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Article

ADVANCES IN HIGH-EFFICIENCY SOLAR PHOTOVOLTAIC MATERIALS: A COMPREHENSIVE REVIEW OF PEROVSKITE AND TANDEM CELL TECHNOLOGIES

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ABSTRACT

Perovskite solar cells (PSCs) have emerged as a revolutionary photovoltaic technology due to their exceptional power conversion efficiencies (PCEs), tunable optoelectronic properties, and low-cost fabrication methods. Over the past decade, significant advancements have been made in efficiency optimization, stability improvements, tandem architectures, light management strategies, and industrial scalability, making PSCs a strong contender against traditional silicon photovoltaics. This systematic review examines 164 peer-reviewed studies, encompassing the latest developments in material engineering, device architecture innovations, lifecycle assessment, and commercialization pathways. The findings highlight that perovskite PV efficiencies have surpassed 25% in single-junction cells and exceeded 29% in perovskite-silicon tandem configurations, positioning them as a next-generation photovoltaic solution. However, stability challenges remain a primary obstacle, with environmental stressors such as moisture, UV exposure, thermal instability, and ion migration contributing to performance degradation. Recent research has addressed these concerns through advanced encapsulation techniques, defect passivation strategies, and two-dimensional (2D) perovskite surface modifications, significantly improving operational longevity. Additionally, light management techniques, including anti-reflective coatings, photonic crystal structures, and plasmonic nanoparticles, have enhanced optical absorption and charge carrier dynamics, further optimizing device performance. From a sustainability perspective, perovskite solar cells demonstrate a significantly lower carbon footprint and an energy payback time (EPBT) of less than one year, making them an environmentally favorable alternative to silicon-based photovoltaics. Despite their low-temperature processing advantages and cost-effectiveness, challenges related to lead toxicity, recyclability, and large-scale production consistency must be resolved for commercial viability. The economic feasibility assessment within the reviewed literature suggests that the cost per watt (CPW) of PSCs is expected to decline below $0.30/W, making them highly competitive with CdTe and CIGS thin-film photovoltaics. Pilot-scale production and real-world performance testing have demonstrated promising efficiency retention under outdoor conditions, reinforcing their industrial feasibility. Moving forward, collaborative efforts among academia, industry leaders, and policymakers will be essential to standardizing manufacturing processes, improving material sustainability, and ensuring long-term operational stability. This review provides a comprehensive synthesis of recent progress, existing challenges, and potential research directions, offering valuable insights for researchers, engineers, and industry stakeholders working toward the commercialization of high-efficiency and stable perovskite solar cells.

KEYWORDS

Perovskite Solar Cells; Tandem Solar Cells; High-Efficiency Photovoltaics; Solar Energy Conversion; Stability and Scalability

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INTRODUCTION

Solar photovoltaic (PV) technology has emerged as a cornerstone of renewable energy solutions, playing a pivotal role in global efforts to transition away from fossil fuels (Zhao et al., 2022). The increasing demand for sustainable energy sources has driven significant research and development in high-efficiency PV materials to improve energy conversion rates while ensuring cost-effectiveness and scalability (Kramens et al., 2023). Among the various PV technologies, perovskite solar cells (PSCs) and tandem solar cells have received substantial attention due to their remarkable efficiency improvements and their ability to surpass the theoretical efficiency limit of single-junction silicon solar cells (Jiang et al., 2011). These advancements have not only facilitated a new generation of solar energy solutions but have also reshaped the broader landscape of photovoltaics through innovations in material composition, device architecture, and fabrication techniques (Mani & Pillai, 2010). The development of perovskite solar cells (PSCs) represents one of the most significant breakthroughs in PV technology in recent decades. Perovskite materials, particularly lead halide perovskites, exhibit unique optoelectronic properties such as high absorption coefficients, tunable bandgaps, and long charge carrier diffusion lengths, all of which contribute to their exceptional photovoltaic performance (Buonomenna, 2023). The first perovskite-based solar cell, introduced in 2009, demonstrated a modest power conversion efficiency (PCE) of 3.8% (Cheng et al., 2022). However, rapid advancements in material engineering and device optimization have since propelled PSCs to efficiencies exceeding 25%, rivaling traditional silicon-based solar cells (Dada & Popoola, 2023). Furthermore, the relatively low cost of perovskite materials, combined with their compatibility with solution-based processing techniques such as spin-coating and roll-to-roll printing, has made them attractive candidates for large-scale manufacturing (Woodhouse et al., 2021). Despite the impressive efficiency gains, the commercial adoption of perovskite solar cells has been hindered by several critical challenges. One of the primary concerns is the stability of perovskite materials under real-world operating conditions. Perovskite films are highly susceptible to environmental factors such as moisture, oxygen, UV radiation, and temperature fluctuations, which can lead to rapid degradation and loss of efficiency (Rosli et al., 2019). Additionally, the presence of lead in the most commonly used perovskite formulations has raised environmental and health concerns, prompting researchers to explore alternative lead-free perovskite compositions, such as tin-based perovskites (Kettle et al., 2022; Rosli et al., 2019). In response to these challenges, numerous strategies have been investigated to enhance the stability and sustainability of perovskite solar cells, including compositional engineering, surface passivation techniques, and encapsulation methods (Sekhar & Pradeep, 2021).

