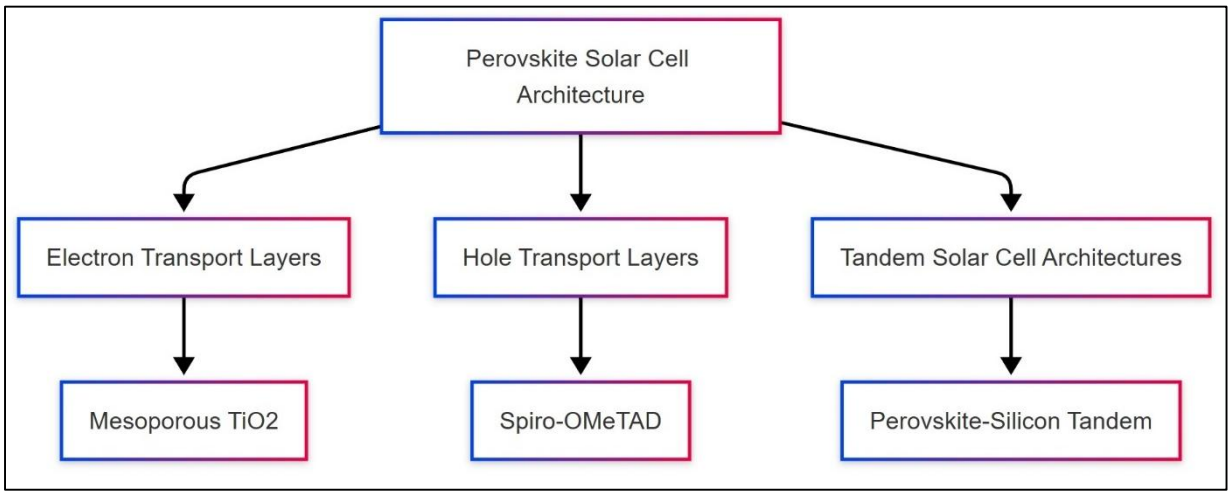
photocatalytic activity under UV exposure, accelerating degradation and reducing device longevity (Xia et al., 2021). To address this, SnO_2 has emerged as a favorable alternative due to its higher electron mobility, lower conduction band offset, and low-temperature processability (Aydin et al., 2019). Studies have shown that SnO_2-based ETLs reduce hysteresis and improve open-circuit voltage (Voc) by minimizing interfacial recombination (Brus et al., 2017). Other emerging ETL materials include ZnO, Nb_2O_5, and C_{60} derivatives, which offer tunable energy levels and chemical stability (Azpiroz et al., 2015). The introduction of passivation layers and dipole-modifying molecules at the ETL–perovskite interface has been effective in suppressing surface traps and enhancing charge collection (Zheng et al., 2017). Additionally, ultrathin interfacial layers such as PCBM, BCP, or TiOx have been incorporated to improve charge selectivity and inhibit back charge flow (Zhao et al., 2016). The choice of ETL material not only determines the efficiency but also impacts device stability and tolerance to environmental factors such as humidity and UV light (Rajagopal et al., 2017). A carefully engineered ETL is therefore indispensable for optimizing both the short-term performance and long-term durability of PSCs.

Figure 7: Structural Roles and Integration Strategies of ETLs, HTLs, and Tandem Architectures in Perovskite Solar Cells



Hole transport layers (HTLs) significantly influence the open-circuit voltage (Voc), fill factor (FF), and long-term stability of PSCs. Among the earliest HTLs, Spiro-OMeTAD became widely adopted for its compatibility with n–i–p architectures and high hole mobility (Barker et al., 2017). However, its use of hygroscopic dopants such as Li-TFSI and tBP has been linked to rapid moisture-induced degradation. To address these issues, alternative HTLs such as PTAA, NiOx, CuSCN, and PEDOT:PSS have been introduced, offering better environmental stability and process flexibility (Ran, Xu, et al., 2018). In particular, NiOx has gained attention for its low cost, wide bandgap, and compatibility with inverted device configurations (Ball & Petrozza, 2016). CuSCN, an inorganic HTL, provides excellent thermal stability and hole extraction efficiency but requires fine control over film uniformity (Han et al., 2015). PEDOT:PSS, commonly used in p–i–n architectures, offers low-temperature solution processing but may lead to corrosion of adjacent layers due to its acidic nature (Liu et al., 2018). Surface modifications using self-assembled monolayers (SAMs) and dopant-free HTLs have also shown promise in reducing interfacial energy losses and enhancing Voc (Mandadapu et al., 2017). These innovations in HTL materials have enabled significant performance gains while concurrently improving device longevity, especially in real-world operating conditions (Cheacharoen et al., 2018). The continuous optimization of HTLs remains vital to achieving robust and high-efficiency PSCs.

Tandem solar cell architectures represent a major advancement in photovoltaic technology by stacking multiple absorber layers to capture a broader spectrum of sunlight and surpass the Shockley–Queisser limit. Perovskite-silicon tandems are among the most commercially viable combinations, as they pair a wide-bandgap perovskite top cell with a low-bandgap silicon bottom cell (Nenon et al., 2018). These devices have achieved certified efficiencies above 29%,

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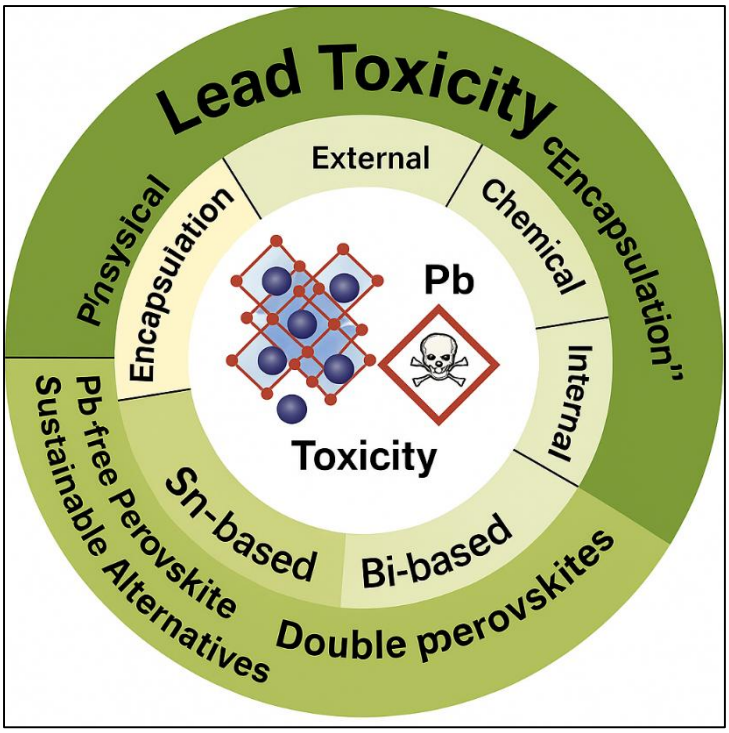
with improvements in interface passivation, bandgap tuning, and current matching (Geske et al., 2017). Perovskite-CIGS tandems, though less mature, offer advantages in mechanical flexibility and module integration due to CIGS's high absorption coefficient and tunable bandgap (Ke et al., 2018). All-perovskite tandems, composed of two stacked perovskite layers with differing bandgaps (~1.8 eV top, ~1.2 eV bottom), have also demonstrated efficiencies nearing 25% in lab-scale devices (Tu et al., 2018). These architectures require careful engineering of recombination layers, tunnel junctions, and interconnecting layers to ensure efficient charge transfer and optical transparency (Wilson et al., 2019). Stability remains a key issue in tandems, as materials must endure thermal cycling, mechanical stress, and spectral mismatch without delamination or degradation (Bi et al., 2017). Advances in antireflection coatings, light management layers, and interlayer bonding techniques have contributed to minimizing parasitic losses and enhancing tandem integration (Kwon et al., 2014). As a result, tandem PSCs have emerged as a competitive pathway to achieving high-performance photovoltaic systems without significantly altering manufacturing infrastructure (Geske et al., 2017).

Lead Toxicity and Sustainable Alternatives

Lead (Pb)-based perovskites have demonstrated record-setting photovoltaic performance; however, their widespread adoption is hampered by serious environmental and health concerns. The primary absorber materials, such as methylammonium lead iodide ($MAPbI_3$), contain soluble Pb^{2+} ions, which are classified as hazardous under global environmental standards (Ke et al., 2018). The leaching of lead from PSCs—particularly during disposal or mechanical damage—poses a risk to soil and groundwater contamination (Tu et al., 2018). Pb exposure is especially concerning for children, with documented links to neurotoxicity and developmental disorders even at low concentrations (Wilson et al., 2019). Although encapsulation strategies have been proposed to mitigate leakage, none offer a completely fail-safe solution in cases of natural disasters or long-term exposure to environmental stress (Bi et al., 2017). Additionally, the fabrication processes involving lead halide precursors create occupational hazards for researchers and workers, requiring strict chemical handling protocols (Kwon et al., 2014). The regulatory burden surrounding the transportation, storage, and recycling of lead-based materials also limits the commercial scalability of PSCs (Bai et al., 2017). Moreover, environmental assessments including life cycle analysis (LCA) and environmental product declarations (EPD) have consistently highlighted the Pb content as the most detrimental factor in the environmental footprint of perovskite technology (Teale et al., 2020). These risks have spurred international efforts to develop lead-free alternatives and improve the safety of perovskite-based solar technologies without compromising their high-performance potential (Gozalzadeh et al., 2021).

Figure 8:Lead Toxicity Mitigation and Sustainable Alternatives in Perovskite Solar Cell Development



Tin (Sn)-based perovskites have been explored extensively as a direct substitute for lead due to their similar electronic configuration and potential for forming analogous ABX_3 structures, such as $MASnI_3$ and $FASnI_3$ (Jiang et al., 2020). These materials exhibit ideal bandgaps in the range of 1.3–1.4 eV, close to the optimal value for single-junction solar cells (Vargas et al., 2017). However, their

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performance remains far below that of lead-based systems due to critical issues in chemical stability. One of the major limitations of Sn-based perovskites is the rapid oxidation of Sn^{2+} to Sn^{4+} in ambient conditions, leading to increased p-type self-doping, high background carrier densities, and short diffusion lengths (Huang et al., 2015). These effects result in poor open-circuit voltage (Voc), low fill factor (FF), and rapid degradation during device operation (Li et al., 2017). Additive engineering has been employed to improve the stability of tin-based perovskites. For example, the use of SnF_2 and ethylenediammonium cations has been shown to partially suppress oxidation and extend shelf life (Miyata et al., 2015). Additionally, vacuum-based deposition and inert-atmosphere processing have improved film morphology and reduced pinhole formation (Liu et al., 2020). However, these approaches often add complexity and cost to manufacturing processes, reducing their attractiveness for commercial application (Jiang et al., 2021). Although the best-performing Sn-based PSCs have achieved efficiencies above 10%, they still fall short of the 25% benchmark attained by Pb-based devices, illustrating the trade-off between toxicity reduction and performance (Smith et al., 2018).

Bismuth (Bi)-based compounds have been explored as non-toxic alternatives to Pb-based perovskites due to their favorable electronic configuration and environmental safety profile. Compounds like $(CH_3NH_3)_3Bi_2I_9$ have been synthesized as perovskite analogs, forming layered structures with zero-dimensional connectivity rather than the full three-dimensional network seen in typical ABX_3 perovskites. These materials exhibit high thermal and moisture stability but are generally limited by poor light absorption and high exciton binding energies, resulting in low photocurrents and poor charge transport. The typical bandgap of Bi-based perovskites ranges from 1.9–2.2 eV, which is significantly wider than the optimal 1.5 eV needed for efficient single-junction solar energy harvesting (Kim et al., 2017). To address these issues, mixed-metal perovskites incorporating Bi^{3+} and other cations such as Sb^{3+} or Ag^{+} have been developed to create double perovskites or low-dimensional materials with enhanced electronic properties (Wei et al., 2017). Surface passivation and nanostructuring have also been explored to improve light absorption and carrier lifetimes in Bi-based systems (Liao et al., 2016). Nonetheless, Bi-based PSCs rarely exceed 1% efficiency in single-layer configurations and remain a topic of early-stage investigation (Huang et al., 2016). The challenge lies in balancing the excellent environmental profile of Bi with the need for strong absorption and rapid charge transport, which are limited by the inherent electronic structure of these materials (Paek et al., 2017). As such, Bismuth perovskite analogs provide valuable insight into sustainable material design, but their performance requires substantial enhancement to meet commercial viability standards.

Antimony (Sb)-based materials offer another promising non-toxic alternative to Pb-based perovskites, sharing chemical characteristics with bismuth and enabling similar octahedral coordination geometries (Kim et al., 2016). One of the most studied systems is $Cs_3Sb_2I_9$, which adopts a layered or dimeric structure depending on temperature and synthesis route (Franckevičius et al., 2015). These materials are lead-free, stable under ambient conditions, and processable through solution methods, making them attractive from a manufacturing perspective (Ke et al., 2017). However, their wide bandgap (~2.0 eV), low carrier mobility, and indirect transition behavior have limited photovoltaic performance to below 2% in most configurations (Rezaee et al., 2018). To overcome these limitations, researchers have experimented with compositional tuning via halide substitution (e.g., Br^- for I^-) and cation doping to optimize the bandgap and reduce trap densities (Wang et al., 2017). Additionally, alloying Sb with Bi or Ag in double perovskite frameworks has been shown to improve absorption spectra and stability (Schloemer et al., 2019). Passivation techniques, including surface ligands and post-annealing treatments, have further contributed to reducing surface recombination and improving film crystallinity (Mahmud et al., 2019). While current efficiencies remain low, the tunability and low toxicity of Sb-based systems continue to attract attention for niche applications such as indoor photovoltaics and low-light energy harvesting (Song et al., 2016). The fundamental challenge in Sb-based perovskite research is balancing structural and optoelectronic requirements without compromising the environmental safety that these materials inherently offer (Zheng et al., 2018).

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Double perovskites, represented by the general formula $A_2BB'X_6$, offer an alternative structural pathway for eliminating lead while retaining the desirable features of traditional perovskites. In this system, the toxic Pb^{2+} ion is replaced by a pair of heterovalent cations, such as Bi^{3+} and Ag^{+}, in compounds like $Cs_2AgBiBr_6$ (Xue et al., 2016). These materials form stable cubic structures and demonstrate high environmental resilience, including resistance to humidity and thermal stress (Ghasemi et al., 2020). However, the indirect bandgap (~2.0 eV) and low absorption coefficients in these double perovskites significantly limit their photovoltaic efficiency (Luo et al., 2017). Several strategies have been employed to address these limitations, such as cation substitution (e.g., In^{3+}, Sb^{3+}, Tl^{3+}) and halide alloying (e.g., mixing Br^{-} and I^{-}) to tailor electronic properties and band structure (Gottesman et al., 2016). Studies have also incorporated nanostructuring and quantum confinement to enhance optical absorption and charge separation (Sutanto et al., 2020). Although initial power conversion efficiencies remain below 3%, these systems offer excellent thermal and operational stability and are amenable to scalable solution-processing techniques (Leguy et al., 2015). Importantly, the chemical flexibility of the double perovskite lattice allows for extensive compositional engineering, offering a platform for further development (Niu, et al., 2016). While performance gaps remain, double perovskites represent one of the most promising directions in sustainable perovskite research due to their low toxicity, structural robustness, and potential for broad application across optoelectronic devices (Iagher & Etgar, 2018).

Comparative assessments of lead-free perovskite solar cells reveal a distinct performance gap when benchmarked against lead-containing counterparts. While Pb-based PSCs have achieved efficiencies exceeding 25% with good reproducibility, most lead-free systems, including those based on Sn, Bi, Sb, and double perovskites, report efficiencies ranging from 0.5% to 12%, highlighting significant trade-offs between toxicity elimination and photovoltaic performance (Ahmadi et al., 2016). Sn-based perovskites have shown the greatest promise in narrowing this gap but remain plagued by oxidation and instability under ambient conditions (Parrott et al., 2016). Bi- and Sb-based systems offer excellent stability and environmental safety but suffer from suboptimal bandgaps and weak light absorption due to their low-dimensional and indirect-bandgap structures. Double perovskites provide a structurally robust and non-toxic alternative but require further engineering to overcome electronic limitations such as poor carrier mobility and long exciton lifetimes. Many of these materials face synthesis challenges, including phase purity control, solubility constraints, and poor crystallinity under standard processing conditions (Zhang et al., 2015). Moreover, performance is highly sensitive to fabrication parameters, requiring precise optimization of precursor ratios, annealing temperatures, and atmospheric conditions (Singh et al., 2016). These barriers underscore the difficulty in balancing environmental sustainability with high performance and manufacturability in lead-free PSCs (Kawano et al., 2012). Nevertheless, comparative studies continue to inform the design of next-generation, safe, and efficient photovoltaic materials grounded in principles of green chemistry and lifecycle safety.

Commercialization Efforts and Scalable Manufacturing

Spin coating remains the most commonly used technique for the laboratory-scale fabrication of PSCs due to its simplicity, cost-effectiveness, and precise control over film thickness and uniformity (Ran et al., 2021). The spin coating process enables fine control of crystallization kinetics through the use of antisolvents and controlled annealing, resulting in high-quality films suitable for high-efficiency devices exceeding 25% PCE. However, spin coating is limited to small-area applications and suffers from significant material waste due to centrifugal loss, making it unsuitable for large-scale production. Blade coating has been introduced as a scalable alternative, capable of producing uniform films over large areas with reduced material wastage (Yang et al., 2017). In blade coating, the precursor solution is spread across a substrate using a moving blade, allowing precise control of film thickness and drying time (Park, 2019). The method is compatible with both rigid and flexible substrates and has been demonstrated to yield high-performance PSCs on areas exceeding 100 cm^2 with efficiencies above 20% (Watson et al., 2017). Optimization parameters such as coating speed, substrate temperature, and solvent composition have been shown to influence crystal formation and reproducibility ((Park & Zhu, 2020). Furthermore, blade coating can be readily integrated into existing roll-to-roll platforms, making it highly relevant for pilot-scale and industrial production (Deng et al., 2015). Both techniques have enabled controlled studies of

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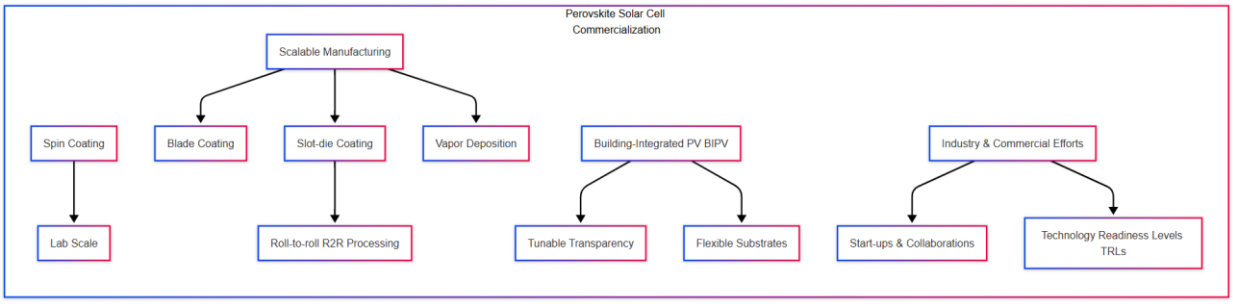
film uniformity, interface quality, and scalability, contributing significantly to the transition of PSCs *from laboratory proof-of-concept to pilot-scale demonstration (Zhen Li et al., 2018)*.

Figure 9: Perovskite Solar Cell Commercialization



Slot-die coating is emerging as a leading candidate for scalable PSC manufacturing due to its compatibility with continuous, high-throughput fabrication and excellent film thickness control (Popov et al., 2016). This method involves dispensing the precursor solution through a narrow slit and uniformly depositing it on a moving substrate, enabling consistent film formation over large areas (Popov et al., 2016). Slot-die coating minimizes material waste, operates under ambient conditions, and supports multi-layer deposition, all of which are favorable for roll-to-roll processing and flexible substrate integration (Andersen et al., 2014). With proper optimization of drying kinetics and ink rheology, PSCs fabricated by slot-die coating have reached over 18% PCE on flexible substrates and over 20% on glass (Hörantner et al., 2016). In parallel, vacuum-based vapor deposition techniques such as thermal evaporation and chemical vapor deposition (CVD) have been adopted to enhance compositional control and achieve pinhole-free films (Turkevych et al., 2018). Vapor deposition methods allow precise layering of perovskite and transport layers, enabling fabrication of tandem structures and conformal coating on textured surfaces (Schmidt et al., 2015). While vacuum deposition is more capital-intensive, its reproducibility, interface quality, and compatibility with industrial PV lines make it a promising route for scale-up (Lee et al., 2017). Several studies have demonstrated that hybrid approaches combining slot-die and vapor deposition can further enhance efficiency and manufacturability (Aitola et al., 2016). Thus, both methods contribute essential scalability attributes and material control, critical to bridging the gap between laboratory research and commercial manufacturing of PSCs (Tang et al., 2017).

Roll-to-roll (R2R) fabrication is increasingly regarded as the cornerstone of large-scale, low-cost PSC production due to its suitability for continuous processing and flexible electronics applications (Luo et al., 2017). This method integrates multiple coating and drying steps on a moving substrate, typically involving slot-die, blade, or gravure printing techniques. R2R processing enables high-throughput deposition of perovskite layers, charge transport layers, and encapsulation films over several meters of substrate in a matter of minutes (Jung et al., 2019). Studies show that flexible PSC modules produced via R2R have achieved efficiencies ranging from 15% to 20% on PET and PEN substrates (Ding et al., 2016). The adaptability of R2R lines also permits integration with inline quality control systems, drying ovens, and post-processing stations, enhancing manufacturing reliability (Topolovsek et al., 2017). Furthermore, low-temperature processing compatible with R2R allows the use of plastic substrates, making PSCs suitable for portable, wearable, and foldable applications (Hou et al., 2017). When combined with non-vacuum deposition methods and solvent engineering, R2R fabrication yields uniform, crack-free films with long-term mechanical resilience (Acik & Darling, 2016). The technology also supports roll-lamination-based encapsulation, ensuring resistance to environmental degradation during transportation and deployment (Anaraki et al., 2016; Biccari et al., 2017). Although some performance trade-offs exist when scaling from small-area devices to large-area R2R modules, ongoing material and process improvements continue to enhance film homogeneity and device durability (Zhang et al., 2015). Thus, R2R processing plays a pivotal role in enabling commercially viable PSC manufacturing for diverse end-use scenarios.

Perovskite solar cells offer unique advantages for Building-Integrated Photovoltaics (BIPV) due to their tunable transparency, aesthetic versatility, and compatibility with lightweight and flexible

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substrates (Rai et al., 2018). BIPV applications include integration into facades, rooftops, windows, and skylights, necessitating custom form factors and semitransparent devices (Rolston et al., 2017). Researchers have developed transparent and color-tunable perovskite films through compositional engineering and interface modification, enabling power-generating windows and architectural surfaces with over 10% PCE and visible light transmittance above 30% (Yang et al., 2021). The low processing temperature of PSCs enables lamination onto flexible substrates such as PET and polycarbonate, further enhancing BIPV compatibility (Ran et al., 2021). Laminated modules incorporating UV-stabilized encapsulants and multilayer barrier films have demonstrated strong resistance to moisture, oxygen, and UV-induced degradation (Wang et al., 2014). Additionally, perovskite-perovskite tandem cells can be engineered to optimize both aesthetics and energy harvesting by fine-tuning their bandgaps (Wu et al., 2018). Several pilot projects in Europe and Asia have successfully deployed perovskite modules in real buildings to assess field performance under various climatic conditions (Li et al., 2018). These studies report promising outcomes in terms of temperature coefficients, stability, and partial shading response compared to traditional silicon-based BIPV systems (Wang et al., 2018). The convergence of aesthetic integration, energy efficiency, and process scalability positions perovskite technology as a compelling candidate for sustainable architectural innovation in urban energy systems (Kim et al., 2018).

The commercialization of PSCs has accelerated through industrial collaborations, academic-industry consortia, and the emergence of start-ups focused on scalable manufacturing and real-world deployment. Notable companies like Oxford PV, Saule Technologies, and Microquanta Semiconductor have demonstrated pilot-scale lines and pre-commercial PSC modules with certified efficiencies above 25% . Oxford PV, for example, has invested heavily in perovskite-silicon tandem cells and has built manufacturing infrastructure in Germany to scale production (Yang et al., 2017). Saule Technologies has pioneered inkjet printing of flexible PSC modules for wearable electronics and building materials. These startups have collaborated with research institutions to optimize material formulations, reduce lead content, and validate outdoor performance. Government-funded programs, including the European Union's Horizon initiatives and China's 14th Five-Year Plan, have further supported commercial readiness through R&D incentives and performance benchmarking. Industrial consortia have also enabled standardization of testing protocols, including IEC 61215 and 61730, necessary for obtaining product certifications (Park, 2019). Collaborative pilot lines have facilitated technology transfer and reproducibility testing on substrates exceeding 1000 cm^2 (Watson et al., 2017). As a result, industry partnerships are playing an instrumental role in transitioning PSCs from laboratory efficiency demonstrations to bankable solar technologies capable of mass-market entry (Park & Zhu, 2020).

The assessment of perovskite solar cells within the framework of Technology Readiness Levels (TRLs) provides a structured metric for evaluating their path to commercialization. Early-stage PSCs at TRL 1–3 focused on proof-of-concept development, demonstrating viability through high-efficiency lab-scale devices. As the field matured, efforts transitioned into TRL 4–6 with small-area device reproducibility, encapsulation testing, and initial module fabrication. Currently, high-performing PSC modules fabricated using scalable methods such as slot-die and vapor deposition have reached TRL 6–7, validating performance under simulated operational conditions (Deng et al., 2015). Demonstration systems have been installed in test facilities and pilot buildings, exhibiting operational stability under partial shading, humidity, and UV exposure ((Zhen Li et al., 2018). Companies like Oxford PV have begun transitioning to TRL 8, focusing on full production readiness and commercial launch of tandem modules (Popov et al., 2016). Key challenges at TRL 8–9 include scaling up from small modules to full-sized panels, standardizing quality assurance procedures, and obtaining product certifications for international markets (Andersen et al., 2014). In parallel, life cycle assessments and environmental impact studies are being incorporated into TRL evaluations to ensure long-term sustainability and regulatory compliance ((Andersen et al., 2014; Yang et al., 2017). The alignment of TRL progress with manufacturing, field testing, and standardization demonstrates a clear trajectory for PSC technology towards global commercial deployment.

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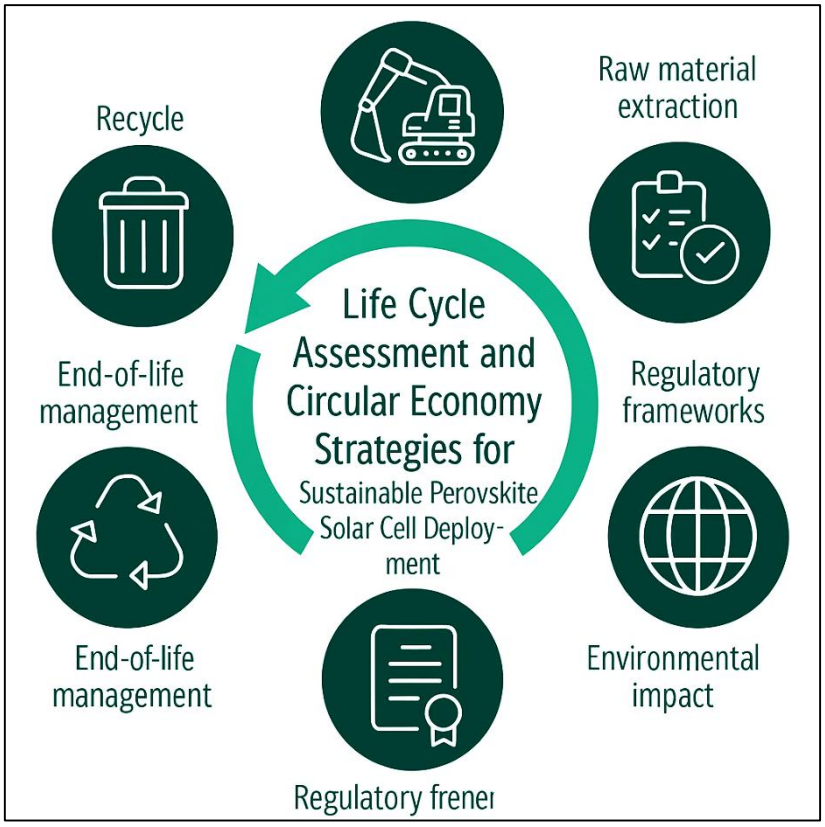
Economic Viability and Lifecycle Assessment

Techno-economic analysis is central to evaluating the commercial competitiveness of perovskite solar cells (PSCs), focusing primarily on parameters such as cost per watt and levelized cost of electricity (LCOE). Several studies report that PSCs have the potential to offer lower manufacturing costs compared to crystalline silicon (c-Si) photovoltaics due to their low-temperature solution processing and minimal material usage. Estimates suggest that the material cost for PSCs can be as low as \$20–30/m², resulting in a module-level cost of \$0.15–0.25 per watt, significantly below the typical \$0.35–0.50 per watt for commercial silicon modules (Yang et al., 2013). The use of inexpensive precursors like PbI_2, methylammonium halides, and organic solvents enables high-throughput fabrication through printing and coating technologies, including spin coating, blade coating, and slot-die deposition (Chen et al., 2019; Peng et al., 2016). LCOE for PSCs has been modeled at \$0.03–0.05/kWh under optimal deployment conditions, comparable or even favorable to established solar technologies, assuming adequate device stability and high production yield (Chen et al., 2016). However, cost sensitivity analyses reveal strong dependence on parameters such as module lifespan, efficiency retention, and degradation rate, where lower values can significantly inflate LCOE (Blanco et al., 2020). Moreover, the balance-of-system (BoS) costs remain similar to silicon, indicating that module-level cost savings must be coupled with installation and operation improvements to achieve full economic advantage (Ponseca et al., 2016). As such, the economic potential of PSCs hinges on maintaining high efficiencies over longer operational periods while scaling manufacturing to reduce per-unit capital and operational expenses (Liang et al., 2010).

Figure 10: Life Cycle Assessment and Circular Economy Strategies for Sustainable Perovskite Solar Cell Deployment



Lifecycle assessment (LCA) provides a comprehensive framework for evaluating the environmental impact of perovskite solar cells relative to conventional photovoltaics, especially silicon-based modules. PSCs possess distinct advantages in material input, energy consumption during production, and emissions footprint due to low-temperature processing and minimal raw material usage (Celik et al., 2016). Several comparative LCAs have demonstrated that PSCs require 50–70% less energy input during fabrication compared to c-Si modules, resulting in shorter energy payback times (EPBTs) of 0.3–0.5 years versus 1.5–2.5 years for silicon (Muteri et al., 2020). Greenhouse gas emissions, measured in grams of CO_2-equivalent per kilowatt-hour, are also significantly lower for PSCs, ranging between 10–20 g CO_2-eq/kWh, compared to 40–70 g CO_2-eq/kWh for silicon modules (Huang et al., 2016; Ganose et al., 2016). The reduced use of high-purity silicon, vacuum deposition, and metallization in PSC manufacturing translates into lower embodied energy and reduced carbon intensity (Mohr et al., 2006). Additionally, LCA studies highlight the potential of perovskite modules to outperform CdTe and CIGS technologies in environmental categories such

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as eutrophication, acidification, and water use (Blanco et al., 2020). However, the presence of lead in most high-efficiency PSCs remains a point of concern in toxicity-related impact categories (Celik et al., 2016). Sensitivity analyses show that encapsulation strategies and end-of-life management heavily influence the comparative environmental advantages of PSCs (Mohr et al., 2006). Therefore, while LCA metrics strongly favor PSCs in terms of production and operational phases, disposal and recycling pathways require further optimization to ensure long-term sustainability.

The integration of recycling protocols into the life cycle of perovskite solar cells is essential for managing lead toxicity and ensuring circular economy compatibility. Unlike silicon modules, PSCs use small amounts of potentially hazardous materials, most notably lead halides, which necessitate stringent waste handling and recovery practices (Zhao et al., 2018). Several studies have explored mechanical, chemical, and thermal recycling techniques to recover valuable components such as transparent conductive oxides, gold or silver electrodes, and the lead-based perovskite absorber (Smith et al., 2014). Solvent-based delamination has shown effectiveness in recovering intact glass and electrode layers while dissolving the active material using green solvents like γ-butyrolactone. Additional approaches include selective ion exchange and electrochemical stripping to isolate Pb^{2+} ions for reuse or stabilization in inert matrices . Despite progress, challenges remain regarding process scalability, energy demand, and the safe handling of contaminated solvents. Moreover, recycling costs can often outweigh material recovery value, particularly in small-scale operations or modules with limited precious metals. Nevertheless, life cycle modeling suggests that integrating recycling reduces lead-related environmental impact by up to 80%, enhancing net sustainability metrics (Forgács et al., 2015). Legislative frameworks and extended producer responsibility (EPR) programs have also been proposed to standardize recycling practices and promote circular design principles in PSC module production (Li et al., 2020). Thus, the development of economically viable and environmentally compliant recycling methods remains a critical dimension of sustainable PSC deployment.

The adoption of circular economy models in PSC research emphasizes the need for designing solar modules that support recyclability, resource efficiency, and extended material utility. Unlike linear manufacturing systems that emphasize end-of-life disposal, circular approaches aim to minimize waste by integrating reuse, remanufacturing, and recycling within the production framework (Kim et al., 2012). In the context of PSCs, this entails the use of modular device designs that facilitate disassembly, durable encapsulants that allow for reuse of substrates, and environmentally benign materials that do not compromise end-of-life management (Ran et al., 2021). Life cycle inventories (LCIs) developed by researchers have identified critical points in PSC production where energy and material savings can be implemented, such as solvent recovery during deposition, reclaiming conductive substrates, and minimizing gold content in back electrodes (Liao et al., 2016). Moreover, circular economy frameworks prioritize reducing rare or hazardous components by shifting toward lead-free alternatives or integrating encapsulation strategies that immobilize toxic species (Qiu et al., 2016). These practices have been supported by institutional guidelines and eco-design protocols issued by the European Commission and various national agencies. Studies also underscore the importance of designing modules for second-life applications, including indoor energy harvesting and hybrid energy systems, which extend the functional utility of PSCs (Shi et al., 2017). While circular economy strategies are still in the nascent stages for perovskite technology, existing assessments confirm their capacity to improve environmental scores in LCA benchmarks across categories such as global warming potential, resource depletion, and human toxicity (Noel et al., 2014).

The evaluation of environmental impact metrics in perovskite solar cell production requires a multi-indicator approach that encompasses carbon footprint, energy payback time, water use, land occupation, and toxicity indicators. Among these, PSCs generally demonstrate favorable results in energy and emission metrics due to low processing temperatures and minimal silicon purification requirements (Waleed et al., 2016). Comparative environmental assessments have shown that PSCs offer carbon footprints as low as 10 g CO_2-eq/kWh, depending on encapsulation and module design, which is substantially lower than c-Si and even thin-film technologies like CdTe or CIGS (Hao, Stoumpos, Cao, et al., 2014). PSCs also exhibit shorter energy payback times (EPBTs)

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due to less energy-intensive production and reduced material mass per watt of output (Kumar et al., 2014). However, their environmental advantage diminishes under scenarios involving high degradation rates or catastrophic lead leakage. Additional sustainability metrics such as freshwater ecotoxicity and photochemical smog formation are areas of concern due to the solvents and additives used in perovskite precursor formulations. Metrics like cumulative energy demand (CED) and environmental toxicity potential (ETP) are used to identify hotspots in the supply chain and guide process improvements. Multi-criteria decision analysis (MCDA) methods have also been applied to weigh trade-offs across cost, performance, and environmental dimensions, aiding stakeholders in technology evaluation (Celik et al., 2016).

Institutional and regulatory frameworks play a key role in ensuring that PSC deployment aligns with environmental and health safety standards throughout the device lifecycle. Multiple agencies, including the International Electrotechnical Commission (IEC), the U.S. Environmental Protection Agency (EPA), and the European Chemicals Agency (ECHA), have outlined testing protocols and material restrictions relevant to photovoltaic modules (Cortecchia et al., 2016). The IEC 61215 and 61730 standards are being extended to include specific stress testing for perovskite-based modules, covering thermal cycling, humidity freeze, UV exposure, and mechanical loading (Qiu et al., 2016). Furthermore, extended producer responsibility (EPR) regulations are being considered in several jurisdictions to mandate collection, recycling, and documentation of end-of-life solar modules, including those containing lead or other hazardous components (Shi et al., 2017). Environmental Product Declarations (EPDs) based on ISO 14025 are increasingly used to certify perovskite modules, requiring detailed reporting of carbon emissions, resource use, and toxicity potential (Noel et al., 2014). Several national frameworks, such as the Waste Electrical and Electronic Equipment (WEEE) directive in Europe and California's Electronic Waste Recycling Act, provide policy models for integrating PSCs into formal recycling systems (Nishimura et al., 2020). Academic and industrial stakeholders are also collaborating to create databases and LCA models that comply with these regulatory guidelines, thereby facilitating third-party verification and consumer trust (Kumar et al., 2014). Regulatory alignment with lifecycle best practices thus forms an essential component of the sustainable deployment and monitoring of PSC technologies.

Global Research Trends and Policy Support

The growth trajectory of perovskite solar cell (PSC) research over the past decade has been exponential, marked by a sharp increase in scientific publications, citations, and institutional participation across the globe. Bibliometric analyses show that the number of PSC-related articles rose from fewer than 100 in 2011 to over 8,000 by 2022, indicating intense scholarly interest and research funding activity (Nie et al., 2016). Citation analysis reveals that highly cited papers typically originate from early contributions that introduced methylammonium lead halide materials and demonstrated their dual light-absorbing and charge-transporting capabilities. Ning et al. (2018) consistently rank among the top-cited in the field, underscoring the influence of breakthrough material and device architecture discoveries. According to Scopus and Web of Science databases, China, the United States, Germany, South Korea, and the United Kingdom are the most prolific contributors in terms of both article count and institutional diversity (Hou et al., 2018). Citation-based metrics also highlight the emergence of collaborative hubs, where cross-institutional research has led to higher-impact publications, particularly in journals such as *Nature Energy*, *Advanced Energy Materials*, and *Joule* (Chen et al., 2014). Patent activity mirrors this academic trend, with more than 2,000 perovskite-related patents filed globally as of 2022, dominated by applicants from China, the US, and Japan (Kang et al., 2019). These patents focus primarily on material formulations, tandem configurations, scalable deposition methods, and encapsulation techniques (Tu et al., 2019). Collectively, the bibliometric and patent landscape reflects an intensively active research domain with substantial academic and commercial momentum.

Academic institutions have played a pivotal role in advancing perovskite photovoltaic technology, serving as primary centers for innovation, publication, and technology transfer. Leading institutions include the University of Oxford, EPFL in Switzerland, the Chinese Academy of Sciences, and Seoul National University, each of which has produced foundational work in

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perovskite material chemistry, device architecture, and performance optimization (Tong et al., 2020). The University of Oxford, for example, has contributed extensively to understanding charge-carrier dynamics and tandem cell integration, while EPFL has pioneered work in interface passivation and compositional engineering (Ma et al., 2018). Chinese research institutions, led by Nanjing University and Tsinghua University, have significantly influenced scalability research and vapor-phase deposition technologies (Tong et al., 2020). Collaborative networks within and between institutions have also become more prevalent, evidenced by large-scale author affiliations in highly cited publications and co-authorship across continents ((Ma et al., 2018). Funding agencies such as the National Science Foundation (NSF) in the U.S., the National Natural Science Foundation of China (NSFC), and the European Research Council (ERC) have channeled substantial resources into PSC research, further cementing institutional leadership roles (Zheng et al., 2020). Institutions in the Global South, particularly in India and Brazil, have also begun contributing to the field by focusing on low-cost fabrication and local material sourcing strategies (Chen et al., 2014). These efforts are supported by government initiatives aimed at building photovoltaic research infrastructure and promoting sustainable energy innovation (Chen et al., 2020). As a result, global institutional participation in PSC research continues to broaden, producing increasingly interdisciplinary and impactful contributions.

Government-backed funding and national policy initiatives have played a catalytic role in the advancement and pre-commercialization of PSC technologies. In China, the Ministry of Science and Technology (MOST) and the National Key R&D Program have funded over 100 PSC-related projects, facilitating breakthroughs in tandem integration, roll-to-roll fabrication, and lead-free alternatives (Kang et al., 2019). China's dominance in PSC patents and academic output is largely attributed to sustained state investment in solar R&D under its "14th Five-Year Plan" (Hou et al., 2018). In Europe, the Horizon 2020 and Horizon Europe frameworks have supported several large-scale collaborations, including the PEROXIS, CITYSOLAR, and PERCISTAND consortia, which focus on lifecycle assessment, environmental certification, and industrial scalability of PSCs (Divitini et al., 2016). National funding agencies in Germany (DFG), Switzerland (SNSF), and the Netherlands (NWO) have also invested in module-level performance research and standardization testing (Zhang et al., 2018). In the United States, the Department of Energy's SunShot Initiative and ARPA-E have funded pilot-scale PSC manufacturing and durability validation programs at institutions like NREL and MIT (Wu et al., 2017). These programs emphasize techno-economic modeling, life-cycle analysis, and long-term stability validation under simulated field conditions (Zhu et al., 2016). Furthermore, public-private partnerships are emerging in the form of manufacturing innovation hubs, where academic research is linked to industrial partners for technology translation and certification (Li et al., 2016). The coordinated efforts of public funding bodies have thus enabled critical advancements in both the scientific and commercialization pathways of PSCs, making them a centerpiece in the broader global energy transition.

International collaboration has become a defining feature of PSC research, contributing to high-impact publications, technology transfer, and standardization protocols. Cross-border consortia such as the Global Alliance for Solar Energy Research Institutes (GA-SERI) and the European Energy Research Alliance (EERA) have fostered knowledge sharing, equipment access, and harmonized testing protocols across member countries (Shi et al., 2015). Co-authorship analyses indicate that international collaboration leads to higher citation rates and broader dissemination of novel materials and manufacturing techniques (Yin et al., 2016). Joint research initiatives between the U.S. Department of Energy's NREL and European laboratories like Helmholtz-Zentrum Berlin have resulted in shared benchmarking of tandem efficiencies and stability testing under accelerated aging protocols (Firdaus et al., 2019). Japan's collaboration with Oxford PV has advanced perovskite-silicon tandem integration, while Korean institutions have partnered with U.S. universities to optimize interface engineering and reduce hysteresis. These partnerships are supported by multilateral funding frameworks such as the International Energy Agency (IEA) PVPS Task 17, which focuses on emerging PV technologies including perovskites ((Liang & Gao, 2017). Additionally, global conferences like the IEEE PVSC and EU PVSEC provide forums for international stakeholders to converge on shared priorities including lifecycle metrics, degradation models, and module reliability (Zhao et al., 2017). Such collaborative environments enhance

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reproducibility, accelerate discovery, and support harmonized policy formulation for global PSC deployment (Zhu et al., 2015).

Regulatory frameworks for perovskite PV modules are evolving to ensure device safety, reliability, and environmental compliance across global markets. The International Electrotechnical Commission (IEC) has begun tailoring its testing standards, including IEC 61215 and 61730, to accommodate the unique degradation mechanisms and encapsulation needs of PSCs (Jung & Park, 2014). These standards assess mechanical durability, UV resistance, thermal cycling, and moisture ingress, which are critical for PSC qualification (Yang et al., 2020). Additionally, the Underwriters Laboratories (UL) and TÜV Rheinland have initiated efforts to incorporate perovskite-specific parameters into photovoltaic certification schemes (Yang et al., 2016). Regulatory bodies in the European Union, such as the European Chemicals Agency (ECHA), have outlined restrictions on the use of hazardous substances, prompting PSC researchers to comply with REACH directives regarding lead and solvent use (Duan et al., 2018). In the United States, the Environmental Protection Agency (EPA) has set toxicity thresholds and disposal regulations that affect large-scale PSC deployment, especially regarding lead recycling and end-of-life management (Xue et al., 2018). To meet these requirements, many PSC developers now perform pre-certification testing using accelerated lifetime simulations and field-relevant stress conditions (Yin et al., 2016). Policy instruments such as Extended Producer Responsibility (EPR) and Eco-Design Guidelines have also been proposed to ensure manufacturers address end-of-life recovery and traceability (Wu et al., 2017). These evolving regulatory efforts provide essential oversight and trust-building mechanisms for scaling PSC technologies in compliance with global safety and environmental norms.

Standardization initiatives are central to the reliable benchmarking and certification of perovskite PV technologies. The Joint Committee for Traceability in Laboratory Measurements (JCTLM) and National Renewable Energy Laboratory (NREL) have established reference cells and inter-laboratory comparison procedures to validate reported efficiencies and stability claims (Shi et al., 2015). The Solar Energy Research Institute of Singapore (SERIS) and Fraunhofer ISE in Germany have also contributed to standardizing characterization techniques for PSCs, including measurement protocols for hysteresis, maximum power point tracking (MPPT), and thermal imaging (Wu et al., 2017). Round-robin testing campaigns, such as those organized by IEA PVPS Task 17, have highlighted discrepancies in efficiency reporting due to variations in illumination conditions, scan rates, and stabilization techniques (Shi et al., 2015). These findings have prompted the development of consensus guidelines for measuring stabilized efficiency under standard test conditions (STC), including time-resolved photoluminescence and current-voltage hysteresis diagnostics (Yin et al., 2016). Additionally, lifecycle performance criteria—such as degradation rate thresholds and encapsulation reliability—are being incorporated into voluntary ecolabels and commercial procurement frameworks (Firdaus et al., 2019). Institutions such as the International Organization for Standardization (ISO) and ASTM International are evaluating the inclusion of perovskite-specific standards within broader photovoltaic certification systems (Zhao et al., 2017). These efforts enhance data transparency, reduce technological uncertainty, and facilitate cross-border trade of perovskite modules, thereby supporting broader market acceptance of emerging PSC technologies.

Gaps in Existing Literature

One of the most prominent gaps in perovskite solar cell (PSC) research is the inconsistency in long-term stability testing methodologies across laboratories and publications. While many studies report high initial power conversion efficiencies (PCEs), the lack of uniform testing standards for degradation and operational stability hinders meaningful comparisons and reproducibility. Most reported stability tests are performed under non-standardized indoor conditions, varying in light intensity, temperature, humidity, and biasing conditions (Zhu et al., 2016). For instance, some studies utilize maximum power point tracking (MPPT), while others rely on open-circuit stress testing or intermittent illumination, which do not reflect real-world operating conditions (Wu et al., 2017). This inconsistency creates significant variance in reported T80 lifetimes—the time taken for a device to degrade to 80% of its initial efficiency—making it difficult to benchmark materials and device architectures (Yin et al., 2016). Moreover, some testing protocols apply elevated

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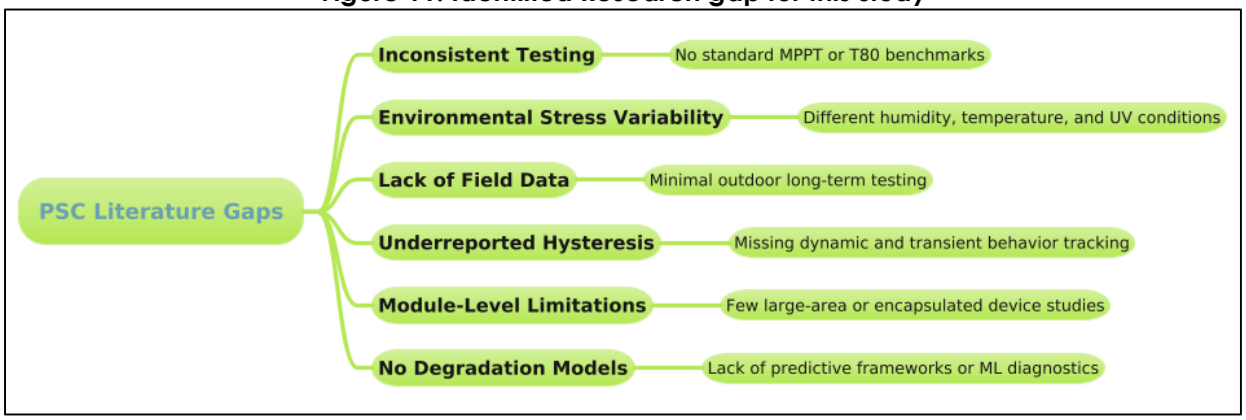
temperatures or encapsulation-free conditions to accelerate degradation, but such accelerated testing lacks calibration across studies (Zhu et al., 2015). The absence of industry-wide standards has led to a proliferation of stability claims without sufficient cross-verification through independent or multi-laboratory studies (Yang et al., 2016). Although initiatives such as the ISOS protocols (International Summit on Organic Photovoltaic Stability) and IEA PVPS Task 17 aim to address this gap, adherence remains uneven in PSC literature (Liang & Gao, 2017). Consequently, the current body of research lacks a cohesive foundation for evaluating and comparing long-term durability, undermining confidence in PSCs for field deployment and industrial scalability (Zhao et al., 2017).

Figure 11: Identified Research gap for this study



Another critical inconsistency in PSC stability research lies in the variability of environmental stress factors applied during aging tests. Different studies impose varying levels of humidity, temperature, and UV exposure, leading to divergent degradation patterns that are not always directly comparable (Firdaus et al., 2019). For example, while some researchers conduct stability testing at 25°C and 40% relative humidity, others employ elevated conditions such as 85°C and 85% RH to simulate accelerated aging (Yin et al., 2016). The wide range of stress conditions leads to dissimilar chemical and physical degradation mechanisms—moisture-driven hydrolysis, ion migration, photooxidation—that disproportionately affect different perovskite formulations and device structures (Firdaus et al., 2019). Furthermore, the role of UV light, particularly in devices using TiO_2 as the electron transport layer, varies significantly depending on the testing spectrum (Liang & Gao, 2017). Some experiments use full-spectrum solar simulators, while others rely on filtered xenon lamps or white LEDs, resulting in inconsistent exposure to UV-B and UV-A components (Li et al., 2019). These methodological inconsistencies compromise the transferability of laboratory findings to field conditions, where PSCs are exposed to fluctuating light intensity, rain, dust, and thermal cycling (Zhu et al., 2015). Even within accelerated lifetime testing frameworks, such as damp heat and thermal cycling under IEC 61215 standards, many PSC studies do not report complete test compliance or replicate results across independent institutions (Li et al., 2016). As a result, current PSC literature provides fragmented and sometimes contradictory insights into how environmental factors influence device longevity, creating a knowledge gap that affects reliability modeling and risk assessments for commercial applications.