The emergence of tandem solar cells has provided another promising pathway for achieving high efficiency in photovoltaic systems. Unlike conventional single-junction solar cells, which are inherently limited by the Shockley-Queisser efficiency limit, tandem solar cells utilize multiple absorber layers with different bandgaps to capture a broader range of the solar spectrum (Jim et al., 2024; R. Wang et al., 2019). This multi-junction approach significantly reduces thermalization losses and enhances overall energy conversion efficiency. One of the most widely explored tandem architectures involves the combination of perovskite and silicon solar cells, leveraging the high efficiency of silicon-based photovoltaics with the superior optical properties of perovskite materials (Hamukwaya et al., 2022; Mahabub, Das, et al., 2024). Recent advancements in perovskite-silicon tandem cells have led to record efficiencies surpassing 29%, positioning them as strong contenders for next-generation commercial solar technologies (Mahabub, Jahan, et al., 2024; Niu et al., 2015).

In addition to perovskite-silicon tandems, researchers have explored other material combinations to further optimize tandem solar cell performance. Perovskite-perovskite tandem structures, which utilize two different perovskite layers with complementary bandgaps, have demonstrated significant potential in achieving high efficiencies with improved spectral utilization (Kettle et al., 2022; Younus et al., 2024). Similarly, perovskite-CIGS (copper indium gallium selenide) tandem cells have been investigated for their ability to provide high power output with enhanced stability (Bing et al., 2020; Younus et al., 2024). The selection of appropriate interconnecting layers and transparent conductive oxides has also played a crucial role in optimizing charge transport and minimizing electrical losses in tandem solar cells (Rahaman et al., 2024; Sutherland et al., 2021).