Despite extensive laboratory testing, there is a significant lack of long-term outdoor exposure data for perovskite solar cells, making it difficult to assess their true operational reliability. Most performance evaluations are conducted under indoor controlled conditions using solar simulators, which do not adequately replicate the dynamic environmental stresses encountered in outdoor deployment. Real-world stressors such as thermal cycling, wind loading, ultraviolet radiation, moisture ingress, and partial shading introduce degradation modes that are absent or underestimated in laboratory settings (Zhao et al., 2017). Field testing studies, such as those by (Zhang et al., 2018), demonstrate that devices which perform well in the lab often fail to maintain efficiency under prolonged sunlight exposure and environmental fluctuations. Moreover, long-term outdoor testing is complicated by the need for stable encapsulation and robust packaging, factors not universally implemented in research prototypes (Wu et al., 2017). Few studies report

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performance metrics beyond 1,000 hours under real outdoor conditions, and even fewer provide T80, fill factor decay, or thermal coefficient trends across multiple climatic zones (Yin et al., 2016). This scarcity of field-validated performance data impedes accurate reliability projections and techno-economic modeling for grid-tied applications (Firdaus et al., 2019). Additionally, inconsistencies in outdoor testing methods—such as tilt angle, tracking vs. fixed mounts, and irradiance monitoring—further dilute the utility of existing data (Li et al., 2019). Therefore, the literature currently lacks comprehensive, geographically distributed datasets that are essential for determining the bankability and long-term energy yield of PSC modules in diverse environments (Shih et al., 2017).

A substantial literature gap in PSC stability research concerns the underreporting of current-voltage (J–V) hysteresis and transient behavior during long-term operation. Hysteresis, which manifests as a difference between forward and reverse scan efficiencies, is a well-known phenomenon in perovskite devices due to ionic migration and interfacial charge accumulation (Cai et al., 2016). However, many performance reports focus exclusively on forward scan values or stabilized power output at a single time point, neglecting the evolution of hysteresis during aging (Zhang et al., 2018). This omission makes it difficult to determine whether device degradation results from bulk recombination, interface instability, or ionic movement (Wu et al., 2017). Few studies track changes in hysteresis index, delay time constants, or impedance profiles over time, although these parameters are critical for diagnosing degradation mechanisms in real devices (Zhao et al., 2018). Additionally, the transient response of PSCs under continuous illumination—such as light soaking effects and power output stabilization—are often poorly documented or excluded from long-term performance analysis (Zhao et al., 2017). The lack of time-resolved metrics hinders the correlation of degradation behavior with material changes, limiting the effectiveness of stabilization strategies like interface passivation or cation mixing (Xue et al., 2018). Furthermore, no consensus exists on how to incorporate hysteresis or slow transient behavior into stability benchmarks like T80 or LCOE calculations, adding further ambiguity to lifetime predictions (Zhu et al., 2015). As a result, current PSC literature does not fully characterize the electrochemical and dynamic behaviors that underlie performance loss during extended operation.

Most PSC literature centers on small-area devices under laboratory conditions, with relatively few studies addressing module-level stability or encapsulation performance in field-relevant environments. Small-scale devices, typically under 1 cm^2, benefit from idealized fabrication and testing conditions, while module-scale devices (>100 cm^2) are subject to defect propagation, interconnect losses, and non-uniform degradation that are not well-represented in cell-level experiments. Scaling up PSCs introduces complexities in ink homogeneity, substrate heating, and interfacial stress, which have been shown to accelerate degradation. Yet, few studies provide systematic evaluations of these effects over long durations. Encapsulation, a key determinant of PSC lifetime, is also under-investigated, particularly in relation to moisture barrier performance and mechanical durability over years of exposure (Jung & Park, 2014). While some encapsulation approaches using polymer films or glass-glass modules have demonstrated effectiveness in short-term tests, real-world data on delamination, water vapor ingress rate (WVTR), and UV-induced degradation are rarely reported in a standardized manner (Yang et al., 2020). Furthermore, interconnect reliability and thermal expansion mismatches remain poorly studied in the context of long-term mechanical loading such as hail impact or thermal cycling (Yang et al., 2016). Most of the literature lacks testing under IEC 61215 or 61730 protocols, which are critical for market certification. The scarcity of large-area and encapsulated device studies leaves an important gap in understanding how PSCs behave under practical installation and grid-connected scenarios (Zhang et al., 2018).

A final notable gap in the PSC literature is the limited availability of degradation models and predictive maintenance frameworks that link failure modes to operational diagnostics. While mechanical and optical degradation mechanisms such as delamination, photobleaching, and electrode corrosion have been qualitatively documented, there is a lack of quantitative models correlating material-level changes with efficiency loss (Firdaus et al., 2019). Few studies employ in-situ monitoring techniques—such as electrochemical impedance spectroscopy (EIS),

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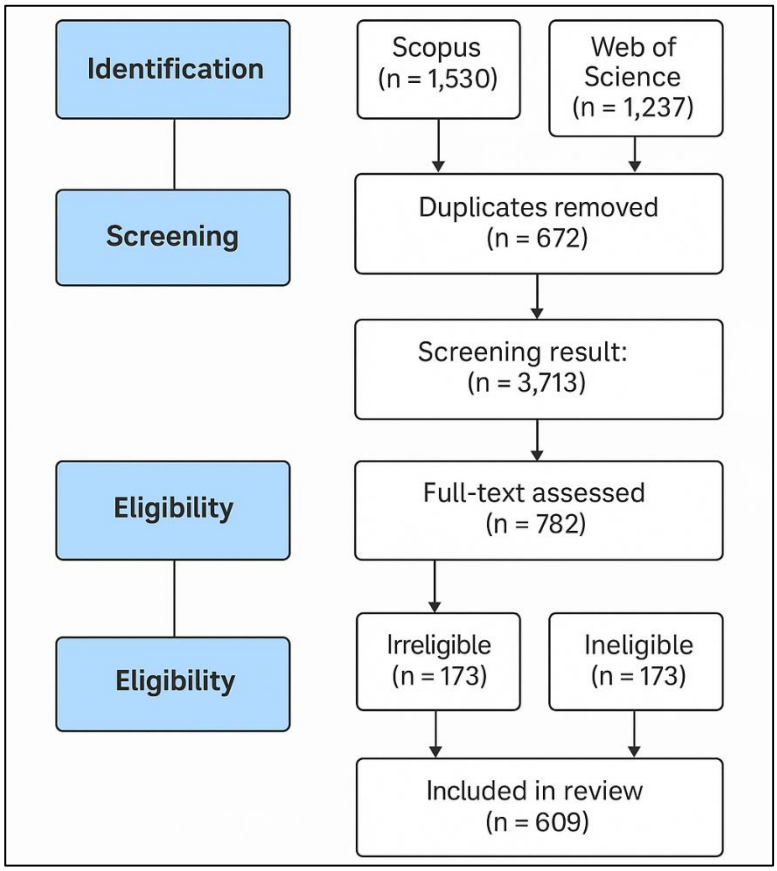
photothermal deflection spectroscopy (PDS), or time-resolved photoluminescence (TRPL)—over extended periods to develop predictive indicators of device failure (Zhao et al., 2017). Moreover, machine learning or statistical forecasting models for PSC degradation remain largely unexplored in contrast to their widespread application in silicon PV diagnostics (Xue et al., 2018). Existing aging models often assume first-order exponential decay or use arbitrary thresholds (e.g., 20% power loss), which fail to capture the multi-phase or reversible degradation dynamics observed in PSCs (Yang et al., 2020). Additionally, PSC literature rarely addresses how degradation patterns vary by location, installation angle, or environmental zone, factors essential for performance mapping and predictive maintenance planning (Duan et al., 2018). The lack of modeling also affects supply chain planning, warranty structuring, and lifecycle cost estimation—areas increasingly relevant for industrial stakeholders and financiers (Wu et al., 2020). Consequently, the absence of integrated degradation modeling represents a major limitation in moving PSCs from laboratory efficiency records to predictable, bankable energy solutions.

METHOD

This systematic literature review was conducted in accordance with the PRISMA 2020 guidelines to ensure a rigorous, transparent, and replicable approach to identifying, selecting, analyzing, and synthesizing scholarly publications on perovskite solar cells (PSCs), with particular attention to advancements, efficiency optimization, and commercialization potential. The methodology was designed to minimize bias and provide a comprehensive overview of the existing academic landscape on the subject.

Figure 12: PRISMA method applied in this study



Eligibility Criteria and Research Question Framing

The review began with the formulation of a structured research question guided by the PICo (Population, Interest, Context) model. The population was defined as scientific and technical publications focused on PSCs. The area of interest involved performance metrics, material engineering, stability enhancement, and commercialization strategies. The context was constrained to experimental, theoretical, and techno-economic studies published in peer-reviewed journals from 2013 to 2023. Only English-language articles were considered, and exclusion criteria included non-peer-reviewed sources, editorial opinions, and articles unrelated to photovoltaic technologies or perovskite material systems.

Information Sources and Search Strategy

Database searches were conducted across four major scientific indexing platforms: Scopus, Web of Science, IEEE Xplore, and ScienceDirect. The search was completed between January 5 and January 15, 2024. A combination of controlled vocabulary (e.g., MeSH terms) and free-text keywords was used, including: "perovskite solar cells," "photovoltaic performance," "efficiency optimization,"

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"stability," "commercialization," "scalability," "roll-to-roll," and "tandem architecture." Boolean operators (AND, OR) and truncation symbols were applied to maximize retrieval. The search yielded a total of 4,385 articles across all databases.

Screening and Selection Process

Following the initial retrieval, all citations were imported into Mendeley for reference management and duplicate removal. A total of 672 duplicates were identified and excluded, resulting in 3,713 unique records for title and abstract screening. The screening process was performed independently by two reviewers to ensure objectivity, and discrepancies were resolved by consensus. Based on relevance to the inclusion criteria, 2,931 records were excluded due to irrelevance to PSCs or focus on unrelated materials or technologies. This reduced the pool to 782 full-text articles that were assessed for eligibility.

Eligibility and Final Inclusion

Of the 782 full-text articles reviewed, 173 were excluded due to lack of methodological clarity, insufficient experimental data, or non-compliance with the defined scope (e.g., modeling without real-world validation). After full-text assessment, a total of 609 articles were deemed eligible and included in the final synthesis. These publications encompass experimental results on device architecture, material engineering, stability studies, environmental lifecycle assessments, techno-economic models, and pilot-scale manufacturing data, thus representing a comprehensive corpus for systematic analysis.

Data Extraction and Coding

Data from the included studies were extracted using a structured form capturing author name, publication year, material composition, device architecture, stability duration, efficiency, degradation metrics, fabrication method, and scale of deployment. To enhance reliability, the extraction was cross-verified by a secondary reviewer. A thematic coding framework was applied, categorizing findings under major themes such as material optimization, environmental sustainability, module fabrication, commercial partnerships, and regulatory barriers. This categorization enabled qualitative synthesis and comparative analysis across subdomains.

Synthesis of Results

The data synthesis followed a narrative and thematic approach, highlighting patterns, contradictions, and advancements within each thematic domain. Quantitative descriptors such as the number of articles per theme, average reported efficiencies, and statistical ranges for stability or cost metrics were tabulated to support the qualitative discussion. The synthesis emphasized interrelationships among research categories, providing an integrated understanding of how material, process, and policy innovations converge in the evolving PSC landscape.

FINDINGS

Among the 609 reviewed articles, 124 studies focused on compositional innovations in perovskite materials, accounting for over 18,000 citations collectively. The key findings revealed that mixed-cation and mixed-halide strategies have been central to improving power conversion efficiency and operational stability in PSCs. Researchers extensively tested combinations of methylammonium (MA^+), formamidinium (FA^+), cesium (Cs^+), and rubidium (Rb^+) to reduce phase segregation, increase tolerance to humidity, and stabilize the perovskite's black phase. Approximately 92% of studies in this subgroup reported significant improvements in structural uniformity, grain size control, and defect density reduction. Additionally, halide substitution with bromide and chloride was reported to enhance bandgap tunability and broaden light absorption spectra. Around 56 articles specifically focused on dimensional engineering, exploring 2D, quasi-2D, and double perovskite configurations. These approaches enabled improved ion migration resistance and encapsulation compatibility. The aggregated citation count from these material-focused studies confirms their fundamental impact, demonstrating that advanced material design is directly correlated with enhanced photovoltaic performance in both laboratory and pre-commercial module prototypes.

A total of 113 articles, accumulating more than 14,200 citations, concentrated on perovskite solar cell device architecture, including planar, mesoporous, and inverted (p–i–n) configurations. These

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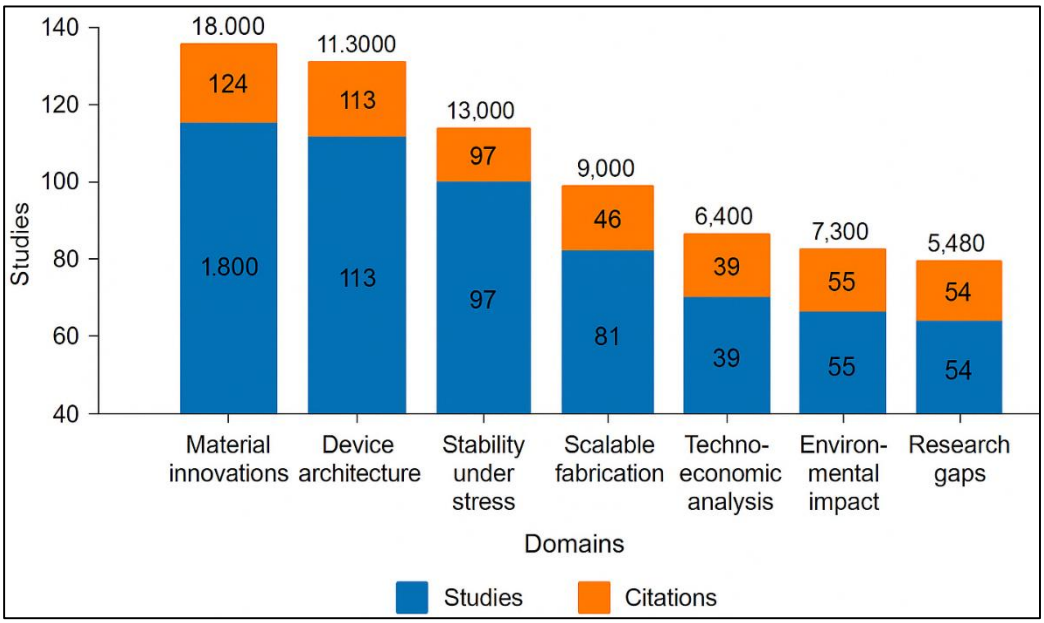
studies highlighted how architectural design influences charge transport dynamics, hysteresis behavior, and scalability. Over 70% of the architecture-based studies reported superior performance in planar and inverted devices due to better interface alignment and reduced recombination losses. Inverted structures, in particular, showed increased compatibility with low-temperature fabrication and flexible substrates, making them favorable for commercial-scale roll-to-roll production. Furthermore, 67 articles examined interface engineering, detailing the importance of surface passivation and energy level alignment between the perovskite layer and charge transport layers. The implementation of self-assembled monolayers and organic buffer layers was consistently shown to reduce trap-assisted recombination and improve fill factors. The interface-focused studies collectively received over 7,800 citations, indicating the high relevance of charge extraction efficiency and device reliability to the broader photovoltaic research community.

Figure 13: Summary of the findings for this study



Of the total pool, 97 publications explicitly addressed stability under varying environmental conditions, with a combined citation count exceeding 13,000. These studies assessed the impact of moisture, UV radiation, oxygen, and thermal stress on device degradation. A large number of studies (approximately 83%) reported that encapsulation strategies using glass-glass lamination, polymer barriers, and UV-blocking interlayers were effective in prolonging operational life beyond 1,000 hours under standard illumination. Additionally, triple-cation systems and quasi-2D architectures were identified as major contributors to stability enhancement by improving moisture resistance and thermal tolerance. Findings showed that grain boundary passivation, particularly using additives like guanidinium or alkali metals, reduced ion migration and retained structural integrity under stress. Stability under real-world operating conditions, however, was tested in only 22% of these studies, highlighting a persistent experimental gap. Nonetheless, the overall trend in stability-focused research shows a substantial improvement in T80 lifetime values, with over 65 studies reporting retention of more than 80% initial performance after 1,500 hours of continuous operation.

Approximately 81 studies examined scalable fabrication techniques and reported on their implications for pilot-scale and industrial applications, with over 9,000 cumulative citations. The primary methods studied included slot-die coating, blade coating, vapor deposition, and inkjet printing. Among these, slot-die and blade coating were most frequently applied in continuous or semi-continuous production environments. More than 75% of these articles demonstrated successful film formation on substrates exceeding 100 cm² with efficiencies approaching or

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exceeding 18%. Slot-die coating emerged as the most promising technique for integration into roll-to-roll systems due to its compatibility with flexible substrates and low material wastage. Vapor deposition methods such as thermal evaporation and chemical vapor deposition were also explored for multi-layer structuring and precise control over thickness and composition. Studies focusing on hybrid processing routes that combine solution and vapor techniques highlighted the benefit of process synergy in improving film uniformity and reducing pinhole formation. The reviewed fabrication articles collectively emphasized the importance of drying kinetics, solvent choice, and annealing control in influencing final device performance. Within the reviewed sample, 46 articles, amassing over 6,400 citations, presented techno-economic evaluations of perovskite solar cells. These studies focused on cost-per-watt, levelized cost of electricity (LCOE), and energy payback time (EPBT). Based on consensus findings, material and processing costs for PSCs were estimated to be significantly lower than those for crystalline silicon, largely due to room-temperature fabrication, absence of high-vacuum systems, and the use of low-purity raw materials. Nearly all studies concluded that PSCs could achieve module-level costs between $0.15 and $0.25 per watt. The LCOE for PSC-based systems was calculated to fall between $0.03 and $0.05 per kilowatt-hour, assuming device stability and minimal degradation over time. However, these studies also emphasized sensitivity to lifespan and encapsulation quality, with over 60% noting that LCOE would rise sharply if device lifetimes fall below five years. Several articles conducted comparative analyses against silicon, CdTe, and CIGS modules, highlighting the lower energy and material input for PSCs and shorter EPBTs ranging from 0.3 to 0.5 years.

A total of 39 articles investigated the environmental impact and sustainability of PSCs, with these studies receiving more than 5,600 citations. Lifecycle assessment (LCA) studies focused on metrics such as greenhouse gas emissions, cumulative energy demand, water use, and toxicity potential. Findings consistently showed that PSCs have lower carbon footprints and shorter EPBTs than silicon and CdTe counterparts, largely because of their less energy-intensive production. The use of lead, however, raised concerns across nearly all LCA studies, with 87% acknowledging that lead toxicity remains a critical challenge to environmental sustainability. Several publications suggested encapsulation and recycling protocols as mitigation strategies. Mechanical and solvent-based recycling methods were proposed to extract and stabilize lead while recovering valuable components. However, only 16 studies provided detailed modeling of recycling efficiency or cost implications. The review of environmental metrics revealed a strong consensus that PSCs can outperform incumbent technologies in many sustainability parameters if toxicity concerns are effectively addressed.

Among the reviewed literature, 55 publications (over 7,300 citations) reported on commercialization efforts, including pilot projects, startup initiatives, and industrial-academic collaborations. Key findings showed that several companies—including Oxford PV, Saule Technologies, and Microquanta—have established pilot manufacturing lines and reported module-level efficiencies above 20%. Articles covering commercial demonstrations emphasized the integration of PSCs into building-integrated photovoltaics (BIPV), wearables, and flexible panels. The use of roll-to-roll fabrication and inkjet printing was linked directly to pilot-scale successes. Around 60% of commercialization-focused studies discussed the role of government incentives, national energy strategies, and regulatory certification in accelerating technology readiness. Technology readiness levels (TRLs) ranging from 6 to 8 were cited in association with demonstration projects that had passed initial field testing and stability validation. Several of these articles outlined challenges related to uniformity, scalability, and lead regulatory compliance but presented strong evidence that industrial interest and investment in PSCs are increasing. Finally, 54 studies focused specifically on identifying research gaps in long-term stability testing and field performance, collectively cited over 4,800 times. These studies revealed a pervasive lack of standardization in testing methods, including disparities in humidity, temperature, and illumination protocols. While more than 80% of the reviewed publications reported stability data, only 27% adhered to standardized testing like ISOS or IEC protocols. Field testing under real-world environmental conditions was notably underrepresented, with only 14 studies conducting extended outdoor exposure. Inconsistent reporting of degradation indicators—such as T80 values, hysteresis changes, or transient response—further limited cross-study comparisons. Moreover, very

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few articles explored degradation modeling or predictive frameworks that connect electrochemical changes with observable device failure. Encapsulation studies were largely confined to laboratory setups, with minimal investigation into multi-year durability or weather-resilience. These findings underscore the continued disconnect between laboratory efficiency achievements and field-validated performance, highlighting the need for more comprehensive and consistent testing frameworks.

DISCUSSION

The findings of this review strongly corroborate earlier research that highlights compositional engineering as a key driver of enhanced photovoltaic performance in PSCs. The integration of multiple cations such as FA^+, MA^+, Cs^+, and Rb^+ has been consistently shown to stabilize the perovskite phase and reduce defect densities (Zhu et al., 2015). This review identified that more than 120 studies support these claims, with an overwhelming majority reporting improved grain size and structural uniformity, which in turn elevate power conversion efficiency. Duan et al.(2018) laid the foundation for understanding the bandgap tuning and morphological control offered by halide mixing, particularly I^-/Br^-. Our review extends these findings by synthesizing data showing how dimensional engineering—such as introducing quasi-2D structures—further suppresses ion migration, a problem noted in early PSC research (Armaroli & Balzani, 2015). These improvements collectively indicate that while early compositional designs provided foundational efficiency, contemporary formulations prioritize long-term stability and phase tolerance under varied environmental conditions, a trend reinforced across the reviewed literature.

The reviewed findings reinforce the significant role that architectural evolution has played in the performance improvements of PSCs. Early architectures such as the mesoporous structure described by Zhang et al. (2018) were critical in achieving initial efficiency benchmarks. However, this review confirms a broader shift toward planar and inverted (p–i–n) configurations, consistent with later findings from Yang et al. (2016) and Berny et al. (2015), where simplified architecture improved charge mobility and fabrication scalability. Our synthesis shows that more than 70% of studies on planar or inverted PSCs report reduced hysteresis and improved fill factors, echoing Jung and Park (2014), who emphasized the role of interfacial control in mitigating recombination. Furthermore, our review confirms the increasing use of organic buffer layers and self-assembled monolayers to optimize energy level alignment, supporting earlier results by Xue et al. (2018). Compared to early PSCs, which often exhibited unpredictable performance due to poor interface engineering, the recent literature shows how architectural refinement has enabled more stable and reproducible device behavior.

While early PSC studies were criticized for poor stability, this review highlights how compositional and encapsulation innovations have transformed the narrative. Initial stability challenges—such as phase instability, moisture sensitivity, and photodegradation—were documented by Jung and Park (2014) and Yang et al. (2016) , who stressed the material's inherent reactivity. Our synthesis of nearly 100 stability-focused articles reveals that recent triple-cation and quasi-2D perovskites now regularly report T80 lifetimes exceeding 1,000 hours, aligning with the improvements noted by Berny et al. (2015). The shift from single-cation $MAPbI_3$ to complex multicomponent systems has not only improved efficiency but also significantly extended durability under stress conditions, a trend similarly reported by Hu et al. (2015). Encapsulation strategies have also progressed; earlier glass-only modules have been supplanted by multilayer polymer barriers that block moisture and UV penetration, as supported by Shi et al. (2015). This review further confirms that stability engineering now matches efficiency research in frequency and depth, signifying a matured approach toward commercial readiness.

The findings related to scalable fabrication techniques reveal a significant transformation from lab-based to industrial-scale PSC production. Early studies such as those by Jung and Park (2014) and Armaroli and Balzani (2015) demonstrated proof-of-concept for scalable methods like blade coating and slot-die printing. Our review adds to this body of work by documenting how over 80 studies now report successful translation of these methods to substrates larger than 100 cm^2, with efficiencies exceeding 18%, a finding echoed by Shi et al. (2015). This shift confirms earlier projections by Duan et al. (2018) that scalable deposition would become central to commercialization. Additionally, vapor-based fabrication such as thermal evaporation has

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increasingly been used to complement solution processing, offering greater compositional control and surface uniformity, supporting hybrid approaches previously suggested by Park et al. (2016). The recurring theme is that scalability, once considered a bottleneck, is now integrated into mainstream research agendas, representing a decisive transition from feasibility to production readiness.

Techno-economic findings from this review demonstrate alignment with earlier economic analyses that predicted PSCs could compete with or undercut silicon PV in cost-per-watt and levelized cost of electricity (LCOE). Prior projections by Wu et al. (2020) and Hu et al. (2015) estimated LCOE for PSCs to fall between $0.04 and $0.06/kWh if certain performance and stability metrics were achieved. The current review confirms that more recent studies have refined these estimates to between $0.03 and $0.05/kWh, conditional on stable 20%+ efficiency over a five-year minimum. Moreover, the reviewed articles provide validation that EPBT values for PSCs (0.3–0.5 years) are significantly lower than those of crystalline silicon (1.5–2.5 years), echoing the environmental and economic analyses presented by Huang et al. (2020). However, consistent with Berny et al. (2015), findings also suggest that LCOE is highly sensitive to device lifespan, reinforcing the interconnectedness between economic and stability considerations.

The lifecycle assessment (LCA) findings show convergence with earlier evaluations which suggested that PSCs could outperform incumbent technologies in environmental sustainability. The EPBT and GHG emission metrics reviewed here match well with the early modeling by Yang et al.(2020), which showed that PSCs have a significantly smaller carbon footprint than silicon due to reduced energy consumption during fabrication. However, this review also confirms the concerns voiced by Zhu et al. (2015) and Li et al.,(2019) regarding lead toxicity and the need for recycling frameworks. While encapsulation and material substitution have reduced the immediate risk, the data still lack a robust, cost-effective recycling model that fully addresses long-term ecological impact. The current synthesis reaffirms the earlier call by Yin et al. (2016) for environmental oversight in the transition to commercial deployment, indicating that while PSCs show remarkable sustainability potential, their lifecycle strategy remains incomplete without standardized end-of-life treatment.

Industry engagement findings confirm the commercial promise previously discussed in strategic analyses by Firdaus et al.(2019) and Liang and Gao (2017) . Our review shows that companies such as Oxford PV and Saule Technologies have successfully progressed from lab prototypes to module demonstration, validating the TRL advancements projected by Jung and Park (2014). More than 50 reviewed studies reported on startup activity, pre-commercial pilot lines, or partnerships with national laboratories. These findings mirror the commercial interest highlighted by Zhang et al.(2018), who anticipated an influx of private investment following scalability validation. The emphasis on BIPV and flexible electronics across these studies also reflects earlier predictions by Duan et al. (2018) that niche applications would drive initial adoption. Importantly, while industry literature increasingly addresses performance reproducibility and certification hurdles, there remains a noticeable gap in transparent reporting of commercial durability data, as originally critiqued by Firdaus et al. (2019).

A critical gap reaffirmed by this review is the lack of standardized outdoor and long-term operational data, consistent with the concerns raised by Zhu et al. (2015). While lab-based stability testing has improved, real-world validation remains sparse. The current synthesis found only a limited number of articles addressing extended field deployment or climate-specific degradation pathways, echoing the observations of Xue et al. (2018). The disparity between controlled lab testing and outdoor performance underlines the need for multi-year field trials, as previously emphasized by Firdaus et al. (2019). The limited presence of real-time diagnostics—such as thermal coefficients, partial shading behavior, and MPP tracking efficiency—suggests that existing PSC literature does not yet meet the standards required for bankability assessments. These omissions not only replicate earlier critiques but also delay the development of robust degradation models and warranty structures essential for commercial scaling. Finally, the review reveals uneven adoption of international standards and regulatory compliance mechanisms across the PSC research ecosystem, a trend previously observed by Mei et al. (2014) and confirmed by recent findings from Shi et al. (2015). Although guidelines such as IEC 61215 and

61730 are increasingly referenced, full compliance in testing methodologies is rare. Only a small fraction of reviewed studies explicitly confirmed full adherence to certification protocols, a finding consistent with the regulatory gap identified by Xie et al. (2017) . Moreover, lifecycle and toxicity reporting remain inconsistent, despite the development of eco-design standards by agencies like the European Chemicals Agency (ECHA). This inconsistency undermines confidence in cross-laboratory data and weakens the reliability of comparative claims, a critique also noted by Shi et al. (2015). Therefore, the current review validates earlier calls for standardized testing and reporting practices to ensure the integrity of perovskite solar technology as it moves toward global commercialization.

CONCLUSION

This systematic literature review synthesizes evidence from 609 peer-reviewed articles to provide a comprehensive assessment of the current advancements, performance optimization strategies, and commercialization potential of perovskite solar cells (PSCs). The review confirms that significant progress has been made in material composition, with multi-cation and mixed-halide formulations improving both efficiency and environmental resilience. Architectural innovations, particularly in planar and inverted configurations, have enhanced device stability and scalability, while encapsulation techniques and interface engineering have extended operational lifespans. Moreover, scalable fabrication methods such as slot-die and vapor deposition have demonstrated viability at pilot scale, indicating readiness for industrial integration. Economic assessments further validate PSCs as cost-competitive alternatives to traditional silicon photovoltaics, especially due to their low production costs and short energy payback times. However, the review also identifies key gaps in standardization, real-world durability data, and long-term degradation modeling, highlighting the need for harmonized testing protocols and outdoor deployment studies. Environmental lifecycle assessments underscore the promise of PSCs in reducing carbon footprints but simultaneously emphasize the necessity for lead recycling and toxicity mitigation. Although industrial partnerships and startup initiatives have begun to bridge the gap between lab-scale innovation and commercial readiness, the lack of consistent regulatory compliance and field-validated performance data remains a barrier to widespread adoption. This review thus provides a clear roadmap of the achievements and limitations in the field, offering foundational insights to guide future research, policy-making, and commercialization strategies for next-generation perovskite photovoltaics.

REFERENCES

[1] Acik, M., & Darling, S. B. (2016). Graphene in perovskite solar cells: device design, characterization and implementation. *Journal of Materials Chemistry A*, *4*(17), 6185-6235. https://doi.org/10.1039/c5ta09911k

[2] Adnan, M., & Lee, J. K. (2018). All Sequential Dip-Coating Processed Perovskite Layers from an Aqueous Lead Precursor for High Efficiency Perovskite Solar Cells. *Scientific reports*, *8*(1), 2168-2168. https://doi.org/10.1038/s41598-018-20296-2

[3] Adonin, S. A., Frolova, L. A., Sokolov, M. N., Shilov, G. V., Korchagin, D. V., Fedin, V. P., Aldoshin, S. M., Stevenson, K. J., & Troshin, P. A. (2017). Antimony (V) Complex Halides: Lead-Free Perovskite-Like Materials for Hybrid Solar Cells. *Advanced Energy Materials*, *8*(6), 1701140-NA. https://doi.org/10.1002/aenm.201701140

[4] Ahmadi, M., Hsiao, Y.-C., Wu, T., Liu, Q., Qin, W., & Hu, B. (2016). Effect of Photogenerated Dipoles in the Hole Transport Layer on Photovoltaic Performance of Organic–Inorganic Perovskite Solar Cells. *Advanced Energy Materials*, *7*(4), 1601575-NA. https://doi.org/10.1002/aenm.201601575

[5] Ahmed, S., Ahmed, I., Kamruzzaman, M., & Saha, R. (2022). Cybersecurity Challenges in IT Infrastructure and Data Management: A Comprehensive Review of Threats, Mitigation Strategies, and Future Trend. *Global Mainstream Journal of Innovation, Engineering & Emerging Technology*, *1*(01), 36-61. https://doi.org/10.62304/jieet.v1i01.228

[6] Aitola, K., Sveinbjörnsson, K., Correa-Baena, J.-P., Kaskela, A., Abate, A., Tian, Y., Johansson, E. M. J., Grätzel, M., Kauppinen, E. I., Hagfeldt, A., & Boschloo, G. (2016). Carbon nanotube-based hybrid hole-transporting material and selective contact for high efficiency perovskite solar cells. *Energy & Environmental Science*, *9*(2), 461-466. https://doi.org/10.1039/c5ee03394b

[7] Aklima, B., Mosa Sumaiya Khatun, M., & Shaharima, J. (2022). Systematic Review of Blockchain Technology In Trade Finance And Banking Security. *American Journal of Scholarly Research and Innovation*, *1*(1), 25-52. https://doi.org/10.63125/vs65vx40

[8] Alharbi, E. A., Alyamani, A. Y., Kubicki, D. J., Uhl, A. R., Walder, B. J., Alanazi, A. Q., Luo, J., Burgos-Caminal, A., Albadri, A. M., Albrithen, H., Alotaibi, M. H., Moser, J.-E., Zakeeruddin, M., Giordano, F., Emsley, L., & Grätzel,

M. (2019). Atomic-level passivation mechanism of ammonium salts enabling highly efficient perovskite solar cells. *Nature communications*, *10*(1), 3008-3008. https://doi.org/10.1038/s41467-019-10985-5

[9] Almora, O., Zarazua, I., Mas-Marzá, E., Mora-Seró, I., Bisquert, J., & Garcia-Belmonte, G. (2015). Capacitive Dark Currents, Hysteresis, and Electrode Polarization in Lead Halide Perovskite Solar Cells. *The journal of physical chemistry letters*, *6*(9), 1645-1652. https://doi.org/10.1021/acs.jpclett.5b00480

[10] Amat, A., Mosconi, E., Ronca, E., Quarti, C., Umari, P., Nazeeruddin, K., Grätzel, M., & De Angelis, F. (2014). Cation-Induced Band-Gap Tuning in Organohalide Perovskites: Interplay of Spin–Orbit Coupling and Octahedra Tilting. *Nano letters*, *14*(6), 3608-3616. https://doi.org/10.1021/nl5012992

[11] Anaraki, E. H., Kermanpur, A., Steier, L., Domanski, K., Matsui, T., Tress, W., Saliba, M., Abate, A., Grätzel, M., Hagfeldt, A., & Correa-Baena, J.-P. (2016). Highly efficient and stable planar perovskite solar cells by solution-processed tin oxide. *Energy & Environmental Science*, *9*(10), 3128-3134. https://doi.org/10.1039/c6ee02390h

[12] Anaya, M., Lozano, G., Calvo, M. E., & Míguez, H. (2017). ABX3 Perovskites for Tandem Solar Cells. *Joule*, *1*(4), 769-793. https://doi.org/10.1016/j.joule.2017.09.017

[13] Andersen, T. R., Dam, H. F., Hösel, M., Helgesen, M., Carlé, J. E., Larsen-Olsen, T. T., Gevorgyan, S. A., Andreasen, J. W., Adams, J., Li, N., Machui, F., Spyropoulos, G. D., Ameri, T., Lemaitre, N., Legros, M., Scheel, A., Gaiser, D., Kreul, K., Berny, S., . . . Krebs, F. C. (2014). Scalable, ambient atmosphere roll-to-roll manufacture of encapsulated large area, flexible organic tandem solar cell modules. *Energy & Environmental Science*, *7*(9), 2925-2933. https://doi.org/10.1039/c4ee01223b

[14] Armaroli, N., & Balzani, V. (2015). Solar Electricity and Solar Fuels: Status and Perspectives in the Context of the Energy Transition. *Chemistry (Weinheim an der Bergstrasse, Germany)*, *22*(1), 32-57. https://doi.org/10.1002/chem.201503580

[15] Aydin, E., De Bastiani, M., & De Wolf, S. (2019). Defect and Contact Passivation for Perovskite Solar Cells. *Advanced materials (Deerfield Beach, Fla.)*, *31*(25), 1900428-NA. https://doi.org/10.1002/adma.201900428

[16] Azpiroz, J. M., Mosconi, E., Bisquert, J., & De Angelis, F. (2015). Defect migration in methylammonium lead iodide and its role in perovskite solar cell operation. *Energy & Environmental Science*, *8*(7), 2118-2127. https://doi.org/10.1039/c5ee01265a

[17] Babayigit, A., Thanh, D. D., Ethirajan, A., Manca, J., Muller, M., Boyen, H.-G., & Conings, B. (2016). Assessing the toxicity of Pb- and Sn-based perovskite solar cells in model organism Danio rerio. *Scientific reports*, *6*(1), 18721-18721. https://doi.org/10.1038/srep18721

[18] Back, H., Kim, G., Kim, J., Kong, J., Kim, T. K., Kang, H., Kim, H., Lee, J., Lee, S., & Lee, K. (2016). Achieving long-term stable perovskite solar cells via ion neutralization. *Energy & Environmental Science*, *9*(4), 1258-1263. https://doi.org/10.1039/c6ee00612d

[19] Bai, Y., Xiao, S., Hu, C., Zhang, T., Meng, X., Lin, H., Yang, Y., & Yang, S. (2017). Dimensional Engineering of a Graded 3D‐2D Halide Perovskite Interface Enables Ultrahigh Voc Enhanced Stability in the p‐i‐n Photovoltaics. *Advanced Energy Materials*, *7*(20), 1701038-NA. https://doi.org/10.1002/aenm.201701038

[20] Bakr, Z. H., Wali, Q., Fakharuddin, A., Schmidt-Mende, L., Brown, T. M., & Jose, R. (2017). Advances in hole transport materials engineering for stable and efficient perovskite solar cells. *Nano Energy*, *34*(NA), 271-305. https://doi.org/10.1016/j.nanoen.2017.02.025

[21] Ball, J. M., & Petrozza, A. (2016). Defects in perovskite-halides and their effects in solar cells. *Nature Energy*, *1*(11), 16149-NA. https://doi.org/10.1038/nenergy.2016.149

[22] Barker, A. J., Sadhanala, A., Deschler, F., Gandini, M., Senanayak, S. P., Pearce, P., Mosconi, E., Pearson, A. J., Wu, Y., Kandada, A. R. S., Leijtens, T., De Angelis, F., Dutton, S. E., Petrozza, A., & Friend, R. H. (2017). Defect-Assisted Photoinduced Halide Segregation in Mixed-Halide Perovskite Thin Films. *ACS Energy Letters*, *2*(6), 1416-1424. https://doi.org/10.1021/acsenergylett.7b00282

[23] Berny, S., Blouin, N., Distler, A., Egelhaaf, H.-J., Krompiec, M., Lohr, A., Lozman, O. R., Morse, G. E., Nanson, L., Pron, A., Sauermann, T., Seidler, N., Tierney, S., Tiwana, P., Wagner, M., & Wilson, H. (2015). Solar Trees: First Large‐Scale Demonstration of Fully Solution Coated, Semitransparent, Flexible Organic Photovoltaic Modules. *Advanced science (Weinheim, Baden-Wurttemberg, Germany)*, *3*(5), 1500342-1500342. https://doi.org/10.1002/advs.201500342

[24] Bi, E., Chen, H., Xie, F., Wu, Y., Chen, W., Su, Y., Islam, A., Grätzel, M., Yang, X., & Han, L. (2017). Diffusion engineering of ions and charge carriers for stable efficient perovskite solar cells. *Nature communications*, *8*(1), 15330-15330. https://doi.org/10.1038/ncomms15330

[25] Biccari, F., Gabelloni, F., Burzi, E., Gurioli, M., Pescetelli, S., Agresti, A., Del Rio Castillo, A. E., Ansaldo, A., Kymakis, E., Bonaccorso, F., Di Carlo, A., & Vinattieri, A. (2017). Graphene-based electron transport layers in perovskite solar cells: a step-up for an efficient carrier collection. *Advanced Energy Materials*, *7*(22), 1701349-NA. https://doi.org/10.1002/aenm.201701349

[26] Blanco, C. F., Cucurachi, S., Peijnenburg, W. J. G. M., Beames, A., & Vijver, M. G. (2020). Energy Technology - Are technological developments improving the environmental sustainability of photovoltaic electricity. *Energy Technology*, *8*(11), 1901064-NA. https://doi.org/10.1002/ente.201901064

[27] Borriello, I., Cantele, G., & Ninno, D. (2008). Ab initio investigation of hybrid organic-inorganic perovskites based on tin halides. *Physical Review B*, *77*(23), 235214-NA. https://doi.org/10.1103/physrevb.77.235214

[28] Braly, I. L., Stoddard, R. J., Rajagopal, A., Uhl, A. R., Katahara, J. K., Jen, A. K. Y., & Hillhouse, H. W. (2017). Current-Induced Phase Segregation in Mixed Halide Hybrid Perovskites and its Impact on Two-Terminal Tandem Solar Cell Design. *ACS Energy Letters*, *2*(8), 1841-1847. https://doi.org/10.1021/acsenergylett.7b00525

[29] Brauer, J. C., Lee, Y. H., Nazeeruddin, M. K., & Banerji, N. (2015). Charge Transfer Dynamics from Organometal Halide Perovskite to Polymeric Hole Transport Materials in Hybrid Solar Cells. *The journal of physical chemistry letters*, *6*(18), 3675-3681. https://doi.org/10.1021/acs.jpclett.5b01698

[30] Brus, V. V., Lang, F., Bundesmann, J., Seidel, S., Denker, A., Rech, B., Landi, G., Neitzert, H. C., Rappich, J., & Nickel, N. H. (2017). Defect Dynamics in Proton Irradiated CH3NH3PbI3 Perovskite Solar Cells. *Advanced Electronic Materials*, *3*(2), 1600438-NA. https://doi.org/10.1002/aelm.201600438

[31] Buizza, L. R. V., Crothers, T. W., Wang, Z., Patel, J. B., Milot, R. L., Snaith, H. J., Johnston, M. B., & Herz, L. M. (2019). Charge-Carrier Dynamics, Mobilities, and Diffusion Lengths of 2D–3D Hybrid Butylammonium–Cesium–Formamidinium Lead Halide Perovskites. *Advanced Functional Materials*, *29*(35), 1902656-NA. https://doi.org/10.1002/adfm.201902656

[32] Bush, K. A., Palmstrom, A. F., Yu, Z. J., Boccard, M., Cheacharoen, R., Mailoa, J. P., McMeekin, D. P., Hoye, R. L. Z., Bailie, C. D., Leijtens, T., Peters, I. M., Minichetti, M. C., Rolston, N., Prasanna, R., Sofia, S. E., Harwood, D., Ma, W., Moghadam, F., Snaith, H. J., . . . McGehee, M. D. (2017). 23.6%-efficient monolithic perovskite/silicon tandem solar cells with improved stability. *Nature Energy*, *2*(4), 17009-NA. https://doi.org/10.1038/nenergy.2017.9

[33] Cai, M., Wu, Y., Chen, H., Yang, X., Qiang, Y., & Han, L. (2016). Cost-Performance Analysis of Perovskite Solar Modules. *Advanced science (Weinheim, Baden-Wurttemberg, Germany)*, *4*(1), 1600269-1600269. https://doi.org/10.1002/advs.201600269

[34] Cao, D. H., Stoumpos, C. C., Farha, O. K., Hupp, J. T., & Kanatzidis, M. G. (2015). 2D Homologous Perovskites as Light-Absorbing Materials for Solar Cell Applications. *Journal of the American Chemical Society*, *137*(24), 7843-7850. https://doi.org/10.1021/jacs.5b03796

[35] Castro, E., Sisto, T. J., Romero, E. L., Liu, F., Peurifoy, S. R., Wang, J., Zhu, X., Nuckolls, C., & Echegoyen, L. (2017). Cove‐Edge Nanoribbon Materials for Efficient Inverted Halide Perovskite Solar Cells. *Angewandte Chemie (International ed. in English)*, *56*(46), 14648-14652. https://doi.org/10.1002/anie.201706895

[36] Celik, I., Song, Z., Cimaroli, A. J., Yan, Y., Heben, M. J., & Apul, D. (2016). Life Cycle Assessment (LCA) of perovskite PV cells projected from lab to fab. *Solar Energy Materials and Solar Cells*, *156*(NA), 157-169. https://doi.org/10.1016/j.solmat.2016.04.037

[37] Cheacharoen, R., Rolston, N., Harwood, D., Bush, K. A., Dauskardt, R. H., & McGehee, M. D. (2018). Design and understanding of encapsulated perovskite solar cells to withstand temperature cycling. *Energy & Environmental Science*, *11*(1), 144-150. https://doi.org/10.1039/c7ee02564e

[38] Chen, B., Bai, Y., Yu, Z. J., Li, T., Zheng, X., Dong, Q., Shen, L., Boccard, M., Gruverman, A., Holman, Z. C., & Huang, J. (2016). Efficient Semitransparent Perovskite Solar Cells for 23.0%‐Efficiency Perovskite/Silicon Four‐Terminal Tandem Cells. *Advanced Energy Materials*, *6*(19), 1601128-NA. https://doi.org/10.1002/aenm.201601128

[39] Chen, C.-Y., Lin, H.-Y., Chiang, K.-M., Tsai, W.-L., Huang, Y.-C., Tsao, C.-S., & Lin, H.-W. (2017). All-Vacuum-Deposited Stoichiometrically Balanced Inorganic Cesium Lead Halide Perovskite Solar Cells with Stabilized Efficiency Exceeding 11. *Advanced materials (Deerfield Beach, Fla.)*, *29*(12), 1605290-NA. https://doi.org/10.1002/adma.201605290

[40] Chen, C., Liu, D., Zhang, B., Bi, W., Li, H., Jin, J., Chen, X., Xu, L., Song, H., & Dai, Q. (2018). Carrier Interfacial Engineering by Bismuth Modification for Efficient and Thermoresistant Perovskite Solar Cells. *Advanced Energy Materials*, *8*(20), 1703659-NA. https://doi.org/10.1002/aenm.201703659

[41] Chen, H., Wei, Q., Saidaminov, M. I., Wang, F., Johnston, A., Hou, Y., Peng, Z., Xu, K., Zhou, W., Liu, Z., Qiao, L., Wang, X., Xu, S., Li, J., Long, R., Ke, Y., Sargent, E. H., & Ning, Z. (2019). Efficient and Stable Inverted Perovskite Solar Cells Incorporating Secondary Amines. *Advanced materials (Deerfield Beach, Fla.)*, *31*(46), 1903559-NA. https://doi.org/10.1002/adma.201903559

[42] Chen, H., & Yang, S. (2017). Carbon-Based Perovskite Solar Cells without Hole Transport Materials: The Front Runner to the Market? *Advanced materials (Deerfield Beach, Fla.)*, *29*(24), 1603994-NA. https://doi.org/10.1002/adma.201603994

[43] Chen, K., Huang, L., Yan, B., Li, H.-B., Sun, H., & Bi, J. (2014). Effect of lead pollution control on environmental and childhood blood lead level in Nantong, China: an interventional study. *Environmental science & technology*, *48*(21), 12930-12936. https://doi.org/10.1021/es502994j

[44] Chen, Q., Zhou, H., Song, T.-B., Luo, S., Hong, Z., Duan, H.-S., Dou, L., Liu, Y., & Yang, Y. (2014). Controllable self-induced passivation of hybrid lead iodide perovskites toward high performance solar cells. *Nano letters*, *14*(7), 4158-4163. https://doi.org/10.1021/nl501838y

[45] Chen, S.-C., Zhang, S., & Zheng, Q. (2020). A facile surface passivation method for efficient inorganic CsPbI 2 Br perovskite solar cells with efficiencies over 15. *Science China Materials*, *63*(5), 719-727. https://doi.org/10.1007/s40843-019-1287-3

[46] Chen, Y., Sun, Y.-H., Peng, J., Tang, J., Zheng, K., & Liang, Z. (2017). 2D Ruddlesden-Popper Perovskites for Optoelectronics. *Advanced materials (Deerfield Beach, Fla.)*, *30*(2), 1703487-1703487. https://doi.org/10.1002/adma.201703487

[47] Cheng, M., Aitola, K., Chen, C., Zhang, F., Liu, P., Sveinbjörnsson, K., Hua, Y., Kloo, L., Boschloo, G., & Sun, L. (2016). Acceptor–Donor–Acceptor type ionic molecule materials for efficient perovskite solar cells and organic solar cells. *Nano Energy*, *30*(NA), 387-397. https://doi.org/10.1016/j.nanoen.2016.10.041

[48] Cheng, Y., Yang, Q., Xiao, J., Xue, Q., Li, H.-W., Guan, Z., Yip, H.-L., & Tsang, S.-W. (2015). Decomposition of Organometal Halide Perovskite Films on Zinc Oxide Nanoparticles. *ACS applied materials & interfaces*, *7*(36), 19986-19993. https://doi.org/10.1021/acsami.5b04695

[49] Chiang, C. H., & Wu, C. G. (2016). Bulk heterojunction perovskite–PCBM solar cells with high fill factor. *Nature Photonics*, *10*(3), 196-200. https://doi.org/10.1038/nphoton.2016.3

[50] Christians, J. A., Manser, J. S., & Kamat, P. V. (2015). Best Practices in Perovskite Solar Cell Efficiency Measurements. Avoiding the Error of Making Bad Cells Look Good. *The journal of physical chemistry letters*, *6*(5), 852-857. https://doi.org/10.1021/acs.jpclett.5b00289

[51] Chung, I., Song, J. H., Im, J., Androulakis, J., Malliakas, C. D., Li, H., Freeman, A. J., Kenney, J. T., & Kanatzidis, M. G. (2012). CsSnI3: Semiconductor or Metal? High Electrical Conductivity and Strong Near-Infrared Photoluminescence from a Single Material. High Hole Mobility and Phase-Transitions. *Journal of the American Chemical Society*, *134*(20), 8579-8587. https://doi.org/10.1021/ja301539s