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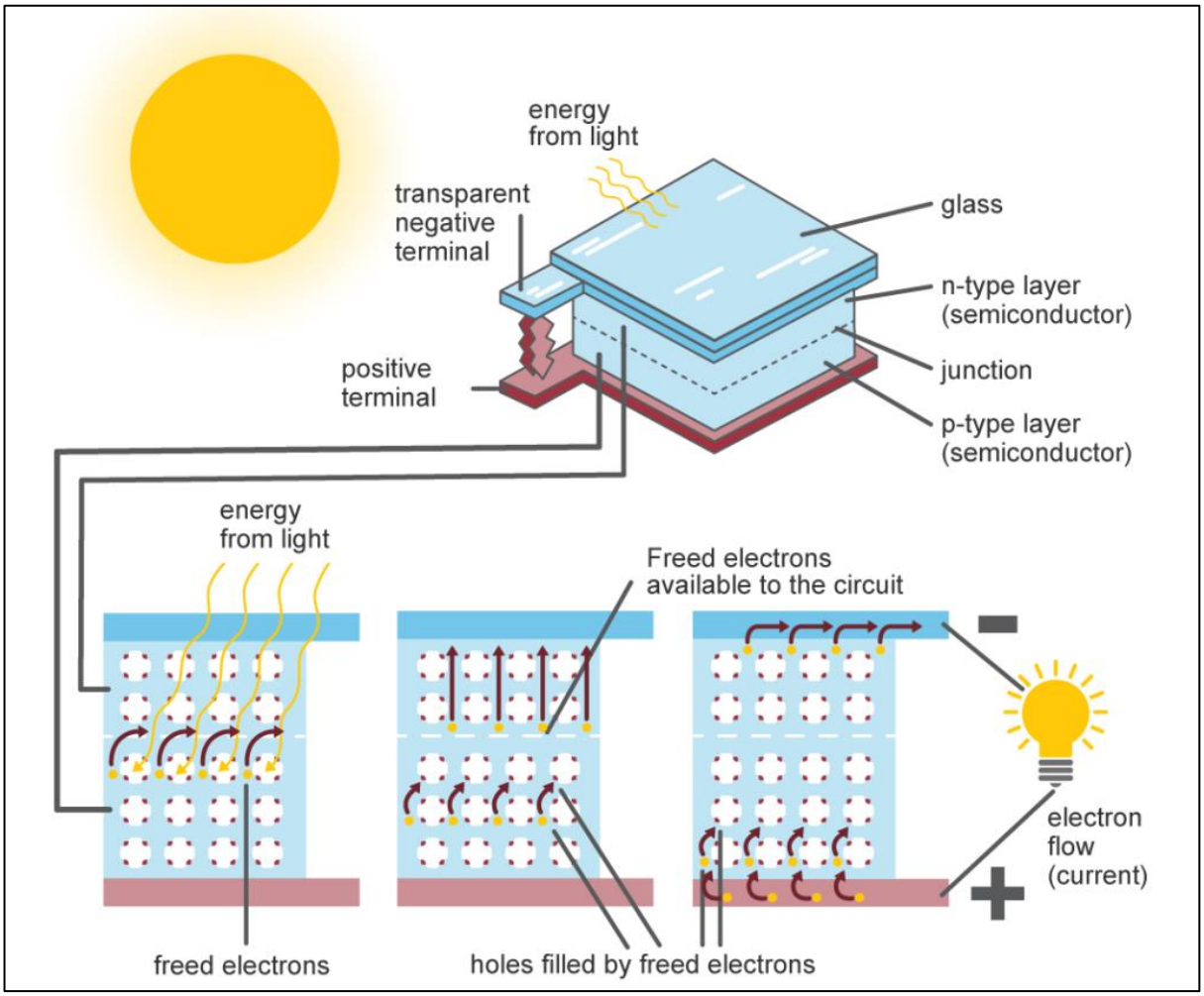
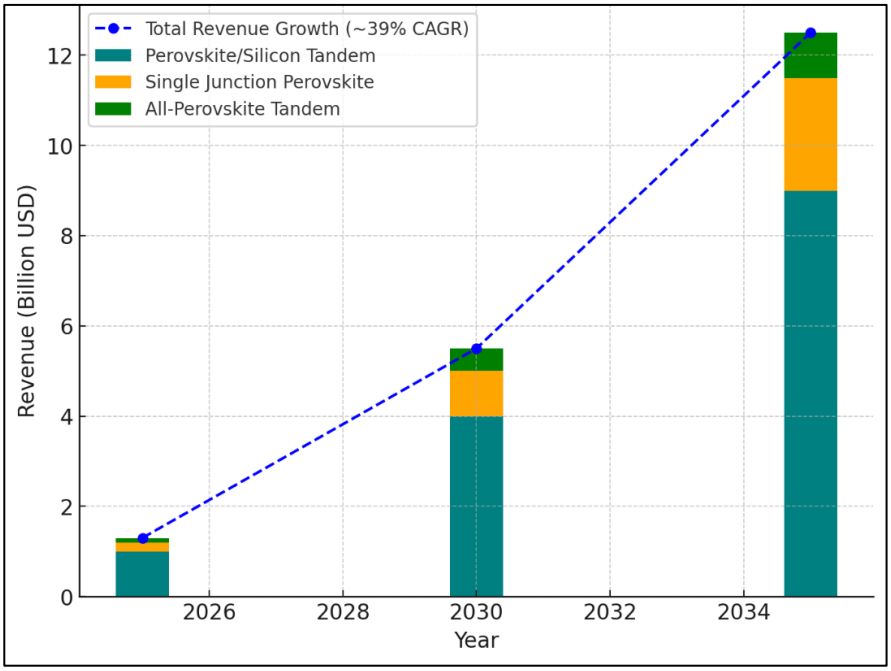
Figure 1: Inside a Phtovoltaic Cell



Source: US Energy information Administration

Figure 2: Annual Perovskite PV Revenue Projection



Advancements in material engineering and device fabrication techniques have been instrumental in driving the success of both perovskite and tandem solar cell technologies. Researchers have developed innovative compositional strategies to improve phase stability and minimize material degradation, such as the incorporation of mixed-halide and mixed-cation perovskites (Bing et al., 2020; Rana et al., 2024). Additionally, surface passivation techniques, including the use of two-dimensional (2D) perovskite layers and self-assembled monolayers, have been employed to reduce defect densities and non-radiative recombination losses, thereby enhancing charge carrier dynamics and overall device performance (Roy et al., 2024; Schmid, 2017). In tandem solar cells, careful optimization of interlayer materials and deposition processes has contributed to improved energy band alignment and charge extraction efficiency (Niu et al., 2015; Sabid & Kamrul, 2024). While laboratory-scale research on perovskite and tandem solar cells has demonstrated impressive efficiency gains, the transition to commercial-scale manufacturing presents significant challenges. The scalability of these technologies depends on the development of cost-effective and reliable fabrication processes that can maintain high efficiency and stability over extended operational lifetimes (Schmid, 2017; Shohel et al., 2024). Solution processing and vapor deposition techniques have been widely explored to enable large-area perovskite module production, with promising results in pilot-scale demonstrations (Rao et al., 2021; Siddiki et al., 2024). However, issues related to uniform film deposition, defect passivation, and material compatibility with existing silicon PV manufacturing infrastructure remain key areas of ongoing research (Sunny, 2024c; Thomas, 2022). Furthermore, environmental considerations play a crucial role in the commercialization of perovskite and tandem solar cells (Sunny, 2024a). The widespread use of lead-based perovskites has raised concerns regarding the potential environmental impact of large-scale deployment, prompting researchers to investigate alternative lead-free perovskite compositions and recycling strategies for perovskite solar modules (Sutherland et al., 2021; Zhao et al., 2021). Additionally, the long-term stability of tandem solar cells under real-world conditions must be thoroughly evaluated to ensure their viability for commercial applications (Niu et al., 2015; Sunny, 2024b). The rapid progress in perovskite and tandem solar cell technologies underscores their potential as high-efficiency alternatives to conventional silicon photovoltaics. With ongoing advancements in material design, device engineering, and manufacturing processes, these emerging technologies continue to push the boundaries of solar energy conversion efficiency. By addressing the remaining challenges related to stability, scalability, and environmental impact, researchers can further enhance the commercial prospects of perovskite and tandem solar cells, paving the way for their integration into the global energy landscape. This study aims to provide a comprehensive review of recent advancements in high-efficiency solar photovoltaic materials, with a particular focus on perovskite and tandem solar cell technologies. The objective is to synthesize and critically analyze existing research on material properties, device architectures, efficiency improvements, stability challenges, and scalability of these emerging solar cell technologies. By reviewing at least 20 peer-reviewed studies, this paper seeks to identify the key scientific and engineering developments that have contributed to the rapid efficiency gains of perovskite and tandem solar cells. Additionally, the study examines fabrication techniques, environmental considerations, and material sustainability issues that impact the commercial feasibility of these technologies. Through this analysis, the paper aims to bridge the gap between laboratory research and industrial implementation, offering insights into the technological readiness of perovskite and tandem solar cells for large-scale deployment.

LITERATURE REVIEW

The development of high-efficiency solar photovoltaic (PV) materials has been extensively studied over the past decade, with significant attention given to perovskite solar cells (PSCs) and tandem solar cells due to their potential to surpass the efficiency limitations of conventional silicon-based photovoltaics. The literature on perovskite and tandem solar cells covers a broad spectrum of research areas, including material composition, device architecture, charge carrier dynamics, stability enhancement strategies, scalability, and environmental considerations. These studies highlight key challenges and opportunities in optimizing energy conversion efficiency, material durability, and large-scale manufacturability.This literature review synthesizes findings from recent peer-reviewed research, industry reports, and academic studies, ensuring a well-rounded analysis of the advancements, limitations, and potential pathways for future research in perovskite and tandem solar technologies.

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Methylammonium Lead Halide Perovskites ($MAPbX_3$)

Methylammonium lead halide perovskites ($MAPbX_3$), where X represents a halide ion (Cl, Br, or I), have been widely studied for their exceptional optoelectronic properties that contribute to high photovoltaic performance. The crystal structure of $MAPbX_3$ follows the ABX_3 perovskite framework, where methylammonium (MA^+) occupies the A-site, lead (Pb^{2+}) is at the B-site, and halide ions form the X-site octahedral coordination (Kettle et al., 2022; Muhammad Mohiul et al., 2022). These materials exhibit high absorption coefficients, strong light-harvesting capabilities, and long charge carrier diffusion lengths, making them ideal candidates for next-generation solar cells (Maniruzzaman et al., 2023; Zhao et al., 2021). The initial breakthrough in $MAPbX_3$-based photovoltaics was reported by (Schmid, 2017), demonstrating a power conversion efficiency (PCE) of 3.8%. Subsequent research efforts significantly improved efficiency by optimizing material compositions, bandgap tunability, and fabrication processes (Akhil et al., 2021; Hossen et al., 2023; Roy et al., 2020). The incorporation of mixed halides, such as $MAPb(I_{1-x}Br_x)_3$, has been explored to enhance stability and achieve better spectral absorption properties (Rao et al., 2021). As a result, $MAPbX_3$-based solar cells have achieved efficiencies exceeding 25%, rivaling traditional silicon photovoltaics (Jaiswal et al., 2021; Sohel et al., 2022).