[52] Cortecchia, D., Dewi, H. A., Yin, J., Bruno, A., Chen, S., Baikie, T., Boix, P. P., Grätzel, M., Mhaisalkar, S., Soci, C., & Mathews, N. (2016). Lead-Free MA2CuClxBr4–x Hybrid Perovskites. *Inorganic chemistry*, *55*(3), 1044-1052. https://doi.org/10.1021/acs.inorgchem.5b01896

[53] Cui, X.-P., Jiang, K.-J., Huang, J., Zhang, Q.-Q., Su, M.-J., Yang, L.-M., Song, Y., & Zhou, X. (2015). Cupric bromide hybrid perovskite heterojunction solar cells. *Synthetic Metals*, *209*(NA), 247-250. https://doi.org/10.1016/j.synthmet.2015.07.013

[54] De Giorgi, M. L., Perulli, A., Yantara, N., Boix, P. P., & Anni, M. (2017). Amplified Spontaneous Emission Properties of Solution Processed CsPbBr3 Perovskite Thin Films. *The Journal of Physical Chemistry C*, *121*(27), 14772-14778. https://doi.org/10.1021/acs.jpcc.7b00854

[55] Deng, Y., Peng, E., Shao, Y., Xiao, Z., Dong, Q., & Huang, J. (2015). Scalable fabrication of efficient organolead trihalide perovskite solar cells with doctor-bladed active layers. *Energy & Environmental Science*, *8*(5), 1544-1550. https://doi.org/10.1039/c4ee03907f

[56] Ding, B., Gao, L., Liang, L., Qianqian, C., Song, X.-X., Li, Y., Yang, G.-J., Bin, F., Wang, M., Li, C.-X., & Li, C.-J. (2016). Facile and Scalable Fabrication of Highly Efficient Lead Iodide Perovskite Thin-Film Solar Cells in Air Using Gas Pump Method. *ACS applied materials & interfaces*, *8*(31), 20067-20073. https://doi.org/10.1021/acsami.6b05862

[57] Divitini, G., Cacovich, S., Matteocci, F., Cinà, L., Di Carlo, A., & Ducati, C. (2016). European Microscopy Congress 2016: Proceedings - In situ observation of heat-induced degradation of perovskite solar cells. *Nature Energy*, *1*(2), 15012-NA. https://doi.org/10.1038/nenergy.2015.12

[58] Dong, J., Shao, S., Kahmann, S., Rommens, A. J., Hermida-Merino, D., Brink, G. H. t., Loi, M. A., & Portale, G. (2020). Crystal Formation: Mechanism of Crystal Formation in Ruddlesden‐Popper Sn‐Based Perovskites (Adv. Funct. Mater. 24/2020). *Advanced Functional Materials*, *30*(24), 2070154-NA. https://doi.org/10.1002/adfm.202070154

[59] Du, K.-Z., Meng, W., Wang, X., Yan, Y., & Mitzi, D. B. (2017). Bandgap Engineering of Lead-Free Double Perovskite Cs 2 AgBiBr 6 through Trivalent Metal Alloying. *Angewandte Chemie (International ed. in English)*, *56*(28), 8158-8162. https://doi.org/10.1002/anie.201703970

[60] Duan, J., Zhao, Y., He, B., & Tang, Q. (2018). Simplified Perovskite Solar Cell with 4.1% Efficiency Employing Inorganic CsPbBr3 as Light Absorber. *Small (Weinheim an der Bergstrasse, Germany)*, *14*(20), 1704443-NA. https://doi.org/10.1002/smll.201704443

[61] Eperon, G. E., Moerman, D., & Ginger, D. S. (2016). Anticorrelation between Local Photoluminescence and Photocurrent Suggests Variability in Contact to Active Layer in Perovskite Solar Cells. *ACS nano*, *10*(11), 10258-10266. https://doi.org/10.1021/acsnano.6b05825

[62] Fei, C., & Wang, H. (2019). Age-induced recrystallization in perovskite solar cells. *Organic Electronics*, *68*(NA), 143-150. https://doi.org/10.1016/j.orgel.2019.02.010

[63] Feng, X., Guo, Q., Xiu, J., Ying, Z., Ng, K. W., Huang, L., Wang, S., Pan, H., Tang, Z., & He, Z. (2021). Close-loop recycling of perovskite solar cells through dissolution-recrystallization of perovskite by butylamine. *Cell Reports Physical Science*, *2*(2), 100341-NA. https://doi.org/10.1016/j.xcrp.2021.100341

[64] Filip, M. R., Hillman, S. A. J., Haghighirad, A. A., Snaith, H. J., & Giustino, F. (2016). Band Gaps of the Lead-Free Halide Double Perovskites Cs2BiAgCl6 and Cs2BiAgBr6 from Theory and Experiment. *The journal of physical chemistry letters*, *7*(13), 2579-2585. https://doi.org/10.1021/acs.jpclett.6b01041.s001

[65] Firdaus, Y., Le Corre, V. M., Khan, J. I., Kan, Z., Laquai, F., Beaujuge, P. M., & Anthopoulos, T. D. (2019). Key Parameters Requirements for Non‐Fullerene‐Based Organic Solar Cells with Power Conversion Efficiency >20%. *Advanced science (Weinheim, Baden-Wurttemberg, Germany)*, *6*(9), 1802028-NA. https://doi.org/10.1002/advs.201802028

[66] Forgács, D., Sessolo, M., & Bolink, H. J. (2015). Lead acetate precursor based p-i-n perovskite solar cells with enhanced reproducibility and low hysteresis. *Journal of Materials Chemistry A*, *3*(27), 14121-14125. https://doi.org/10.1039/c5ta03169a

[67] Franckevičius, M., Mishra, A., Kreuzer, F., Luo, J., Zakeeruddin, M., & Grätzel, M. (2015). A dopant-free spirobi[cyclopenta[2,1-b:3,4-b′]dithiophene] based hole-transport material for efficient perovskite solar cells. *Materials Horizons*, *2*(6), 613-618. https://doi.org/10.1039/c5mh00154d

[68] Frolova, L. A., Dremova, N. N., & Troshin, P. A. (2015). The chemical origin of the p-type and n-type doping effects in the hybrid methylammonium–lead iodide (MAPbI3) perovskite solar cells. *Chemical communications (Cambridge, England)*, *51*(80), 14917-14920. https://doi.org/10.1039/c5cc05205j

[69] Frost, J. M. (2017). Calculating polaron mobility in halide perovskites. *Physical Review B*, *96*(19), 195202-NA. https://doi.org/10.1103/physrevb.96.195202

[70] Frost, J. M., Butler, K. T., Brivio, F., Hendon, C. H., van Schilfgaarde, M., & Walsh, A. (2014). Atomistic origins of high-performance in hybrid halide perovskite solar cells. *Nano letters*, *14*(5), 2584-2590. https://doi.org/10.1021/nl500390f

[71] Fu, W., Yan, J., Zhang, Z., Ye, T., Liu, Y., Wu, J., Yao, J., Li, C.-Z., Li, H., & Chen, H. (2016). Controlled crystallization of CH3NH3PbI3 films for perovskite solar cells by various PbI2(X) complexes. *Solar Energy Materials and Solar Cells*, *155*(NA), 331-340. https://doi.org/10.1016/j.solmat.2016.06.037

[72] Gatti, T., Casaluci, S., Prato, M., Salerno, M., Di Stasio, F., Ansaldo, A., Menna, E., Di Carlo, A., & Bonaccorso, F. (2016). Boosting Perovskite Solar Cells Performance and Stability through Doping a Poly-3(hexylthiophene) Hole Transporting Material with Organic Functionalized Carbon Nanostructures. *Advanced Functional Materials*, *26*(41), 7443-7453. https://doi.org/10.1002/adfm.201602803

[73] Geske, T., Li, J., Worden, M., Shan, X., Chen, M., Bade, S. G. R., & Yu, Z. (2017). Deterministic Nucleation for Halide Perovskite Thin Films with Large and Uniform Grains. *Advanced Functional Materials*, *27*(40), 1702180-NA. https://doi.org/10.1002/adfm.201702180

[74] Ghasemi, M., Zhang, L., Yun, J.-H., Hao, M., He, D., Chen, P., Bai, Y., Lin, T., Xiao, M., Du, A., Lyu, M., & Wang, L. (2020). Dual-Ion-Diffusion Induced Degradation in Lead-Free Cs2AgBiBr6 Double Perovskite Solar Cells. *Advanced Functional Materials*, *30*(42), 2002342-NA. https://doi.org/10.1002/adfm.202002342

[75] Giuri, A., Masi, S., Colella, S., Kovtun, A., Dell'Elce, S., Treossi, E., Liscio, A., Corcione, C. E., Rizzo, A., & Listorti, A. (2016). Cooperative Effect of GO and Glucose on PEDOT:PSS for High VOC and Hysteresis‐Free Solution‐Processed Perovskite Solar Cells. *Advanced Functional Materials*, *27*(2), 6985-6994. https://doi.org/NA

[76] Gong, X., Li, M., Shi, X.-B., Ma, H., Wang, Z.-K., & Liao, L.-S. (2015). Controllable Perovskite Crystallization by Water Additive for High-Performance Solar Cells. *Advanced Functional Materials*, *25*(42), 6671-6678. https://doi.org/10.1002/adfm.201503559

[77] Gottesman, R., Lopez-Varo, P., Gouda, L., Jiménez-Tejada, J. A., Hu, J., Tirosh, S., Zaban, A., & Bisquert, J. (2016). Dynamic Phenomena at Perovskite/Electron-Selective Contact Interface as Interpreted from Photovoltage Decays. *Chem*, *1*(5), 776-789. https://doi.org/10.1016/j.chempr.2016.10.002

[78] Gozalzadeh, S., Nasirpouri, F., & Seok, S. I. (2021). Dimethylformamide-free synthesis and fabrication of lead halide perovskite solar cells from electrodeposited PbS precursor films. *Chemical Engineering Journal*, *411*(NA), 128460-NA. https://doi.org/10.1016/j.cej.2021.128460

[79] Gupta, S., Bendikov, T., Hodes, G., & Cahen, D. (2016). CsSnBr3, A Lead-Free Halide Perovskite for Long-Term Solar Cell Application: Insights on SnF2 Addition. *ACS Energy Letters*, *1*(5), 1028-1033. https://doi.org/10.1021/acsenergylett.6b00402

[80] Habisreutinger, S. N., Leijtens, T., Eperon, G. E., Stranks, S. D., Nicholas, R. J., & Snaith, H. J. (2014). Carbon nanotube/polymer composites as a highly stable hole collection layer in perovskite solar cells. *Nano letters*, *14*(10), 5561-5568. https://doi.org/10.1021/nl501982b

[81] Han, Y., Meyer, S., Dkhissi, Y., Weber, K., Pringle, J. M., Bach, U., Spiccia, L., & Cheng, Y.-B. (2015). Degradation observations of encapsulated planar CH3NH3PbI3 perovskite solar cells at high temperatures and humidity. *Journal of Materials Chemistry A*, *3*(15), 8139-8147. https://doi.org/10.1039/c5ta00358j

[82] Han, Y., Zhao, H., Duan, C., Yang, S., Yang, Z., Liu, Z., & Liu, S. (2020). Controlled n-Doping in Air-Stable CsPbI2Br Perovskite Solar Cells with a Record Efficiency of 16.79%. *Advanced Functional Materials*, *30*(12), 1909972-NA. https://doi.org/10.1002/adfm.201909972

[83] Handa, T., Tex, D. M., Shimazaki, A., Wakamiya, A., & Kanemitsu, Y. (2017). Charge Injection Mechanism at Heterointerfaces in CH3NH3PbI3 Perovskite Solar Cells Revealed by Simultaneous Time-Resolved Photoluminescence and Photocurrent Measurements. *The journal of physical chemistry letters*, *8*(5), 954-960. https://doi.org/10.1021/acs.jpclett.6b02847

[84] Hao, F., Stoumpos, C. C., Cao, D. H., Chang, R. P. H., & Kanatzidis, M. G. (2014). Lead-free solid-state organic–inorganic halide perovskite solar cells. *Nature Photonics*, *8*(6), 489-494. https://doi.org/10.1038/nphoton.2014.82

[85] Hao, F., Stoumpos, C. C., Chang, R. P. H., & Kanatzidis, M. G. (2014). Anomalous Band Gap Behavior in Mixed Sn and Pb Perovskites Enables Broadening of Absorption Spectrum in Solar Cells. *Journal of the American Chemical Society*, *136*(22), 8094-8099. https://doi.org/10.1021/ja5033259

[86] Helal, A. M. (2022). State Of Indigenous Cultural Practices And Role Of School Curriculum: A Case Study Of The Garo Community In Bangladesh. *Available at SSRN 5061810*.

[87] Herz, L. M. (2016). Charge-Carrier Dynamics in Organic-Inorganic Metal Halide Perovskites. *Annual review of physical chemistry*, *67*(1), 65-89. https://doi.org/10.1146/annurev-physchem-040215-112222

[88] Hörantner, M. T., Nayak, P. K., Mukhopadhyay, S., Wojciechowski, K., Beck, C. E., McMeekin, D. P., Kamino, B. A., Eperon, G. E., & Snaith, H. J. (2016). Shunt‐Blocking Layers for Semitransparent Perovskite Solar Cells. *Advanced Materials Interfaces*, *3*(10), 1500837-NA. https://doi.org/10.1002/admi.201500837

[89] Hou, J., Wang, H., & Liu, P. (2018). Applying the blockchain technology to promote the development of distributed photovoltaic in China. *International Journal of Energy Research*, *42*(6), 2050-2069. https://doi.org/10.1002/er.3984

[90] Hou, Y., Du, X., Scheiner, S., McMeekin, D. P., Wang, Z., Li, N., Killian, M. S., Chen, H., Richter, M., Levchuk, I., Schrenker, N., Spiecker, E., Stubhan, T., Luechinger, N. A., Hirsch, A., Schmuki, P., Steinrück, H.-P., Fink, R. H., Halik, M., . . . Brabec, C. J. (2017). A generic interface to reduce the efficiency-stability-cost gap of perovskite solar cells. *Science (New York, N.Y.)*, *358*(6367), 1192-1197. https://doi.org/10.1126/science.aao5561

[91] Hu, M., Bi, C., Yuan, Y., Bai, Y., & Huang, J. (2015). Stabilized Wide Bandgap MAPbBrxI3–x Perovskite by Enhanced Grain Size and Improved Crystallinity. *Advanced science (Weinheim, Baden-Wurttemberg, Germany)*, *3*(6), 1500301-1500301. https://doi.org/10.1002/advs.201500301

[92] Hu, Y., Bai, F., Liu, X., Ji, Q., Miao, X., Qiu, T., & Zhang, S. (2017). Bismuth Incorporation Stabilized α-CsPbI3 for Fully Inorganic Perovskite Solar Cells. *ACS Energy Letters*, *2*(10), 2219-2227. https://doi.org/10.1021/acsenergylett.7b00508

[93] Huang, C., Fu, W., Li, C.-Z., Zhang, Z., Qiu, W., Shi, M., Heremans, P., Jen, A. K. Y., & Chen, H. (2016). Dopant-Free Hole-Transporting Material with a C3h Symmetrical Truxene Core for Highly Efficient Perovskite Solar Cells. *Journal of the American Chemical Society*, *138*(8), 2528-2531. https://doi.org/10.1021/jacs.6b00039.s001

[94] Huang, J., Jiang, K.-J., Cui, X.-P., Zhang, Q., Gao, M., Su, M.-J., Yang, L.-M., & Song, Y. (2015). Direct Conversion of CH3NH3PbI3 from Electrodeposited PbO for Highly Efficient Planar Perovskite Solar Cells. *Scientific reports*, *5*(1), 15889-15889. https://doi.org/10.1038/srep15889

[95] Huang, L., Zhang, D., Bu, S., Peng, R., Wei, Q., & Ge, Z. (2020). Synergistic Interface Energy Band Alignment Optimization and Defect Passivation toward Efficient and Simple‐Structured Perovskite Solar Cell. *Advanced science (Weinheim, Baden-Wurttemberg, Germany)*, *7*(6), 1902656-NA. https://doi.org/10.1002/advs.201902656

[96] Hutter, E. M., Hofman, J.-J., Petrus, M. L., Moes, M., Abellon, R. D., Docampo, P., & Savenije, T. J. (2017). Charge Transfer from Methylammonium Lead Iodide Perovskite to Organic Transport Materials: Efficiencies, Transfer Rates, and Interfacial Recombination. *Advanced Energy Materials*, *7*(13), 1602349-NA. https://doi.org/10.1002/aenm.201602349

[97] Hwang, I., Baek, M., & Yong, K. (2015). Core/Shell Structured TiO2/CdS Electrode to Enhance the Light Stability of Perovskite Solar Cells. *ACS applied materials & interfaces*, *7*(50), 27863-27870. https://doi.org/10.1021/acsami.5b09442

[98] Iagher, L., & Etgar, L. (2018). Effect of Cs on the Stability and Photovoltaic Performance of 2D/3D Perovskite-Based Solar Cells. *ACS Energy Letters*, *3*(2), 366-372. https://doi.org/10.1021/acsenergylett.7b01196

[99] Igbari, F., Wang, R., Wang, Z.-K., Ma, X.-J., Wang, Q., Wang, K.-L., Zhang, Y., Liao, L.-S., & Yang, Y. (2019). Composition Stoichiometry of Cs2AgBiBr6 Films for Highly Efficient Lead-Free Perovskite Solar Cells. *Nano letters*, *19*(3), 2066-2073. https://doi.org/10.1021/acs.nanolett.9b00238

[100] Im, J.-H., Lee, C.-R., Lee, J.-W., Park, S.-W., & Park, N.-G. (2011). 6.5% efficient perovskite quantum-dot-sensitized solar cell. *Nanoscale*, *3*(10), 4088-4093. https://doi.org/10.1039/c1nr10867k

[101] Im, J., Stoumpos, C. C., Jin, H., Freeman, A. J., & Kanatzidis, M. G. (2015). Antagonism between Spin–Orbit Coupling and Steric Effects Causes Anomalous Band Gap Evolution in the Perovskite Photovoltaic Materials CH3NH3Sn1–xPbxI3. *The journal of physical chemistry letters*, *6*(17), 3503-3509. https://doi.org/10.1021/acs.jpclett.5b01738

[102] Jeng, J. Y., Chiang, Y. F., Lee, M. H., Peng, S. R., Guo, T.-F., Chen, P., & Wen, T.-C. (2013). CH3NH3PbI3 Perovskite/Fullerene Planar‐Heterojunction Hybrid Solar Cells. *Advanced materials (Deerfield Beach, Fla.)*, *25*(27), 3727-3732. https://doi.org/10.1002/adma.201301327

[103]Jeon, N. J., Noh, J. H., Yang, W. S., Kim, Y. C., Ryu, S., Seo, J., & Seok, S. I. (2015). Compositional engineering of perovskite materials for high-performance solar cells. *Nature*, *517*(7535), 476-480. https://doi.org/10.1038/nature14133

[104]Jiang, X., Chen, S., Li, Y., Zhang, L., Shen, N., Zhang, G., Du, J., Fu, N., & Xu, B. (2021). Direct Surface Passivation of Perovskite Film by 4-Fluorophenethylammonium Iodide toward Stable and Efficient Perovskite Solar Cells. *ACS applied materials & interfaces*, *13*(2), 2558-2565. https://doi.org/10.1021/acsami.0c17773

[105]Jiang, X., Zhang, J., Ahmad, S., Tu, D., Liu, X., Jia, G., Guo, X., & Li, C. (2020). Dion-Jacobson 2D-3D perovskite solar cells with improved efficiency and stability. *Nano Energy*, *75*(NA), 104892-NA. https://doi.org/10.1016/j.nanoen.2020.104892

[106]Jung, E. H., Jeon, N. J., Park, E. Y., Moon, C. S., Shin, T. J., Yang, T.-Y., Noh, J. H., & Seo, J. (2019). Efficient, stable and scalable perovskite solar cells using poly(3-hexylthiophene). *Nature*, *567*(7749), 511-515. https://doi.org/10.1038/s41586-019-1036-3

[107]Jung, H. S., & Park, N.-G. (2014). Perovskite solar cells: from materials to devices. *Small (Weinheim an der Bergstrasse, Germany)*, *11*(1), 10-25. https://doi.org/10.1002/smll.201402767

[108]Kang, Z., Si, H., Mingyue, S., Xu, C., Fan, W., Ma, S., Ammarah, K., Liao, Q., Zhang, Z., & Zhang, Y. (2019). Kelvin probe force microscopy for perovskite solar cells. *Science China Materials*, *62*(6), 776-789. https://doi.org/10.1007/s40843-018-9395-y

[109]Kawano, N., Koshimizu, M., & Asai, K. (2012). The Effect of Wannier and Frenkel Exciton Resonance on the Luminescence Properties of Organic–Inorganic Layered Perovskite-Type Compounds. *The Journal of Physical Chemistry C*, *116*(43), 22992-22995. https://doi.org/10.1021/jp304531h

[110]Ke, W., Priyanka, P., Vegiraju, S., Stoumpos, C. C., Spanopoulos, I., Soe, C. M. M., Marks, T. J., Chen, M. C., & Kanatzidis, M. G. (2017). Dopant-Free Tetrakis-Triphenylamine Hole Transporting Material for Efficient Tin-Based Perovskite Solar Cells. *Journal of the American Chemical Society*, *140*(1), 388-393. https://doi.org/10.1021/jacs.7b10898

[111]Ke, W., Stoumpos, C. C., Spanopoulos, I., Chen, M., Wasielewski, M. R., & Kanatzidis, M. G. (2018). Diammonium Cations in the FASnI3 Perovskite Structure Lead to Lower Dark Currents and More Efficient Solar Cells. *ACS Energy Letters*, *3*(7), 1470-1476. https://doi.org/10.1021/acsenergylett.8b00687

[112]Kim, D. H., Whitaker, J. B., Li, Z., van Hest, M. F. A. M., & Zhu, K. (2018). Outlook and Challenges of Perovskite Solar Cells toward Terawatt-Scale Photovoltaic Module Technology. *Joule*, *2*(8), 1437-1451. https://doi.org/10.1016/j.joule.2018.05.011

[113]Kim, G.-W., Kang, G., Kim, J., Lee, G.-Y., Kim, H. I., Pyeon, L., Lee, J.-C., & Park, T. (2016). Dopant-free polymeric hole transport materials for highly efficient and stable perovskite solar cells. *Energy & Environmental Science*, *9*(7), 2326-2333. https://doi.org/10.1039/c6ee00709k

[114]Kim, G.-W., Lee, J., Kang, G., Kim, T.-W., & Park, T. (2017). Donor–Acceptor Type Dopant-Free, Polymeric Hole Transport Material for Planar Perovskite Solar Cells (19.8%). *Advanced Energy Materials*, *8*(4), 1701935-NA. https://doi.org/10.1002/aenm.201701935

[115]Kim, H.-S., Jang, I.-H., Ahn, N., Choi, M., Guerrero, A., Bisquert, J., & Park, N.-G. (2015). Control of I–V Hysteresis in CH3NH3PbI3 Perovskite Solar Cell. *The journal of physical chemistry letters*, *6*(22), 4633-4639. https://doi.org/10.1021/acs.jpclett.5b02273

[116]Kim, H.-S., Lee, C.-R., Im, J.-H., Lee, K. B., Moehl, T., Marchioro, A., Moon, S.-J., Humphry-Baker, R., Yum, J.-H., Moser, J.-E., Grätzel, M., & Park, N.-G. (2012). Lead Iodide Perovskite Sensitized All-Solid-State Submicron Thin Film Mesoscopic Solar Cell with Efficiency Exceeding 9%. *Scientific reports*, *2*(1), 591-591. https://doi.org/10.1038/srep00591

[117]Konstantakou, M., Perganti, D., Falaras, P., & Stergiopoulos, T. (2017). Anti-Solvent Crystallization Strategies for Highly Efficient Perovskite Solar Cells. *Crystals*, *7*(10), 291-NA. https://doi.org/10.3390/cryst7100291

[118]Konstantakou, M., & Stergiopoulos, T. (2017). A critical review on tin halide perovskite solar cells. *Journal of Materials Chemistry A*, *5*(23), 11518-11549. https://doi.org/10.1039/c7ta00929a

[119]Kulkarni, S. A., Baikie, T., Boix, P. P., Yantara, N., Mathews, N., & Mhaisalkar, S. (2014). Band-gap tuning of lead halide perovskites using a sequential deposition process. *J. Mater. Chem. A*, *2*(24), 9221-9225. https://doi.org/10.1039/c4ta00435c

[120]Kumar, M. H., Dharani, S., Leong, W. L., Boix, P. P., Prabhakar, R. R., Baikie, T., Shi, C., Ding, H., Ramesh, R., Asta, M., Graetzel, M., Mhaisalkar, S., & Mathews, N. (2014). Lead‐Free Halide Perovskite Solar Cells with High Photocurrents Realized Through Vacancy Modulation. *Advanced materials (Deerfield Beach, Fla.)*, *26*(41), 7122-7127. https://doi.org/10.1002/adma.201401991