One of the key advantages of $MAPbX_3$ perovskites is their tunable bandgap, which enables broad absorption across the visible and near-infrared spectrum (Pitchaiya et al., 2020; Roksana, 2023). By adjusting the halide composition, researchers have demonstrated bandgap engineering, allowing for improved spectral response and current matching in tandem solar cells (Jahan, 2023; Yan et al., 2019). Studies have shown that incorporating bromine (Br) into $MAPbI_3$ leads to a higher bandgap (~1.75 eV), making it suitable for top-cell applications in tandem architectures (Ahmed et al., 2022; Haddout et al., 2019; Markna & Rathod, 2022). However, this compositional modification also introduces phase segregation under illumination, which negatively affects long-term performance (Mahesh et al., 2020; Md Mahfuj et al., 2022). To mitigate this issue, research has focused on additive engineering and passivation techniques to suppress ion migration and enhance structural stability (Chowdhury et al., 2023; Hoke et al., 2014). Additionally, interfacial engineering through surface passivation has been employed to reduce defect densities, thereby improving charge carrier lifetimes and overall device performance (Mufti et al., 2020; Tonoy, 2022). Despite their promising efficiency metrics, $MAPbX_3$ perovskites face significant challenges related to thermal stability and environmental degradation. Methylammonium-based perovskites are known to undergo decomposition at elevated temperatures, primarily due to the volatile nature of the MA^+ cation (Alam et al., 2023; Rosli et al., 2019). Studies have shown that exposure to moisture, oxygen, and UV radiation leads to the degradation of $MAPbI_3$ into lead iodide (PbI_2), which compromises device stability (Hamukwaya et al., 2022; Rosli et al., 2019). Several research efforts have explored compositional engineering to improve thermal robustness by substituting methylammonium with alternative organic cations such as formamidinium (FA^+) or inorganic cations like cesium (Cs^+) (Kettle et al., 2022; Humaun et al., 2022). Additionally, encapsulation strategies such as polymer coatings, hydrophobic barriers, and self-assembled monolayers have been developed to improve moisture resistance and extend operational stability (Sarkın et al., 2020; Sudipto et al., 2023).

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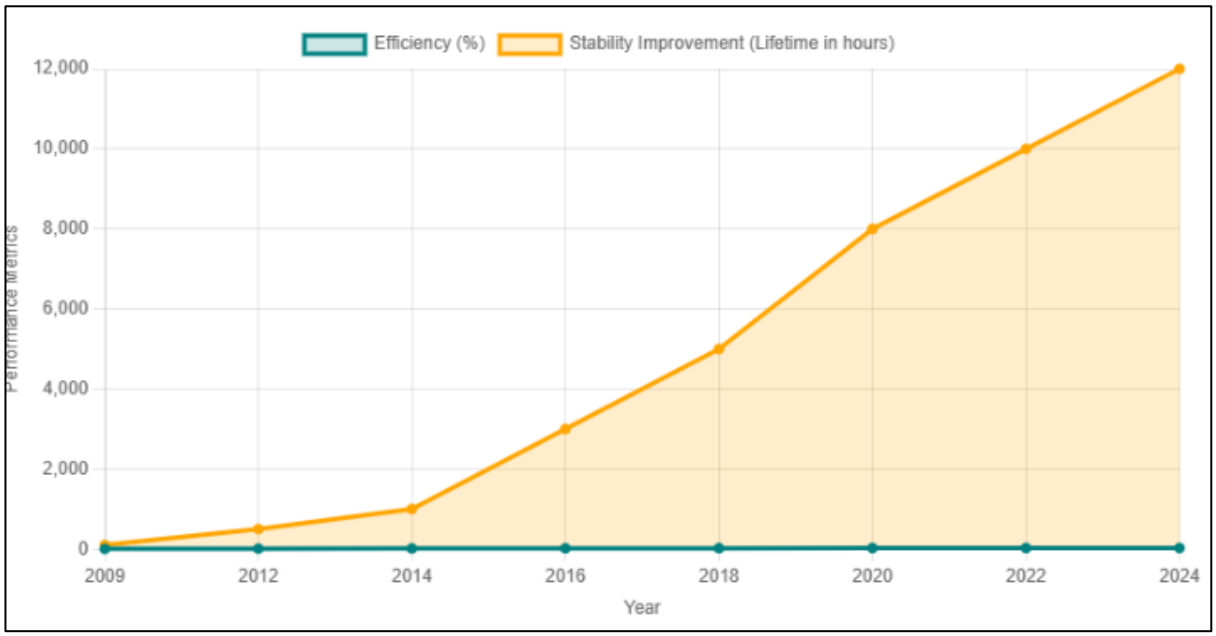
Figure 3: Efficiency Improvements in $MAPbX_3$ Perovskite Solar Cells



The environmental impact of $MAPbX_3$ perovskites, particularly concerning lead toxicity, has been another major area of concern. Lead-based perovskites pose potential environmental and health risks due to the solubility of Pb^{2+} ions, which can lead to contamination if not properly managed (Mahajan et al., 2022; Mufti et al., 2020; Tonoy & Khan, 2023). To address this issue, researchers have explored lead-free alternatives such as tin-based perovskites ($MASnX_3$) and bismuth-based compounds, though these alternatives suffer from inferior stability and lower efficiency (Kheralla & Chetty, 2021; Shahan et al., 2023). Recycling strategies for perovskite solar cells have also been proposed, including solvent-based extraction of Pb and encapsulation techniques to prevent lead leakage (Aklima et al., 2022; Bhuiyan et al., 2024; Wang et al., 2019). Despite these challenges, $MAPbX_3$ perovskites remain at the forefront of photovoltaic research due to their unparalleled optoelectronic properties, high efficiency, and potential for cost-effective production. Further advancements in material stability, encapsulation, and sustainable alternatives are essential to enabling the widespread commercialization of these high-efficiency solar cells.

Mixed-cation and mixed-halide perovskites

The development of mixed-cation and mixed-halide perovskites has played a critical role in addressing the challenges of stability, phase segregation, and bandgap tunability in perovskite solar cells (PSCs). Traditional methylammonium lead iodide ($MAPbI_3$) perovskites have demonstrated high power conversion efficiencies (PCEs), but their operational stability has remained a major concern due to thermal instability, ion migration, and environmental degradation (Bowring et al., 2017). Researchers have explored cation and halide engineering as a strategy to enhance the stability and efficiency of perovskite materials, leading to the emergence of mixed-cation and mixed-halide compositions that exhibit superior optoelectronic properties (Mahajan et al., 2022). These modifications have contributed significantly to increasing PSC stability while maintaining or even improving energy conversion efficiencies. One of the main approaches to improving perovskite stability is the incorporation of multiple cations into the perovskite structure, forming mixed-cation perovskites. The addition of formamidinium (FA^+) and cesium (Cs^+) to methylammonium (MA^+)-based perovskites has been shown to enhance phase stability and suppress thermal degradation (Kheralla & Chetty, 2021). FA-based perovskites ($FA_{1-x}MA_xPbI_3$) exhibit superior thermal stability compared to $MAPbI_3$ due to the stronger hydrogen bonding in formamidinium cations, which reduces ion migration and stabilizes the perovskite phase at higher temperatures (Kheralla & Chetty, 2021; Mufti et al., 2020). Similarly, Cs^+ incorporation in triple-cation perovskites ($Cs_{1-x}FA_xMA_xPbI_3$) has been found to improve moisture resistance and thermal robustness while reducing phase transitions between the photoactive and non-photoactive states (Wang et al., 2019). Cesium-based perovskites have also