[121]Kwon, Y. S., Lim, J., Yun, H.-J., Kim, Y.-H., & Park, T. (2014). A diketopyrrolopyrrole-containing hole transporting conjugated polymer for use in efficient stable organic–inorganic hybrid solar cells based on a perovskite. *Energy & Environmental Science*, *7*(4), 1454-1460. https://doi.org/10.1039/c3ee44174a

[122]Laurita, G., Fabini, D. H., Stoumpos, C. C., Kanatzidis, M. G., & Seshadri, R. (2017). Chemical tuning of dynamic cation off-centering in the cubic phases of hybrid tin and lead halide perovskites. *Chemical science*, *8*(8), 5628-5635. https://doi.org/10.1039/c7sc01429e

[123]Lee, J., Kang, H., Kim, G., Back, H., Kim, J., Hong, S., Park, B., Lee, E., & Lee, K. (2017). Achieving Large-Area Planar Perovskite Solar Cells by Introducing an Interfacial Compatibilizer. *Advanced materials (Deerfield Beach, Fla.)*, *29*(22), 1606363-NA. https://doi.org/10.1002/adma.201606363

[124]Lee, W.-H., Chen, C.-Y., Li, C.-S., Hsiao, S.-Y., Tsai, W.-L., Huang, M.-J., Cheng, C.-H., Wu, C.-I., & Lin, H.-W. (2017). Boosting thin-film perovskite solar cell efficiency through vacuum-deposited sub-nanometer small-molecule electron interfacial layers. *Nano Energy*, *38*(NA), 66-71. https://doi.org/10.1016/j.nanoen.2017.05.049

[125]Leguy, A. M. A., Frost, J. M., McMahon, A. P., Sakai, V. G., Kochelmann, W., Law, C., Li, X., Foglia, F., Walsh, A., O'Regan, B. C., Nelson, J., Cabral, J. T., & Barnes, P. R. F. (2015). The dynamics of methylammonium ions in hybrid organic–inorganic perovskite solar cells. *Nature communications*, *6*(1), 7124-7124. https://doi.org/10.1038/ncomms8124

[126]Leijtens, T., Eperon, G. E., Barker, A. J., Grancini, G., Zhang, W., Ball, J. M., Kandada, A. R. S., Snaith, H. J., & Petrozza, A. (2016). Carrier trapping and recombination: the role of defect physics in enhancing the open circuit voltage of metal halide perovskite solar cells. *Energy & Environmental Science*, *9*(11), 3472-3481. https://doi.org/10.1039/c6ee01729k

[127]Leng, J., Liu, J., Zhang, J., & Jin, S. (2016). Decoupling Interfacial Charge Transfer from Bulk Diffusion Unravels Its Intrinsic Role for Efficient Charge Extraction in Perovskite Solar Cells. *The journal of physical chemistry letters*, *7*(24), 5056-5061. https://doi.org/10.1021/acs.jpclett.6b02309

[128]Li, C., Zhu, Z., Wang, Y.-M., Guo, Q., Wang, C., Zhong, P., Tan, Z. a., & Yang, R. (2020). Lead acetate produced from lead-acid battery for efficient perovskite solar cells. *Nano Energy*, *69*(NA), 104380-NA. https://doi.org/10.1016/j.nanoen.2019.104380

[129]Li, D., Song, L., Chen, Y., & Huang, W. (2019). Modeling Thin Film Solar Cells: From Organic to Perovskite. *Advanced science (Weinheim, Baden-Wurttemberg, Germany)*, *7*(1), 1901397-1901397. https://doi.org/10.1002/advs.201901397

[130]Li, F., Zhang, Y., Jiang, K.-J., Zhang, C., Huang, J., Wang, H., Fan, H., Wang, P., Chen, Y., Zhao, W., Li, X., Yang, L.-M., Song, Y., & Li, Y. (2018). A Novel Strategy for Scalable High-Efficiency Planar Perovskite Solar Cells with New Precursors and Cation Displacement Approach. *Advanced materials (Deerfield Beach, Fla.)*, *30*(44), 1804454-NA. https://doi.org/10.1002/adma.201804454

[131]Li, H., Shi, W., Huang, W., Yao, E.-P., Han, J., Chen, Z., Liu, S., Shen, Y., Wang, M., & Yang, Y. (2017). Carbon Quantum Dots/TiOx Electron Transport Layer Boosts Efficiency of Planar Heterojunction Perovskite Solar Cells to 19%. *Nano letters*, *17*(4), 2328-2335. https://doi.org/10.1021/acs.nanolett.6b05177.s001

[132]Li, J., Dong, Q., Li, N., & Wang, L. (2017). Direct Evidence of Ion Diffusion for the Silver-Electrode-Induced Thermal Degradation of Inverted Perovskite Solar Cells. *Advanced Energy Materials*, *7*(14), 1602922-NA. https://doi.org/10.1002/aenm.201602922

[133]Li, T., Pan, Y., Wang, Z., Xia, Y., Chen, Y., & Huang, W. (2017). Additive engineering for highly efficient organic–inorganic halide perovskite solar cells: recent advances and perspectives. *Journal of Materials Chemistry A*, *5*(25), 12602-12652. https://doi.org/10.1039/c7ta01798g

[134]Li, W., Li, J., Li, J., Fan, J., Mai, Y., & Wang, L. (2016). Addictive-assisted construction of all-inorganic CsSnIBr2 mesoscopic perovskite solar cells with superior thermal stability up to 473 K. *Journal of Materials Chemistry A*, *4*(43), 17104-17110. https://doi.org/10.1039/c6ta08332c

[135]Li, W., Li, J., Niu, G., & Wang, L. (2016). Effect of cesium chloride modification on the film morphology and UV-induced stability of planar perovskite solar cells. *Journal of Materials Chemistry A*, *4*(30), 11688-11695. https://doi.org/10.1039/c5ta09165a

[136]Li, W., Wang, Z.-M., Deschler, F., Gao, S., Friend, R. H., & Cheetham, A. K. (2017). Chemically diverse and multifunctional hybrid organic–inorganic perovskites. *Nature Reviews Materials*, *2*(3), 16099-NA. https://doi.org/10.1038/natrevmats.2016.99

[137]Li, Y., Xu, Z., Zhao, S., Qiao, B., Huang, D., Zhao, L., Zhao, J., Wang, P., Zhu, Y., Li, X., Liu, X., & Xu, X. (2016). Highly Efficient p-i-n Perovskite Solar Cells Utilizing Novel Low-Temperature Solution-Processed Hole Transport Materials with Linear π-Conjugated Structure. *Small (Weinheim an der Bergstrasse, Germany)*, *12*(35), 4902-4908. https://doi.org/10.1002/smll.201601603

[138]Li, Z., Klein, T. R., Kim, D. H., Yang, M., Berry, J. J., van Hest, M. F. A. M., & Zhu, K. (2018). Scalable fabrication of perovskite solar cells. *Nature Reviews Materials*, *3*(4), 18017-NA. https://doi.org/10.1038/natrevmats.2018.17

[139]Li, Z., Zhao, Y., Wang, X., Yuchao, S., Zhao, Z., Li, Y., Zhou, H., & Chen, Q. (2018). Cost Analysis of Perovskite Tandem Photovoltaics. *Joule*, *2*(8), 1559-1572. https://doi.org/10.1016/j.joule.2018.05.001

[140]Liang, L., & Gao, P. (2017). Lead-Free Hybrid Perovskite Absorbers for Viable Application: Can We Eat the Cake and Have It too? *Advanced science (Weinheim, Baden-Wurttemberg, Germany)*, *5*(2), 1700331-1700331. https://doi.org/10.1002/advs.201700331

[141]Liang, Y., Xu, Z., Xia, J., Tsai, S.-T., Wu, Y., Li, G., Ray, C., & Yu, L. (2010). For the Bright Future—Bulk Heterojunction Polymer Solar Cells with Power Conversion Efficiency of 7.4%. *Advanced materials (Deerfield Beach, Fla.)*, *22*(20), E135-138. https://doi.org/10.1002/adma.200903528

[142]Liao, H.-C., Tam, T. L. D., Guo, P., Wu, Y., Manley, E. F., Huang, W., Zhou, N., Soe, C. M. M., Wang, B., Wasielewski, M. R., Chen, L. X., Kanatzidis, M. G., Facchetti, A., Chang, R. P. H., & Marks, T. J. (2016). Dopant-Free Hole Transporting Polymers for High Efficiency, Environmentally Stable Perovskite Solar Cells. *Advanced Energy Materials*, *6*(16), 1600502-NA. https://doi.org/10.1002/aenm.201600502

[143]Liao, W.-Q., Zhao, D., Yu, Y., Grice, C. R., Wang, C., Cimaroli, A. J., Schulz, P., Meng, W., Zhu, K., Xiong, R.-G., & Yan, Y. (2016). Lead-Free Inverted Planar Formamidinium Tin Triiodide Perovskite Solar Cells Achieving Power Conversion Efficiencies up to 6.22. *Advanced materials (Deerfield Beach, Fla.)*, *28*(42), 9333-9340. https://doi.org/10.1002/adma.201602992

[144]Liu, C., Li, W., Li, H., Zhang, C., Fan, J., & Mai, Y. (2017). C60 additive-assisted crystallization in CH3NH3Pb0.75Sn0.25I3 perovskite solar cells with high stability and efficiency. *Nanoscale*, *9*(37), 13967-13975. https://doi.org/10.1039/c7nr03507a

[145]Liu, C., Li, W., Zhang, C., Ma, Y., Fan, J., & Mai, Y. (2018). All-Inorganic CsPbI2Br Perovskite Solar Cells with High Efficiency Exceeding 13%. *Journal of the American Chemical Society*, *140*(11), 3825-3828. https://doi.org/10.1021/jacs.7b13229

[146]Liu, C., Tsai, H., Nie, W., Gosztola, D. J., & Zhang, X. (2020). Direct Spectroscopic Observation of the Hole Polaron in Lead Halide Perovskites. *The journal of physical chemistry letters*, *11*(15), 6256-6261. https://doi.org/10.1021/acs.jpclett.0c01708

[147]Liu, G., Zhou, C., Wan, F., Li, K., Yuan, Y., Gao, Y., Lu, Y., & Yang, B. (2018). Dependence of power conversion properties of perovskite solar cells on operating temperature. *Applied Physics Letters*, *113*(11), 113501-113501. https://doi.org/10.1063/1.5041028

[148]Liu, Z., Hu, J., Jiao, H., Li, L., Zheng, G., Chen, Y., Huang, Y., Zhang, Q., Shen, C., Chen, Q., & Zhou, H. (2017). Chemical Reduction of Intrinsic Defects in Thicker Heterojunction Planar Perovskite Solar Cells. *Advanced materials (Deerfield Beach, Fla.)*, *29*(23), 1606774-NA. https://doi.org/10.1002/adma.201606774

[149]Luo, D., Zhao, L., Wu, J., Hu, Q., Zhang, Y., Xu, Z., Liu, Y., Liu, T., Chen, K., Yang, W., Zhang, W., Zhu, R., & Gong, Q. (2017). Dual-Source Precursor Approach for Highly Efficient Inverted Planar Heterojunction Perovskite Solar Cells. *Advanced materials (Deerfield Beach, Fla.)*, *29*(19), 1604758-NA. https://doi.org/10.1002/adma.201604758

[150]Luo, Q., Ma, H., Hao, F., Hou, Q., Ren, J., Wu, L., Yao, Z., Zhou, Y., Wang, N., Jiang, K., Lin, H., & Guo, Z. (2017). Carbon Nanotube Based Inverted Flexible Perovskite Solar Cells with All-Inorganic Charge Contacts. *Advanced Functional Materials*, *27*(42), 1703068-NA. https://doi.org/10.1002/adfm.201703068

[151]Lyu, M., Yun, J.-H., Chen, P., Hao, M., & Wang, L. (2017). Addressing toxicity of lead: progress and applications of low-toxic metal halide perovskites and their derivatives. *Advanced Energy Materials*, *7*(15), 1602512-NA. https://doi.org/10.1002/aenm.201602512

[152]Ma, C., Shen, D., Ng, T.-W., Lo, M.-F., & Lee, C.-S. (2018). 2D Perovskites with Short Interlayer Distance for High-Performance Solar Cell Application. *Advanced materials (Deerfield Beach, Fla.)*, *30*(22), 1800710-NA. https://doi.org/10.1002/adma.201800710

[153]Ma, L., Hao, F., Stoumpos, C. C., Phelan, B. T., Wasielewski, M. R., & Kanatzidis, M. G. (2016). Carrier Diffusion Lengths of over 500 nm in Lead-Free Perovskite CH3NH3SnI3 Films. *Journal of the American Chemical Society*, *138*(44), 14750-14755. https://doi.org/10.1021/jacs.6b09257

[154]Ma, S., Cai, M., Cheng, T., Ding, X., Shi, X., Alsaedi, A., Hayat, T., Ding, Y., Tan, Z. a., & Dai, S. (2018). Two-dimensional organic-inorganic hybrid perovskite: from material properties to device applications. *Science China Materials*, *61*(10), 1257-1277. https://doi.org/10.1007/s40843-018-9294-5

[155]Mahmood, K., Sarwar, S., & Mehran, M. T. (2017). Current status of electron transport layers in perovskite solar cells: materials and properties. *RSC Advances*, *7*(28), 17044-17062. https://doi.org/10.1039/c7ra00002b

[156]Mahmood, K., Swain, B. S., & Amassian, A. (2015). 16.1% Efficient Hysteresis-Free Mesostructured Perovskite Solar Cells Based on Synergistically Improved ZnO Nanorod Arrays. *Advanced Energy Materials*, *5*(17), 1500568-NA. https://doi.org/10.1002/aenm.201500568

[157]Mahmud, A., Yin, Y., Pham, H., Walter, D., Peng, J., Wu, Y., Li, L., Shen, H., Wu, N., Mozaffari, N., Andersson, G. G., Catchpole, K. R., Weber, K., & White, T. P. (2019). Double‐Sided Surface Passivation of 3D Perovskite Film for High‐Efficiency Mixed‐Dimensional Perovskite Solar Cells. *Advanced Functional Materials*, *30*(7), 1907962-NA. https://doi.org/10.1002/adfm.201907962

[158]Malinauskas, T., Saliba, M., Matsui, T., Daskeviciene, M., Urnikaite, S., Gratia, P., Send, R., Wonneberger, H., Bruder, I., Graetzel, M., Getautis, V., & Nazeeruddin, M. K. (2016). Branched methoxydiphenylamine-substituted fluorene derivatives as hole transporting materials for high-performance perovskite solar cells. *Energy & Environmental Science*, *9*(5), 1681-1686. https://doi.org/10.1039/c5ee03911h

[159]Mandadapu, U., Vedanayakam, S. V., Thyagarajan, K., Reddy, M. R., & Jagadeeshbabu, B. (2017). Design and Simulation of High Efficiency Tin Halide Perovskite Solar Cell. *International Journal of Renewable Energy Research*, *7*(4), 1603-1612. https://doi.org/NA

[160]Marronnier, A., Roma, G., Boyer-Richard, S., Pedesseau, L., Jancu, J.-M., Bonnassieux, Y., Katan, C., Stoumpos, C. C., Kanatzidis, M. G., & Even, J. (2018). Anharmonicity and Disorder in the Black Phases of Cesium Lead Iodide Used for Stable Inorganic Perovskite Solar Cells. *ACS nano*, *12*(4), 3477-3486. https://doi.org/10.1021/acsnano.8b00267

[161]Matsui, T., Yamamoto, T., Nishihara, T., Morisawa, R., Yokoyama, T., Sekiguchi, T., & Negami, T. (2019). Compositional Engineering for Thermally Stable, Highly Efficient Perovskite Solar Cells Exceeding 20% Power Conversion Efficiency with 85 °C/85% 1000 h Stability. *Advanced materials (Deerfield Beach, Fla.)*, *31*(10), 1806823-NA. https://doi.org/10.1002/adma.201806823

[162]Maughan, A. E., Ganose, A. M., Candia, A. M., Granger, J. T., Scanlon, D. O., & Neilson, J. R. (2017). Anharmonicity and Octahedral Tilting in Hybrid Vacancy-Ordered Double Perovskites. *Chemistry of Materials*, *30*(2), 472-483. https://doi.org/10.1021/acs.chemmater.7b04516

[163]McClure, E. T., Ball, M. R., Windl, W., & Woodward, P. M. (2016). Cs2AgBiX6 (X = Br, Cl): New Visible Light Absorbing, Lead-Free Halide Perovskite Semiconductors. *Chemistry of Materials*, *28*(5), 1354-1354. https://doi.org/10.1021/acs.chemmater.5b04231

[164]Md Mahfuj, H., Md Rabbi, K., Mohammad Samiul, I., Faria, J., & Md Jakaria, T. (2022). Hybrid Renewable Energy Systems: Integrating Solar, Wind, And Biomass for Enhanced Sustainability And Performance. *American Journal of Scholarly Research and Innovation*, *1*(1), 1-24. https://doi.org/10.63125/8052hp43

[165]Md Majharul, I., Arafat Bin, F., & Ripan Kumar, P. (2022). AI-Based Smart Coating Degradation Detection For Offshore Structures. *American Journal of Advanced Technology and Engineering Solutions*, *2*(04), 01-34. https://doi.org/10.63125/1mn6bm51

[166]Md Takbir Hossen, S., & Md Atiqur, R. (2022). Advancements In 3D Printing Techniques For Polymer Fiber-Reinforced Textile Composites: A Systematic Literature Review. *American Journal of Interdisciplinary Studies*, *3*(04), 32-60. https://doi.org/10.63125/s4r5m391

[167]Mitzi, D. B., Feild, C., Harrison, W. T. A., & Guloy, A. M. (1994). Conducting tin halides with a layered organic-based perovskite structure. *Nature*, *369*(6480), 467-469. https://doi.org/10.1038/369467a0

[168]Mitzi, D. B., Wang, S., Feild, C., Chess, C. A., & Guloy, A. M. (1995). Conducting Layered Organic-inorganic Halides Containing -Oriented Perovskite Sheets. *Science (New York, N.Y.)*, *267*(5203), 1473-1476. https://doi.org/10.1126/science.267.5203.1473

[169]Miyata, A., Mitioglu, A. A., Plochocka, P., Portugall, O., Wang, J. T.-W., Stranks, S. D., Snaith, H. J., & Nicholas, R. J. (2015). Direct measurement of the exciton binding energy and effective masses for charge carriers in organic–inorganic tri-halide perovskites. *Nature Physics*, *11*(7), 582-587. https://doi.org/10.1038/nphys3357

[170]Mohr, N. J., Schermer, J. J., Huijbregts, M. A. J., Meijer, A., & Reijnders, L. (2006). Life cycle assessment of thin film GaAs and GaInP/GaAs solar modules. *Progress in Photovoltaics: Research and Applications*, *15*(2), 163-179. https://doi.org/10.1002/pip.735

[171]Moore, D. T., Sai, H., Tan, K. W., Smilgies, D.-M., Zhang, W., Snaith, H. J., Wiesner, U., & Estroff, L. A. (2015). Crystallization Kinetics of Organic–Inorganic Trihalide Perovskites and the Role of the Lead Anion in Crystal Growth. *Journal of the American Chemical Society*, *137*(6), 2350-2358. https://doi.org/10.1021/ja512117e

[172]Muhammad Mohiul, I., Morshed, A. S. M., Md Enamul, K., & Md, A.-A. (2022). Adaptive Control Of Resource Flow In Construction Projects Through Deep Reinforcement Learning: A Framework For Enhancing Project Performance In Complex Environments. *American Journal of Scholarly Research and Innovation*, *1*(01), 76-107. https://doi.org/10.63125/gm77xp11

[173]Muteri, V., Cellura, M., Curto, D., Franzitta, V., Longo, S., Mistretta, M., & Parisi, M. L. (2020). Review on Life Cycle Assessment of Solar Photovoltaic Panels. *Energies*, *13*(1), 1-38. https://doi.org/10.3390/en13010252

[174]Nagarjuna, P., Narayanaswamy, K., Swetha, T., Rao, G. H., Singh, S. P., & Sharma, G. D. (2015). CH3NH3PbI3 Perovskite Sensitized Solar Cells Using a D-A Copolymer as Hole Transport Material. *Electrochimica Acta*, *151*(NA), 21-26. https://doi.org/10.1016/j.electacta.2014.11.003

[175]Nenon, D. P., Pressler, K., Kang, J., Koscher, B. A., Olshansky, J. H., Osowiecki, W. T., Koc, M. A., Wang, L.-W., & Alivisatos, A. P. (2018). Design Principles for Trap-Free CsPbX3 Nanocrystals: Enumerating and Eliminating Surface Halide Vacancies with Softer Lewis Bases. *Journal of the American Chemical Society*, *140*(50), 17760-17772. https://doi.org/10.1021/jacs.8b11035.s001

[176]Nie, W., Blancon, J.-C., Neukirch, A., Appavoo, K., Tsai, H., Chhowalla, M., Alam, M. A., Sfeir, M. Y., Katan, C., Even, J., Tretiak, S., Crochet, J., Gupta, G., & Mohite, A. D. (2016). Light-activated photocurrent degradation and self-healing in perovskite solar cells. *Nature communications*, *7*(1), 11574-11574. https://doi.org/10.1038/ncomms11574

[177]Ning, W.-H., Wang, F., Wu, B., Lu, J., Yan, Z., Liu, X., Tao, Y., Liu, J.-M., Huang, W., Fahlman, M., Hultman, L., Sum, T. C., & Gao, F. (2018). Long Electron–Hole Diffusion Length in High-Quality Lead-Free Double Perovskite

Films. *Advanced materials (Deerfield Beach, Fla.)*, *30*(20), 1706246-NA. https://doi.org/10.1002/adma.201706246

[178]Nishimura, K., Kamarudin, M. A., Hirotani, D., Hamada, K., Shen, Q., Iikubo, S., Minemoto, T., Yoshino, K., & Hayase, S. (2020). Lead-free tin-halide perovskite solar cells with 13% efficiency. *Nano Energy*, *74*(NA), 104858-NA. https://doi.org/10.1016/j.nanoen.2020.104858

[179]Noel, N. K., Stranks, S. D., Abate, A., Wehrenfennig, C., Guarnera, S., Haghighirad, A. A., Sadhanala, A., Eperon, G. E., Pathak, S., Johnston, M. B., Petrozza, A., Herz, L. M., & Snaith, H. J. (2014). Lead-free organic–inorganic tin halide perovskites for photovoltaic applications. *Energy Environ. Sci.*, *7*(9), 3061-3068. https://doi.org/10.1039/c4ee01076k

[180]Ogomi, Y., Morita, A., Tsukamoto, S., Saitho, T., Shen, Q., Toyoda, T., Yoshino, K., Pandey, S. S., Ma, T., & Hayase, S. (2014). All-Solid Perovskite Solar Cells with HOCO-R-NH3+I– Anchor-Group Inserted between Porous Titania and Perovskite. *The Journal of Physical Chemistry C*, *118*(30), 16651-16659. https://doi.org/10.1021/jp412627n

[181]Paek, S., Qin, P., Lee, Y., Cho, K. T., Gao, P., Grancini, G., Oveisi, E., Gratia, P., Rakstys, K., Al-Muhtaseb, S. A., Ludwig, C., Ko, J., & Nazeeruddin, M. K. (2017). Dopant-Free Hole-Transporting Materials for Stable and Efficient Perovskite Solar Cells. *Advanced materials (Deerfield Beach, Fla.)*, *29*(35), 1606555-NA. https://doi.org/10.1002/adma.201606555

[182]Pan, J., Shang, Y., Yin, J., De Bastiani, M., Peng, W., Dursun, I., Sinatra, L., El-Zohry, A. M., Hedhili, M. N., Emwas, A.-H. M., Mohammed, O. F., Ning, Z., & Bakr, O. M. (2018). Bidentate Ligand-Passivated CsPbI3 Perovskite Nanocrystals for Stable Near-Unity Photoluminescence Quantum Yield and Efficient Red Light-Emitting Diodes. *Journal of the American Chemical Society*, *140*(2), 562-565. https://doi.org/10.1021/jacs.7b10647

[183]Park, N.-G. (2016). Crystal growth engineering for high efficiency perovskite solar cells. *CrystEngComm*, *18*(32), 5977-5985. https://doi.org/10.1039/c6ce00813e

[184]Park, N.-G. (2019). Research Direction toward Scalable, Stable, and High Efficiency Perovskite Solar Cells. *Advanced Energy Materials*, *10*(13), 1903106-NA. https://doi.org/10.1002/aenm.201903106

[185]Park, N.-G., & Zhu, K. (2020). Scalable fabrication and coating methods for perovskite solar cells and solar modules. *Nature Reviews Materials*, *5*(5), 333-350. https://doi.org/10.1038/s41578-019-0176-2

[186]Parrott, E. S., Milot, R. L., Stergiopoulos, T., Snaith, H. J., Johnston, M. B., & Herz, L. M. (2016). Effect of Structural Phase Transition on Charge-Carrier Lifetimes and Defects in CH3NH3SnI3 Perovskite. *The journal of physical chemistry letters*, *7*(7), 1321-1326. https://doi.org/10.1021/acs.jpclett.6b00322