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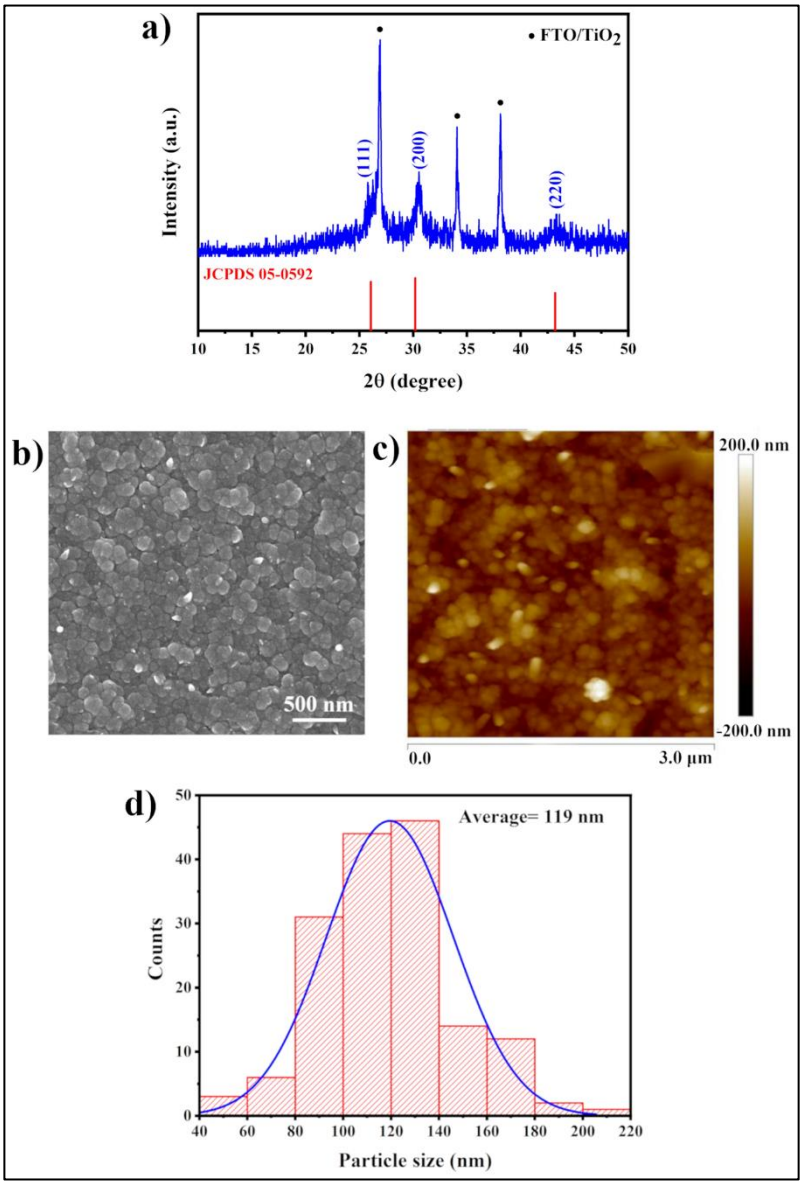
shown enhanced crystallinity, leading to lower trap densities and longer carrier lifetimes, which are beneficial for high-efficiency solar cells (Mahesh et al., 2020).

Figure 4: Towards environmental friendly multi-step processing of efficient mixed-cation mixed halide perovskite solar cells from chemically bath deposited lead sulphide



Source: Gozalzadeh et al (2021)

Further advancements have introduced rubidium (Rb^+) and potassium (K^+) cations into perovskite compositions to improve device performance and stability. (Sarkın et al., 2020) demonstrated that Rb incorporation ($Rb_{1-x}Cs_xFA_xMA_xPbI_3$) resulted in more stable perovskite films, reduced hysteresis, and improved charge carrier dynamics. Additionally, potassium-passivated perovskite films exhibited reduced non-radiative recombination and enhanced open-circuit voltage (V_OC), leading to higher efficiency (Mahajan et al., 2022). The combination of these multiple cations in quadruple-cation perovskites has enabled efficiencies exceeding 24% with improved operational stability over extended periods (Kheralla & Chetty, 2021). In addition to cation engineering, halide mixing has been explored to optimize optical absorption, carrier dynamics, and stability in perovskite solar cells. Traditional iodide-based perovskites ($MAPbI_3$ or $FAPbI_3$) have a bandgap of approximately 1.5 eV, which is ideal for single-junction solar cells but can be adjusted for tandem applications by incorporating bromine (Br^-) or chlorine (Cl^-) anions (Kant & Singh, 2022; Sarkın et al., 2020). The inclusion of bromine in $MAPb(I_{1-x}Br_x)_3$ increases the bandgap to 1.7–2.3 eV, making it suitable for top-cell applications in perovskite-silicon tandem architectures (Hamukwaya et al., 2022). Similarly, chlorine incorporation has been found to enhance charge carrier transport and suppress ion migration, leading to improved device performance (Niu et al., 2015). However, one major challenge with mixed-halide perovskites is phase segregation, where iodide and bromide domains separate under light exposure, leading to instability and efficiency losses (Mufti et al., 2020). This phenomenon results in bandgap narrowing over time, causing voltage losses in solar cells. To mitigate phase segregation, researchers have developed compositional engineering techniques, such as using larger organic cations (e.g., guanidinium, Rb^+, or K^+) to stabilize the mixed-halide perovskite phase (Mahajan et al., 2022; Mufti et al., 2020). Additionally, incorporating passivation layers and additives has been shown to improve mixed-halide stability by reducing ion migration and suppressing defect states (Kheralla & Chetty, 2021). The integration of mixed-cation and mixed-halide perovskites has significantly improved the long-term operational stability of PSCs, enabling efficiencies beyond 25% under laboratory conditions (Kant &