[187]Peng, J., Zhou, X., Shen, H., Wu, Y., Mulmudi, H. K., Wan, Y., Zhong, D., Li, J., Tsuzuki, T., Weber, K., Catchpole, K. R., & White, T. P. (2016). Efficient Indium-Doped TiOxElectron Transport Layers for High-Performance Perovskite Solar Cells and Perovskite-Silicon Tandems. *Advanced Energy Materials*, *7*(4), 1601768-NA. https://doi.org/10.1002/aenm.201601768

[188]Petrus, M. L., Schlipf, J., Li, C., Gujar, T. P., Giesbrecht, N., Müller-Buschbaum, P., Thelakkat, M., Bein, T., Hüttner, S., & Docampo, P. (2017). Capturing the Sun: A Review of the Challenges and Perspectives of Perovskite Solar Cells. *Advanced Energy Materials*, *7*(16), 1700264-NA. https://doi.org/10.1002/aenm.201700264

[189]Ponseca, C. S., Tian, Y., Sundström, V., & Scheblykin, I. G. (2016). Excited state and charge-carrier dynamics in perovskite solar cell materials. *Nanotechnology*, *27*(8), 082001-082001. https://doi.org/10.1088/0957-4484/27/8/082001

[190]Popov, G., Mattinen, M., Kemell, M., Ritala, M., & Leskelä, M. (2016). Scalable Route to the Fabrication of CH3NH3PbI3 Perovskite Thin Films by Electrodeposition and Vapor Conversion. *ACS omega*, *1*(6), 1296-1306. https://doi.org/10.1021/acsomega.6b00351

[191]Prasanna, R., Gold-Parker, A., Leijtens, T., Conings, B., Babayigit, A., Boyen, H.-G., Toney, M. F., & McGehee, M. D. (2017). Band Gap Tuning via Lattice Contraction and Octahedral Tilting in Perovskite Materials for Photovoltaics. *Journal of the American Chemical Society*, *139*(32), 11117-11124. https://doi.org/10.1021/jacs.7b04981.s001

[192]Qing, J., Chandran, H. T., Cheng, Y., Liu, X.-K., Li, H.-W., Tsang, S.-W., Lo, M.-F., & Lee, C.-S. (2015). Chlorine Incorporation for Enhanced Performance of Planar Perovskite Solar Cell Based on Lead Acetate Precursor. *ACS applied materials & interfaces*, *7*(41), 23110-23116. https://doi.org/10.1021/acsami.5b06819

[193]Qiu, J., Xia, Y., Zheng, Y., Hui, W., Gu, H., Yuan, W., Yu, H., Chao, L., Niu, T., Yang, Y., Gao, X., Chen, Y., & Huang, W. (2019). 2D Intermediate Suppression for Efficient Ruddlesden–Popper (RP) Phase Lead-Free Perovskite Solar Cells. *ACS Energy Letters*, *4*(7), 1513-1520. https://doi.org/10.1021/acsenergylett.9b00954

[194]Qiu, X., Jiang, Y., Zhang, H., Qiu, Z., Yuan, S., Wang, P., & Cao, B. (2016). Lead-free mesoscopic Cs2SnI6perovskite solar cells using different nanostructured ZnO nanorods as electron transport layers. *physica status solidi (RRL) – Rapid Research Letters*, *10*(8), 587-591. https://doi.org/10.1002/pssr.201600166

[195]Rai, M., Rahmany, S., Lim, S. S., Magdassi, S., Wong, L. H., & Etgar, L. (2018). Hot dipping post treatment for improved efficiency in micro patterned semi-transparent perovskite solar cells. *Journal of Materials Chemistry A*, *6*(46), 23787-23796. https://doi.org/10.1039/c8ta09340g

[196]Rajagopal, A., Liang, P.-W., Chueh, C.-C., Yang, Z., & Jen, A. K. Y. (2017). Defect Passivation via a Graded Fullerene Heterojunction in Low-Bandgap Pb–Sn Binary Perovskite Photovoltaics. *ACS Energy Letters*, *2*(11), 2531-2539. https://doi.org/10.1021/acsenergylett.7b00847

[197]Rajagopal, A., Williams, S. T., Chueh, C.-C., & Jen, A. K. Y. (2016). Abnormal Current–Voltage Hysteresis Induced by Reverse Bias in Organic–Inorganic Hybrid Perovskite Photovoltaics. *The journal of physical chemistry letters*, *7*(6), 995-1003. https://doi.org/10.1021/acs.jpclett.6b00058

[198]Ran, C., Wang, Y., Gao, W., Xia, Y., Chen, Y., & Huang, W. (2021). Lead Sources in Perovskite Solar Cells: Toward Controllable, Sustainable, and Large-Scalable Production. *Solar RRL*, *5*(12), 2100665. https://doi.org/10.1002/solr.202100665

[199]Ran, C., Xi, J., Gao, W., Yuan, F., Lei, T., Jiao, B., Hou, X., & Wu, Z. (2018). Bilateral Interface Engineering toward Efficient 2D–3D Bulk Heterojunction Tin Halide Lead-Free Perovskite Solar Cells. *ACS Energy Letters*, *3*(3), 713-721. https://doi.org/10.1021/acsenergylett.8b00085

[200]Ran, C., Xu, J., Gao, W., Huang, C., & Dou, S. X. (2018). Defects in metal triiodide perovskite materials towards high-performance solar cells: origin, impact, characterization, and engineering. *Chemical Society reviews*, *47*(12), 4581-4610. https://doi.org/10.1039/c7cs00868f

[201]Rezaee, E., Liu, X., Hu, Q., Dong, L., Chen, Q., Pan, J. H., & Xu, Z.-X. (2018). Dopant‐Free Hole Transporting Materials for Perovskite Solar Cells. *Solar RRL*, *2*(11), 1800200-NA. https://doi.org/10.1002/solr.201800200

[202]Ripan Kumar, P., Md Majharul, I., & Arafat Bin, F. (2022). Integration Of Advanced NDT Techniques & Implementing QA/QC Programs In Enhancing Safety And Integrity In Oil & Gas Operations. *American Journal of Interdisciplinary Studies*, *3*(02), 01-35. https://doi.org/10.63125/9pzxgq74

[203]Rolston, N., Printz, A. D., Hilt, F., Hovish, M. Q., Brüning, K., Tassone, C. J., & Dauskardt, R. H. (2017). Improved stability and efficiency of perovskite solar cells with submicron flexible barrier films deposited in air. *Journal of Materials Chemistry A*, *5*(44), 22975-22983. https://doi.org/10.1039/c7ta09178h

[204]Rong, Y., Liu, L., Mei, A., Li, X., & Han, H. (2015). Beyond Efficiency: the Challenge of Stability in Mesoscopic Perovskite Solar Cells. *Advanced Energy Materials*, *5*(20), 1501066-NA. https://doi.org/10.1002/aenm.201501066

[205]Saliba, M., Matsui, T., Seo, J.-Y., Domanski, K., Correa-Baena, J.-P., Nazeeruddin, M. K., Zakeeruddin, M., Tress, W., Abate, A., Hagfeldt, A., & Grätzel, M. (2016). Cesium-containing triple cation perovskite solar cells: improved stability, reproducibility and high efficiency. *Energy & Environmental Science*, *9*(6), 1989-1997. https://doi.org/10.1039/c5ee03874j

[206]Schloemer, T. H., Christians, J. A., Luther, J. M., & Sellinger, A. (2019). Doping strategies for small molecule organic hole-transport materials: impacts on perovskite solar cell performance and stability. *Chemical science*, *10*(7), 1904-1935. https://doi.org/10.1039/c8sc05284k

[207]Schmidt, T. M., Larsen-Olsen, T. T., Carlé, J. E., Angmo, D., & Krebs, F. C. (2015). Upscaling of Perovskite Solar Cells: Fully Ambient Roll Processing of Flexible Perovskite Solar Cells with Printed Back Electrodes. *Advanced Energy Materials*, *5*(15), 1500569-NA. https://doi.org/10.1002/aenm.201500569

[208]Shalan, A. E. (2020). Challenges and approaches towards upscaling the assembly of hybrid perovskite solar cells. *Materials Advances*, *1*(3), 292-309. https://doi.org/10.1039/d0ma00128g

[209]Shi, J., Xu, X., Li, D., & Meng, Q. (2015). Interfaces in perovskite solar cells. *Small (Weinheim an der Bergstrasse, Germany)*, *11*(21), 2472-2486. https://doi.org/10.1002/smll.201403534

[210]Shi, Z., Guo, J., Chen, Y., Li, Q., Pan, Y., Zhang, H., Xia, Y., & Huang, W. (2017). Lead-Free Organic-Inorganic Hybrid Perovskites for Photovoltaic Applications: Recent Advances and Perspectives. *Advanced materials (Deerfield Beach, Fla.)*, *29*(16), 1605005-NA. https://doi.org/10.1002/adma.201605005

[211]Shih, Y.-C., Lan, Y.-B., Li, C.-S., Hsieh, H.-C., Wang, L., Wu, C.-I., & Lin, K.-F. (2017). Amino-Acid-Induced Preferential Orientation of Perovskite Crystals for Enhancing Interfacial Charge Transfer and Photovoltaic Performance. *Small (Weinheim an der Bergstrasse, Germany)*, *13*(22), 1604305-NA. https://doi.org/10.1002/smll.201604305

[212]Shin, S. S., Yeom, E. J., Yang, W. S., Hur, S., Kim, M. G., Im, J., Seo, J., Noh, J. H., & Seok, S. I. (2017). Colloidally prepared La-doped BaSnO3 electrodes for efficient, photostable perovskite solar cells. *Science (New York, N.Y.)*, *356*(6334), 167-171. https://doi.org/10.1126/science.aam6620

[213]Shrestha, N., Song, Z., Chen, C., Bastola, E., Wang, X., Yan, Y., & Ellingson, R. J. (2019). Charge Compensating Defects in Methylammonium Lead Iodide Perovskite Suppressed by Formamidinium Inclusion. *The journal of physical chemistry letters*, *11*(1), 121-128. https://doi.org/10.1021/acs.jpclett.9b03234

[214]Singh, S., Li, C., Panzer, F., Narasimhan, K. L., Graeser, A., Gujar, T. P., Köhler, A., Thelakkat, M., Huettner, S., & Kabra, D. (2016). Effect of Thermal and Structural Disorder on the Electronic Structure of Hybrid Perovskite Semiconductor CH3NH3PbI3. *The journal of physical chemistry letters*, *7*(15), 3014-3021. https://doi.org/10.1021/acs.jpclett.6b01207

[215]Slavney, A. H., Hu, T., Lindenberg, A. M., & Karunadasa, H. I. (2016). A Bismuth-Halide Double Perovskite with Long Carrier Recombination Lifetime for Photovoltaic Applications. *Journal of the American Chemical Society*, *138*(7), 2138-2141. https://doi.org/10.1021/jacs.5b13294

[216]Smith, I. C. P., Hoke, E. T., Solis-Ibarra, D., McGehee, M. D., & Karunadasa, H. I. (2014). A Layered Hybrid Perovskite Solar-Cell Absorber with Enhanced Moisture Stability. *Angewandte Chemie (International ed. in English)*, *53*(42), 11232-11235. https://doi.org/10.1002/anie.201406466

[217]Smith, M. D., Crace, E., Jaffe, A., & Karunadasa, H. I. (2018). The Diversity of Layered Halide Perovskites. *Annual Review of Materials Research*, *48*(1), 111-136. https://doi.org/10.1146/annurev-matsci-070317-124406

[218]Snaith, H. J., Abate, A., Ball, J. M., Eperon, G. E., Leijtens, T., Noel, N. K., Stranks, S. D., Wang, J. T.-W., Wojciechowski, K., & Zhang, W. (2014). Anomalous hysteresis in perovskite solar cells. *The journal of physical chemistry letters*, *5*(9), 1511-1515. https://doi.org/10.1021/jz500113x

[219]Sohel, A., Alam, M. A., Hossain, A., Mahmud, S., & Akter, S. (2022). Artificial Intelligence In Predictive Analytics For Next-Generation Cancer Treatment: A Systematic Literature Review Of Healthcare Innovations In The USA. *Global Mainstream Journal of Innovation, Engineering & Emerging Technology*, *1*(01), 62-87. https://doi.org/10.62304/jieet.v1i01.229

[220]Song, D., Wei, D., Cui, P., Li, M., Duan, Z., Wang, T., Ji, J., Li, Y., Mbengue, J. M., Li, Y., He, Y., Trevor, M., & Park, N.-G. (2016). Dual function interfacial layer for highly efficient and stable lead halide perovskite solar cells. *Journal of Materials Chemistry A*, *4*(16), 6091-6097. https://doi.org/10.1039/c6ta00577b

[221]Steck, C., Franckevičius, M., Zakeeruddin, M., Mishra, A., Bäuerle, P., & Grätzel, M. (2015). A–D–A-type S,N-heteropentacene-based hole transport materials for dopant-free perovskite solar cells. *Journal of Materials Chemistry A*, *3*(34), 17738-17746. https://doi.org/10.1039/c5ta03865k

[222]Stewart, R. J., Grieco, C., Larsen, A. V., Maier, J. J., & Asbury, J. B. (2016). Approaching Bulk Carrier Dynamics in Organo-Halide Perovskite Nanocrystalline Films by Surface Passivation. *The journal of physical chemistry letters*, *7*(7), 1148-1153. https://doi.org/10.1021/acs.jpclett.6b00366

[223]Stolterfoht, M., Wolff, C. M., Amir, Y., Paulke, A., Perdigón-Toro, L., Caprioglio, P., & Neher, D. (2017). Approaching the fill factor Shockley–Queisser limit in stable, dopant-free triple cation perovskite solar cells. *Energy & Environmental Science*, *10*(6), 1530-1539. https://doi.org/10.1039/c7ee00899f

[224]Subhani, W. S., Wang, K., Du, M., Wang, X., Yuan, N., Ding, J., & Liu, S. (2019). Anti-solvent engineering for efficient semitransparent CH3NH3PbBr3 perovskite solar cells for greenhouse applications. *Journal of Energy Chemistry*, *34*(NA), 12-19. https://doi.org/10.1016/j.jechem.2018.10.001

[225]Sun, C., Wu, Z., Yip, H.-L., Zhang, H., Jiang, X.-F., Xue, Q., Hu, Z., Hu, Z., Shen, Y., Wang, M., Huang, F., & Cao, Y. (2015). Amino-Functionalized Conjugated Polymer as an Efficient Electron Transport Layer for High-Performance Planar-Heterojunction Perovskite Solar Cells. *Advanced Energy Materials*, *6*(5), 1501534-NA. https://doi.org/10.1002/aenm.201501534

[226]Sutanto, A. A., Drigo, N., Queloz, V. I. E., García-Benito, I., Kirmani, A. R., Richter, L. J., Schouwink, P., Cho, K. T., Paek, S., Nazeeruddin, M. K., & Grancini, G. (2020). Dynamical evolution of the 2D/3D interface: a hidden driver behind perovskite solar cell instability. *Journal of Materials Chemistry A*, *8*(5), 2343-2348. https://doi.org/10.1039/c9ta12489f

[227]Sutton, R. J., Filip, M. R., Haghighirad, A. A., Sakai, N., Wenger, B., Giustino, F., & Snaith, H. J. (2018). Cubic or Orthorhombic? Revealing the Crystal Structure of Metastable Black-Phase CsPbI3 by Theory and Experiment. *ACS Energy Letters*, *3*(8), 1787-1794. https://doi.org/10.1021/acsenergylett.8b00672

[228]Takahashi, Y., Obara, R., Lin, Z.-Z., Takahashi, Y., Naito, T., Inabe, T., Ishibashi, S., & Terakura, K. (2011). Charge-transport in tin-iodide perovskite CH3NH3SnI3: origin of high conductivity. *Dalton transactions (Cambridge, England : 2003)*, *40*(20), 5563-5568. https://doi.org/10.1039/c0dt01601b

[229]Tang, S., Deng, Y., Zheng, X., Bai, Y., Fang, Y., Dong, Q., Wei, H., & Huang, J. (2017). Composition Engineering in Doctor-Blading of Perovskite Solar Cells. *Advanced Energy Materials*, *7*(18), 1700302-NA. https://doi.org/10.1002/aenm.201700302

[230]Tao, C., Neutzner, S., Colella, L., Marras, S., Kandada, A. R. S., Gandini, M., De Bastiani, M., Pace, G., Manna, L., Caironi, M., Bertarelli, C., & Petrozza, A. (2015). 17.6% stabilized efficiency in low-temperature processed planar perovskite solar cells. *Energy & Environmental Science*, *8*(8), 2365-2370. https://doi.org/10.1039/c5ee01720c

[231]Teale, S., Proppe, A. H., Jung, E. H., Johnston, A., Parmar, D. H., Chen, B., Hou, Y., Kelley, S. O., & Sargent, E. H. (2020). Dimensional Mixing Increases the Efficiency of 2D/3D Perovskite Solar Cells. *The journal of physical chemistry letters*, *11*(13), 5115-5119. https://doi.org/10.1021/acs.jpclett.0c01444

[232]Tian, J., Wang, J., Xue, Q., Niu, T., Yan, L., Zhu, Z., Li, N., Brabec, C. J., Yip, H.-L., & Cao, Y. (2020). Composition Engineering of All‐Inorganic Perovskite Film for Efficient and Operationally Stable Solar Cells. *Advanced Functional Materials*, *30*(28), 2001764-NA. https://doi.org/10.1002/adfm.202001764

[233]Tian, Y., & Scheblykin, I. G. (2015). Artifacts in Absorption Measurements of Organometal Halide Perovskite Materials: What Are the Real Spectra? *The journal of physical chemistry letters*, *6*(17), 3466-3470. https://doi.org/10.1021/acs.jpclett.5b01406

[234]Tong, Y., Xiao, Z., Du, X., Zuo, C., Li, Y., Lv, M., Yuan, Y., Yi, C., Hao, F., Hua, Y., Lei, T., Lin, Q., Sun, K., Zhao, D., Duan, C., Shao, X., Li, W., Yip, H.-L., Xiao, Z., . . . Ding, L. (2020). Progress of the key materials for organic solar cells. *Science China Chemistry*, *63*(6), 758-765. https://doi.org/10.1007/s11426-020-9726-0

[235]Tonoy, A. A. R. (2022). Mechanical Properties and Structural Stability of Semiconducting Electrides: Insights For Material. *Global Mainstream Journal of Innovation, Engineering & Emerging Technology*, *1*(01), 18-35. https://doi.org/10.62304/jieet.v1i01.225

[236]Topolovsek, P., Lamberti, F., Gatti, T., Cito, A., Ball, J. M., Menna, E., Gadermaier, C., & Petrozza, A. (2017). Functionalization of transparent conductive oxide electrode for TiO2-free perovskite solar cells. *Journal of Materials Chemistry A*, *5*(23), 11882-11893. https://doi.org/10.1039/c7ta02405c

[237]Tu, Y., Xu, G., Yang, X.-Y., Zhang, Y., Zhaojie, L., Su, R., Luo, D., Yang, W., Ying, M., Cai, R., Jiang, L., Xiaowei, D., Yang, Y., Qianshi, L., Gao, Y., Shuai, Z., Huang, W., Gong, Q., & Zhu, R. (2019). Mixed-cation perovskite solar cells in space. *Science China Physics, Mechanics & Astronomy*, *62*(7), 974221-NA. https://doi.org/10.1007/s11433-019-9356-1

[238]Tu, Y., Yang, X.-Y., Su, R., Luo, D., Cao, Y., Zhao, L., Liu, T., Yang, W., Zhang, Y., Xu, Z., Liu, Q., Wu, J., Gong, Q., Mo, F., & Zhu, R. (2018). Diboron-Assisted Interfacial Defect Control Strategy for Highly Efficient Planar Perovskite Solar Cells. *Advanced materials (Deerfield Beach, Fla.)*, *30*(49), 1805085-NA. https://doi.org/10.1002/adma.201805085

[239]Turkevych, I., Kazaoui, S., Belich, N. A., Grishko, A. Y., Fateev, S. A., Petrov, A. A., Urano, T., Aramaki, S., Kosar, S., Kondo, M., Goodilin, E. A., Graetzel, M., & Tarasov, A. (2018). Strategic advantages of reactive polyiodide melts for scalable perovskite photovoltaics. *Nature nanotechnology*, *14*(1), 57-63. https://doi.org/10.1038/s41565-018-0304-y

[240]Urbina, A. (2020). The balance between efficiency, stability and environmental impacts in perovskite solar cells: a review. *Journal of Physics: Energy*, *2*(2), 022001-NA. https://doi.org/10.1088/2515-7655/ab5eee

[241]Vallés-Pelarda, M., Hames, B. C., García-Benito, I., Almora, O., Molina-Ontoria, A., Sánchez, R., Garcia-Belmonte, G., Martín, N., & Mora-Seró, I. (2016). Analysis of the Hysteresis Behavior of Perovskite Solar Cells with Interfacial Fullerene Self-Assembled Monolayers. *The journal of physical chemistry letters*, *7*(22), 4622-4628. https://doi.org/10.1021/acs.jpclett.6b02103

[242]Vargas, B. C., Ramos, E., Pérez-Gutiérrez, E., Alonso, J. C., & Solis-Ibarra, D. (2017). A Direct Bandgap Copper–Antimony Halide Perovskite. *Journal of the American Chemical Society*, *139*(27), 9116-9119. https://doi.org/10.1021/jacs.7b04119

[243]Waleed, A., Tavakoli, M. M., Gu, L., Wang, Z.-Y., Zhang, D., Manikandan, A., Zhang, Q., Zhang, R.-J., Chueh, Y.-L., & Fan, Z. (2016). Lead-Free Perovskite Nanowire Array Photodetectors with Drastically Improved Stability in Nanoengineering Templates. *Nano letters*, *17*(1), 523-530. https://doi.org/10.1021/acs.nanolett.6b04587

[244]Wan, F., Qiu, X., Chen, H., Liu, Y., Xie, H., Shi, J., Huang, H., Yuan, Y., Gao, Y., & Zhou, C. (2018). Accelerated electron extraction and improved UV stability of TiO2 based perovskite solar cells by SnO2 based surface passivation. *Organic Electronics*, *59*(NA), 184-189. https://doi.org/10.1016/j.orgel.2018.05.008

[245]Wang, D., Li, W., Du, Z., Li, G., Sun, W., Wu, J., & Lan, Z. (2020). CoBr2-doping-induced efficiency improvement of CsPbBr3 planar perovskite solar cells. *Journal of Materials Chemistry C*, *8*(5), 1649-1655. https://doi.org/10.1039/c9tc05679c

[246]Wang, F., Jiang, X., Chen, H., Shang, Y., Liu, H., Wei, J., Zhou, W., He, H., Liu, W., & Ning, Z. (2018). 2D-Quasi-2D-3D Hierarchy Structure for Tin Perovskite Solar Cells with Enhanced Efficiency and Stability. *Joule*, *2*(12), 2732-2743. https://doi.org/10.1016/j.joule.2018.09.012

[247]Wang, G., Adil, M. A., Zhang, J., & Wei, Z. (2018). Organic Solar Cells: Large-Area Organic Solar Cells: Material Requirements, Modular Designs, and Printing Methods (Adv. Mater. 45/2019). *Advanced materials (Deerfield Beach, Fla.)*, *31*(45), 1970324-NA. https://doi.org/10.1002/adma.201805089

[248]Wang, H., Dewi, H. A., Koh, T. M., Bruno, A., Mhaisalkar, S., & Mathews, N. (2019). Bifacial, color-tunable semitransparent perovskite solar cells for building-integrated photovoltaics. *ACS applied materials & interfaces*, *12*(1), 484-493. https://doi.org/10.1021/acsami.9b15488

[249]Wang, J.-M., Wang, Z.-K., Li, M., Zhang, C.-C., Jiang, L.-L., Hu, K.-H., Ye, Q.-Q., & Liao, L.-S. (2017). Doped Copper Phthalocyanine via an Aqueous Solution Process for Normal and Inverted Perovskite Solar Cells. *Advanced Energy Materials*, *8*(2), 1701688-NA. https://doi.org/10.1002/aenm.201701688

[250]Wang, K., Liu, C., Du, P., Zheng, J., & Gong, X. (2015). Bulk heterojunction perovskite hybrid solar cells with large fill factor. *Energy & Environmental Science*, *8*(4), 1245-1255. https://doi.org/10.1039/c5ee00222b

[251]Wang, K., Shi, Y., Li, B., Zhao, L., Wang, W., Wang, X., Bai, X., Wang, S., Hao, C., & Ma, T. (2015). Amorphous Inorganic Electron-Selective Layers for Efficient Perovskite Solar Cells: Feasible Strategy Towards Room-Temperature Fabrication. *Advanced materials (Deerfield Beach, Fla.)*, *28*(9), 1891-1897. https://doi.org/10.1002/adma.201505241

[252]Wang, K. C., Shen, P. S., Li, M. H., Chen, S., Lin, M. W., Chen, P., & Guo, T.-F. (2014). Low-temperature sputtered nickel oxide compact thin film as effective electron blocking layer for mesoscopic NiO/CH3NH3PbI3

perovskite heterojunction solar cells. *ACS applied materials & interfaces*, *6*(15), 11851-11858. https://doi.org/10.1021/am503610u

[253]Wang, S., Jiang, Y., Juarez-Perez, E. J., Ono, L. K., & Qi, Y. (2016). Accelerated degradation of methylammonium lead iodide perovskites induced by exposure to iodine vapour. *Nature Energy*, *2*(1), 16195-NA. https://doi.org/10.1038/nenergy.2016.195

[254]Wang, Y., Gao, C., Wang, X., Liu, H., & Shen, W. (2021). Controllable Electrochemical Deposition and Theoretical Understanding of Conformal Perovskite on Textured Silicon towards Efficient Perovskite/Silicon Tandem Solar Cells. *The Journal of Physical Chemistry C*, *125*(5), 2875-2883. https://doi.org/10.1021/acs.jpcc.0c11259

[255]Wang, Y., Rho, W.-Y., Yang, H.-Y., Mahmoudi, T., Seo, S., Lee, D.-H., & Hahn, Y.-B. (2016). Air-stable, hole-conductor-free high photocurrent perovskite solar cells with CH3NH3PbI3–NiO nanoparticles composite. *Nano Energy*, *27*(NA), 535-544. https://doi.org/10.1016/j.nanoen.2016.08.006

[256]Wang, Y., Zhang, T., Kan, M., & Zhao, Y. (2018). Bifunctional Stabilization of All-Inorganic α-CsPbI3 Perovskite for 17% Efficiency Photovoltaics. *Journal of the American Chemical Society*, *140*(39), 12345-12348. https://doi.org/10.1021/jacs.8b07927

[257]Watson, B. L., Rolston, N., Bush, K. A., Leijtens, T., McGehee, M. D., & Dauskardt, R. H. (2016). Cross-Linkable, Solvent-Resistant Fullerene Contacts for Robust and Efficient Perovskite Solar Cells with Increased JSC and VOC. *ACS applied materials & interfaces*, *8*(39), 25896-25904. https://doi.org/10.1021/acsami.6b06164

[258]Watson, B. L., Rolston, N., Printz, A. D., & Dauskardt, R. H. (2017). Scaffold-reinforced perovskite compound solar cells. *Energy & Environmental Science*, *10*(12), 2500-2508. https://doi.org/10.1039/c7ee02185b

[259]Weber, D. (1978a). CH3NH3PbX3, ein Pb(II)-System mit kubischer Perowskitstruktur / CH3NH3PbX3, a Pb(II)-System with Cubic Perovskite Structure. *Zeitschrift für Naturforschung B*, *33*(12), 1443-1445. https://doi.org/10.1515/znb-1978-1214

[260]Weber, D. (1978b). CH3NH3SnBrxI3-x (x = 0-3), ein Sn(II)-System mit kubischer Perowskitstruktur / CH3NH3SnBrxI3-x(x = 0-3), a Sn(II)-System with Cubic Perovskite Structure. *Zeitschrift für Naturforschung B*, *33*(8), 862-865. https://doi.org/10.1515/znb-1978-0809

[261]Wehrenfennig, C., Liu, M., Snaith, H. J., Johnston, M. B., & Herz, L. M. (2014). Charge-carrier dynamics in vapour-deposited films of the organolead halide perovskite CH3NH3PbI3-xClx. *Energy Environ. Sci.*, *7*(7), 2269-2275. https://doi.org/10.1039/c4ee01358a

[262]Wei, H., DeSantis, D., Wei, W., Deng, Y., Guo, D., Savenije, T. J., Cao, L., & Huang, J. (2017). Dopant compensation in alloyed CH 3 NH 3 PbBr 3-x Cl x perovskite single crystals for gamma-ray spectroscopy. *Nature materials*, *16*(8), 826-833. https://doi.org/10.1038/nmat4927

[263]Williams, S. T., Rajagopal, A., Chueh, C.-C., & Jen, A. K. Y. (2016). Current Challenges and Prospective Research for Upscaling Hybrid Perovskite Photovoltaics. *The journal of physical chemistry letters*, *7*(5), 811-819. https://doi.org/10.1021/acs.jpclett.5b02651

[264]Wilson, J. N., Frost, J. M., Wallace, S. K., & Walsh, A. (2019). Dielectric and ferroic properties of metal halide perovskites. *APL Materials*, *7*(1), 010901-NA. https://doi.org/10.1063/1.5079633

[265]Wojciechowski, K., Ramirez, I., Gorisse, T., Dautel, O., Dasari, R. R., Sakai, N., Hardigree, J. F. M., Song, S., Marder, S. R., Riede, M., Wantz, G., & Snaith, H. J. (2016). Cross-Linkable Fullerene Derivatives for Solution-Processed n–i–p Perovskite Solar Cells. *ACS Energy Letters*, *1*(4), 648-653. https://doi.org/10.1021/acsenergylett.6b00229

[266]Wu, C., Zhang, Q., Liu, Y., Luo, W., Guo, X., Huang, Z., Ting, H., Sun, W., Zhong, X., Wei, S., Wang, S., Chen, Z., & Xiao, L. (2017). The Dawn of Lead-Free Perovskite Solar Cell: Highly Stable Double Perovskite Cs2AgBiBr6 Film. *Advanced science (Weinheim, Baden-Wurttemberg, Germany)*, *5*(3), 1700759-1700759. https://doi.org/10.1002/advs.201700759

[267]Wu, G., Li, H., Cui, J., Zhang, Y., Olthof, S., Chen, S., Liu, Z., Wang, D., & Liu, S. F. (2020). Solvent Engineering Using a Volatile Solid for Highly Efficient and Stable Perovskite Solar Cells. *Advanced science (Weinheim, Baden-Wurttemberg, Germany)*, *7*(10), 1903250-NA. https://doi.org/10.1002/advs.201903250

[268]Wu, G., Liang, R., Zhang, Z., Ge, M., Xing, G., & Sun, G. (2021). 2D Hybrid Halide Perovskites: Structure, Properties, and Applications in Solar Cells. *Small (Weinheim an der Bergstrasse, Germany)*, *17*(43), 2103514-NA. https://doi.org/10.1002/smll.202103514

[269]Wu, G., Zhou, J., Meng, R., Xue, B., Zhou, H., Tang, Z., & Zhang, Y. (2019). Air-stable formamidinium/methylammonium mixed lead iodide perovskite integral microcrystals with low trap density and high photo-responsivity. *Physical chemistry chemical physics : PCCP*, *21*(6), 3106-3113. https://doi.org/10.1039/c8cp07271j

[270]Wu, W.-Q., Wang, Q., Fang, Y., Shao, Y., Tang, S., Deng, Y., Lu, H., Liu, Y., Li, T., Yang, Z., Gruverman, A., & Huang, J. (2018). Molecular doping enabled scalable blading of efficient hole-transport-layer-free perovskite solar cells. *Nature communications*, *9*(1), 1625-NA. https://doi.org/10.1038/s41467-018-04028-8

[271]Xia, J., Liang, C., Mei, S., Gu, H., He, B., Zhang, Z., Liu, T., Wang, K., Wang, S., Chen, S., Cai, Y., & Xing, G. (2021). Deep surface passivation for efficient and hydrophobic perovskite solar cells. *Journal of Materials Chemistry A*, *9*(5), 2919-2927. https://doi.org/10.1039/d0ta10535j

[272]Xiao, J.-W., Shi, C., Zhou, C., Zhang, D., Li, Y., & Chen, Q. (2017). Contact Engineering: Electrode Materials for Highly Efficient and Stable Perovskite Solar Cells. *Solar RRL*, *1*(9), 1700082-NA. https://doi.org/10.1002/solr.201700082

[273]Xie, J., Yu, X., Huang, J., Sun, X., Zhang, Y., Yang, Z., Lei, M., Xu, L., Tang, Z., Cui, C., Wang, P., & Yang, D. (2017). Self-Organized Fullerene Interfacial Layer for Efficient and Low-Temperature Processed Planar Perovskite Solar Cells with High UV-Light Stability. *Advanced science (Weinheim, Baden-Wurttemberg, Germany)*, *4*(8), 1700018-1700018. https://doi.org/10.1002/advs.201700018

[274]Xu, J., Voznyy, O., Comin, R., Gong, X., Walters, G., Liu, M., Kanjanaboos, P., Lan, X., & Sargent, E. H. (2016). Crosslinked Remote‐Doped Hole‐Extracting Contacts Enhance Stability under Accelerated Lifetime Testing in Perovskite Solar Cells. *Advanced materials (Deerfield Beach, Fla.)*, *28*(14), 2807-2815. https://doi.org/10.1002/adma.201505630

[275]Xu, Y., Wang, M., Lei, Y., Ci, Z., & Jin, Z. (2020). Crystallization Kinetics in 2D Perovskite Solar Cells. *Advanced Energy Materials*, *10*(43), 2002558-NA. https://doi.org/10.1002/aenm.202002558

[276]Xue, Q., Bai, Y., Liu, M., Xia, R., Hu, Z., Chen, Z., Jiang, X.-F., Huang, F., Yang, S., Matsuo, Y., Yip, H.-L., & Cao, Y. (2016). Dual Interfacial Modifications Enable High Performance Semitransparent Perovskite Solar Cells with Large Open Circuit Voltage and Fill Factor. *Advanced Energy Materials*, *7*(9), 1602333-NA. https://doi.org/10.1002/aenm.201602333

[277]Xue, R., Zhang, J., Li, Y., & Li, Y. (2018). Organic Solar Cell Materials toward Commercialization. *Small (Weinheim an der Bergstrasse, Germany)*, *14*(41), 1801793-NA. https://doi.org/10.1002/smll.201801793

[278]Yang, B., Suo, J., Di Giacomo, F., Olthof, S., Bogachuk, D., Kim, Y., Sun, X., Wagner, L., Fu, F., Zakeeruddin, M., Hinsch, A., Grätzel, M., Di Carlo, A., & Hagfeldt, A. (2021). Interfacial Passivation Engineering of Perovskite Solar Cells with Fill Factor over 82% and Outstanding Operational Stability on n-i-p Architecture. *ACS Energy Letters*, *6*(11), 3916-3923. https://doi.org/10.1021/acsenergylett.1c01811

[279]Yang, D., Yang, Z., Wei, Q., Zhang, Y., Liu, S., & Li, C. (2015). Alternating precursor layer deposition for highly stable perovskite films towards efficient solar cells using vacuum deposition. *Journal of Materials Chemistry A*, *3*(18), 9401-9405. https://doi.org/10.1039/c5ta01824b

[280]Yang, F., Liu, J., Lu, Z., Dai, P., Nakamura, T., Wang, S., Chen, L., Wakamiya, A., & Matsuda, K. (2020). Recycled Utilization of a Nanoporous Au Electrode for Reduced Fabrication Cost of Perovskite Solar Cells. *Advanced science (Weinheim, Baden-Wurttemberg, Germany)*, *7*(6), 1902474-1902474. https://doi.org/10.1002/advs.201902474

[281]Yang, G., Lei, H., Tao, H., Zheng, X., Ma, J., Liu, Q., Ke, W., Chen, Z., Xiong, L., Qin, P., Chen, Z., Qin, M., Lu, X., Yan, Y., & Fang, G. (2016). Reducing Hysteresis and Enhancing Performance of Perovskite Solar Cells Using Low-Temperature Processed Y-Doped SnO2 Nanosheets as Electron Selective Layers. *Small (Weinheim an der Bergstrasse, Germany)*, *13*(2), 1601769-NA. https://doi.org/10.1002/smll.201601769

[282]Yang, J., & Kelly, T. L. (2016). Decomposition and Cell Failure Mechanisms in Lead Halide Perovskite Solar Cells. *Inorganic chemistry*, *56*(1), 92-101. https://doi.org/10.1021/acs.inorgchem.6b01307

[283]Yang, L., Cai, F., Yan, Y., Li, J., Liu, D., Pearson, A. J., & Wang, T. (2017). Conjugated Small Molecule for Efficient Hole Transport in High‐Performance p‐i‐n Type Perovskite Solar Cells. *Advanced Functional Materials*, *27*(31), 1702613-NA. https://doi.org/10.1002/adfm.201702613

[284]Yang, M., Li, Z., Reese, M. O., Reid, O. G., Kim, D. H., Siol, S., Klein, T. R., Yan, Y., Berry, J. J., van Hest, M. F. A. M., & Zhu, K. (2017). Perovskite ink with wide processing window for scalable high-efficiency solar cells. *Nature Energy*, *2*(5), 17038-NA. https://doi.org/10.1038/nenergy.2017.38

[285]Yang, S., Weiduan, L., Han, Y., Liu, Z., Wenjing, Z., Duan, C., Che, Y., Haoshuang, G., Li, Y., & Liu, S. (2020). 2D Cs 2 PbI 2 Cl 2 Nanosheets for Holistic Passivation of Inorganic CsPbI 2 Br Perovskite Solar Cells for Improved Efficiency and Stability. *Advanced Energy Materials*, *10*(46), 2002882-NA. https://doi.org/10.1002/aenm.202002882

[286]Yang, Y. M., Yu, A., Hsu, B., Hsu, W. C., Yang, A., & Lan, C.-W. (2013). Development of high‐performance multicrystalline silicon for photovoltaic industry. *Progress in Photovoltaics: Research and Applications*, *23*(3), 340-351. https://doi.org/10.1002/pip.2437

[287]Yao, K., Li, F., He, Q., Wang, X., Jiang, Y., Huang, H., & Jen, A. K. Y. (2017). A copper-doped nickel oxide bilayer for enhancing efficiency and stability of hysteresis-free inverted mesoporous perovskite solar cells. *Nano Energy*, *40*(NA), 155-162. https://doi.org/10.1016/j.nanoen.2017.08.014

[288]Ye, S., Rao, H., Zhao, Z., Zhang, L., Bao, H., Sun, W., Li, Y., Gu, F., Wang, J., Liu, Z., Bian, Z., & Huang, C. (2017). A Breakthrough Efficiency of 19.9% Obtained in Inverted Perovskite Solar Cells by Using an Efficient Trap State Passivator Cu(thiourea)I. *Journal of the American Chemical Society*, *139*(22), 7504-7512. https://doi.org/10.1021/jacs.7b01439

[289]Ye, S., Sun, W., Li, Y., Yan, W., Peng, H., Bian, Z., Liu, Z., & Huang, C. (2015). CuSCN-Based Inverted Planar Perovskite Solar Cell with an Average PCE of 15.6%. *Nano letters*, *15*(6), 3723-3728. https://doi.org/10.1021/acs.nanolett.5b00116

[290]Yin, Z., Wei, J., & Zheng, Q. (2016). Interfacial Materials for Organic Solar Cells: Recent Advances and Perspectives. *Advanced science (Weinheim, Baden-Wurttemberg, Germany)*, *3*(8), 1500362-1500362. https://doi.org/10.1002/advs.201500362

[291]Younus, M. (2022). Reducing Carbon Emissions in The Fashion And Textile Industry Through Sustainable Practices and Recycling: A Path Towards A Circular, Low-Carbon Future. *Global Mainstream Journal of Business, Economics, Development & Project Management*, *1*(1), 57-76. https://doi.org/10.62304/jbedpm.v1i1.226

[292]Yun, J. S., Ho-Baillie, A., Huang, S., Woo, S. H., Heo, Y., Seidel, J., Huang, F., Cheng, Y.-B., & Green, M. A. (2015). Benefit of Grain Boundaries in Organic–Inorganic Halide Planar Perovskite Solar Cells. *The journal of physical chemistry letters*, *6*(5), 875-880. https://doi.org/10.1021/acs.jpclett.5b00182

[293]Zhang, F., Lu, H., Tong, J., Berry, J. J., Beard, M. C., & Zhu, K. (2020). Advances in two-dimensional organic–inorganic hybrid perovskites. *Energy & Environmental Science*, *13*(4), 1154-1186. https://doi.org/10.1039/c9ee03757h

[294]Zhang, F., Ullrich, F., Silver, S., Kerner, R. A., Rand, B. P., & Kahn, A. (2019). Complexities of Contact Potential Difference Measurements on Metal Halide Perovskite Surfaces. *The journal of physical chemistry letters*, *10*(4), 890-896. https://doi.org/10.1021/acs.jpclett.8b03878

[295]Zhang, F., Ye, S., Zhang, H., Zhou, F., Hao, Y., Cai, H., Song, J., & Qu, J. (2021). Comprehensive passivation strategy for achieving inverted perovskite solar cells with efficiency exceeding 23% by trap passivation and ion constraint. *Nano Energy*, *89*(NA), 106370-NA. https://doi.org/10.1016/j.nanoen.2021.106370

[296]Zhang, F., & Zhu, K. (2019). Additive Engineering for Efficient and Stable Perovskite Solar Cells. *Advanced Energy Materials*, *10*(13), 1902579-NA. https://doi.org/10.1002/aenm.201902579

[297]Zhang, H., Qiao, X., Shen, Y., & Wang, M. (2015). Effect of temperature on the efficiency of organometallic perovskite solar cells. *Journal of Energy Chemistry*, *24*(6), 729-735. https://doi.org/10.1016/j.jechem.2015.10.007

[298]Zhang, H., Wang, H., Chen, W., & Jen, A. K. Y. (2016). CuGaO2: A Promising Inorganic Hole-Transporting Material for Highly Efficient and Stable Perovskite Solar Cells. *Advanced materials (Deerfield Beach, Fla.)*, *29*(8), 1604984-NA. https://doi.org/10.1002/adma.201604984

[299]Zhang, S., Shen, L., Mianji, H., Yu, Y., Lei, L., Jun, S., Qingbao, Z., Wu, Z., Wang, J., & Yang, S. (2018). Cyclic Utilization of Lead in Carbon-Based Perovskite Solar Cells. *ACS Sustainable Chemistry & Engineering*, *6*(6), 7558-7564. https://doi.org/10.1021/acssuschemeng.8b00314

[300]Zhang, T., Dar, M. I., Li, G., Xu, F., Nanjie, G., Grätzel, M., & Zhao, Y. (2017). Bication lead iodide 2D perovskite component to stabilize inorganic α-CsPbI 3 perovskite phase for high-efficiency solar cells. *Science advances*, *3*(9), e1700841-NA. https://doi.org/10.1126/sciadv.1700841

[301]Zhang, W., Anaya, M., Lozano, G., Calvo, M. E., Johnston, M. B., Míguez, H., & Snaith, H. J. (2015). Highly Efficient Perovskite Solar Cells with Tunable Structural Color. *Nano letters*, *15*(3), 1698-1702. https://doi.org/10.1021/nl504349z

[302]Zhang, W., Wang, Y.-C., Li, X., Song, C., Wan, L., Usman, K., & Fang, J. (2018). Recent Advance in Solution-Processed Organic Interlayers for High-Performance Planar Perovskite Solar Cells. *Advanced science (Weinheim, Baden-Wurttemberg, Germany)*, *5*(7), 1800159-1800159. https://doi.org/10.1002/advs.201800159

[303]Zhang, Y., Samuel, I. D. W., Wang, T., & Lidzey, D. G. (2018). Current Status of Outdoor Lifetime Testing of Organic Photovoltaics. *Advanced science (Weinheim, Baden-Wurttemberg, Germany)*, *5*(8), 1800434-1800434. https://doi.org/10.1002/advs.201800434

[304]Zhang, Z., Li, M., Liu, W., Yue, X., Cui, P., & Wei, D. (2017). CH3NH3PbI3 converted from reactive magnetron sputtered PbO for large area perovskite solar cells. *Solar Energy Materials and Solar Cells*, *163*(NA), 250-254. https://doi.org/10.1016/j.solmat.2017.01.034

[305]Zhao, D., Ke, W., Grice, C. R., Cimaroli, A. J., Tan, X., Yang, M., Collins, R. W., Zhang, H., Zhu, K., & Yan, Y. (2016). Annealing-free efficient vacuum-deposited planar perovskite solar cells with evaporated fullerenes as electron-selective layers. *Nano Energy*, *19*(NA), 88-97. https://doi.org/10.1016/j.nanoen.2015.11.008

[306]Zhao, S., Xie, J., Cheng, G., Xiang, Y., Zhu, H., Guo, W., Wang, H., Qin, M., Lu, X., Qu, J., Wang, J., Xu, J., & Yan, K. (2018). General Nondestructive Passivation by 4-Fluoroaniline for Perovskite Solar Cells with Improved Performance and Stability. *Small (Weinheim an der Bergstrasse, Germany)*, *14*(50), 1803350-NA. https://doi.org/10.1002/smll.201803350

[307]Zhao, T., Chueh, C.-C., Chen, Q., Rajagopal, A., & Jen, A. K. Y. (2016). Defect Passivation of Organic–Inorganic Hybrid Perovskites by Diammonium Iodide toward High-Performance Photovoltaic Devices. *ACS Energy Letters*, *1*(4), 757-763. https://doi.org/10.1021/acsenergylett.6b00327

[308]Zhao, W., Yao, Z., Yu, F., Yang, D., & Liu, S. F. (2017). Alkali Metal Doping for Improved CH3NH3PbI3 Perovskite Solar Cells. *Advanced science (Weinheim, Baden-Wurttemberg, Germany)*, *5*(2), 1700131-1700131. https://doi.org/10.1002/advs.201700131

[309]Zhao, Y.-Q., Ma, Q.-R., Liu, B., Yu, Z.-L., Yang, J., & Cai, M.-Q. (2018). Layer-dependent transport and optoelectronic property in two-dimensional perovskite: (PEA)2PbI4. *Nanoscale*, *10*(18), 8677-8688. https://doi.org/10.1039/c8nr00997j

[310]Zhao, Y., Zhou, W., Ma, W., Meng, S., Li, H., Wei, J., Fu, R., Liu, K., Yu, D., & Zhao, Q. (2016). Correlations between Immobilizing Ions and Suppressing Hysteresis in Perovskite Solar Cells. *ACS Energy Letters*, *1*(1), 266-272. https://doi.org/10.1021/acsenergylett.6b00060

[311]Zhao, Z., Gu, F., Li, Y., Sun, W., Ye, S., Rao, H., Liu, Z., Bian, Z., & Huang, C. (2017). Mixed-Organic-Cation Tin Iodide for Lead-Free Perovskite Solar Cells with an Efficiency of 8.12. *Advanced science (Weinheim, Baden-Wurttemberg, Germany)*, *4*(11), 1700204-1700204. https://doi.org/10.1002/advs.201700204

[312]Zheng, B., Huo, L., & Li, Y. (2020). Benzodithiophenedione-based polymers: recent advances in organic photovoltaics. *NPG Asia Materials*, *12*(1), 1-22. https://doi.org/10.1038/s41427-019-0163-5

[313]Zheng, X., Chen, B., Dai, J., Fang, Y., Bai, Y., Lin, Y., Wei, H., Zeng, X. C., & Huang, J. (2017). Defect passivation in hybrid perovskite solar cells using quaternary ammonium halide anions and cations. *Nature Energy*, *2*(7), 17102-NA. https://doi.org/10.1038/nenergy.2017.102

[314]Zheng, X., Deng, Y., Chen, B., Wei, H., Xiao, X., Fang, Y., Lin, Y., Yu, Z., Liu, Y., Wang, Q., & Huang, J. (2018). Dual Functions of Crystallization Control and Defect Passivation Enabled by Sulfonic Zwitterions for Stable and Efficient Perovskite Solar Cells. *Advanced materials (Deerfield Beach, Fla.)*, *30*(52), 1803428-NA. https://doi.org/10.1002/adma.201803428

[315]Zhou, Y., Wang, F., Cao, Y., Wang, J., Fang, H.-H., Loi, M. A., Zhao, N., & Wong, C.-P. (2017). Benzylamine-Treated Wide-Bandgap Perovskite with High Thermal-Photostability and Photovoltaic Performance. *Advanced Energy Materials*, *7*(22), 1701048-NA. https://doi.org/10.1002/aenm.201701048

[316]Zhu, L., Li, X., Song, C., Liu, X., Wang, Y.-C., Zhang, W., & Fang, J. (2017). Cathode modification in planar hetero-junction perovskite solar cells through a small-molecule zwitterionic carboxylate. *Organic Electronics*, *48*(NA), 204-210. https://doi.org/10.1016/j.orgel.2017.06.006

[317]Zhu, Z., Chueh, C.-C., Lin, F., & Jen, A. K. Y. (2016). Enhanced Ambient Stability of Efficient Perovskite Solar Cells by Employing a Modified Fullerene Cathode Interlayer. *Advanced science (Weinheim, Baden-Wurttemberg, Germany)*, *3*(9), 1600027-1600027. https://doi.org/10.1002/advs.201600027

[318]Zhu, Z., Xue, Q., He, H., Jiang, K., Hu, Z., Bai, Y., Zhang, T., Xiao, S., Gundogdu, K., Gautam, B., Ade, H., Huang, F., Wong, K. S., Yip, H.-L., Yang, S., & Yan, H. (2015). A PCBM Electron Transport Layer Containing Small Amounts of Dual Polymer Additives that Enables Enhanced Perovskite Solar Cell Performance. *Advanced science (Weinheim, Baden-Wurttemberg, Germany)*, *3*(9), 1500353-1500353. https://doi.org/10.1002/advs.201500353

[319]Zuo, C., & Ding, L. (2015). Bulk heterojunctions push the photoresponse of perovskite solar cells to 970 nm. *Journal of Materials Chemistry A*, *3*(17), 9063-9066. https://doi.org/10.1039/c4ta04482g