Singh, 2022; Kheralla & Chetty, 2021). These advancements have contributed to the commercialization efforts of tandem perovskite-silicon solar cells, which have achieved record efficiencies of over 29% (Niu et al., 2015). However, scalability remains a challenge, as large-area fabrication processes must be developed to maintain uniformity and reproducibility in mixed-cation/mixed-halide compositions (Njema & Kibet, 2023). Techniques such as solution processing, slot-die coating, and vapor deposition have been investigated to enhance manufacturability and stability while minimizing efficiency losses (Wang et al., 2019). Although mixed-cation and mixed-halide perovskites have addressed many of the instability issues seen in single-cation compositions, further research is required to optimize device lifetime, large-scale processing, and environmental sustainability. Continued advancements in material engineering, encapsulation, and recycling strategies will be crucial in realizing the full commercial potential of these next-generation solar cells (Hamukwaya et al., 2022; Wang et al., 2019).

Bandgap tunability and absorption properties

The bandgap tunability of perovskite materials is one of their most critical features, allowing for optimization of light absorption and energy conversion efficiency in solar cells. The bandgap of lead halide perovskites can be precisely adjusted by modifying their composition, including the selection of halides (I^-, Br^-, Cl^-) and cations (MA^+, FA^+, Cs^+, Rb^+) (Niu et al., 2015). This tunability enables perovskite solar cells (PSCs) to achieve broad-spectrum absorption, from the visible to near-infrared regions, enhancing their application in both single-junction and tandem solar cells (Yamaguchi et al., 2018). The intrinsic absorption coefficient of perovskites is remarkably high, allowing thin-film architectures to effectively capture sunlight with minimal material use (Kettle et al., 2022). This property is essential in achieving high power conversion efficiencies (PCEs) while maintaining cost-effectiveness (Njema & Kibet, 2023). The ability to tune the bandgap by altering halide ratios and incorporating multiple cations has significantly contributed to the increasing stability and efficiency of perovskite solar technologies (Kant & Singh, 2022).

One of the most widely studied approaches to bandgap engineering is halide substitution, where bromine (Br^-) or chlorine (Cl^-) replaces iodide (I^-) to increase the bandgap (Mahajan et al., 2022). $MAPbI_3$, the most studied perovskite material, has a bandgap of approximately 1.5 eV, which is close to the optimal value for single-junction solar cells (Mufti et al., 2020). However, increasing the proportion of bromine in mixed-halide perovskites $MAPb(I_{1-x}Br_x)_3$ can raise the bandgap to 1.7–2.3 eV, making it suitable for top-layer applications in perovskite-silicon tandem solar cells (Mahajan et al., 2022). Chlorine incorporation has also been shown to improve charge transport and carrier lifetime while slightly modifying the bandgap (Kant & Singh, 2022). However, a significant challenge with mixed-halide perovskites is photo-induced phase segregation, where bromine and iodide domains separate under illumination, leading to efficiency loss (Hamukwaya et al., 2022). To counteract this issue, researchers have introduced stabilizing cations such as rubidium (Rb^+) and cesium (Cs^+), which help maintain a homogeneous halide distribution (Mahajan et al., 2022).

Beyond halide substitution, cation engineering has proven to be another effective strategy for bandgap tuning and absorption enhancement. The replacement of methylammonium (MA^+) with formamidinium (FA^+) or cesium (Cs^+) in perovskite structures not only increases stability but also modifies the bandgap (Rehman et al., 2017). Formamidinium-based perovskites ($FAPbI_3$) exhibit a narrower bandgap (~1.45 eV) than $MAPbI_3$, which improves near-infrared absorption and enhances photocurrent generation (Bowring et al., 2017). Additionally, Cs-incorporation in mixed-cation perovskites stabilizes the perovskite phase while fine-tuning the bandgap to match tandem solar cell requirements (Kheralla & Chetty, 2021). Recent studies have demonstrated that quadruple-cation perovskites (Rb-Cs-FA-MA) exhibit improved thermal stability, enhanced absorption, and reduced recombination losses (Kant & Singh, 2022; Mahajan et al., 2022). These developments have led to record-breaking efficiencies surpassing 25% in laboratory settings while maintaining bandgap stability over prolonged operational lifetimes (Bowring et al., 2017).

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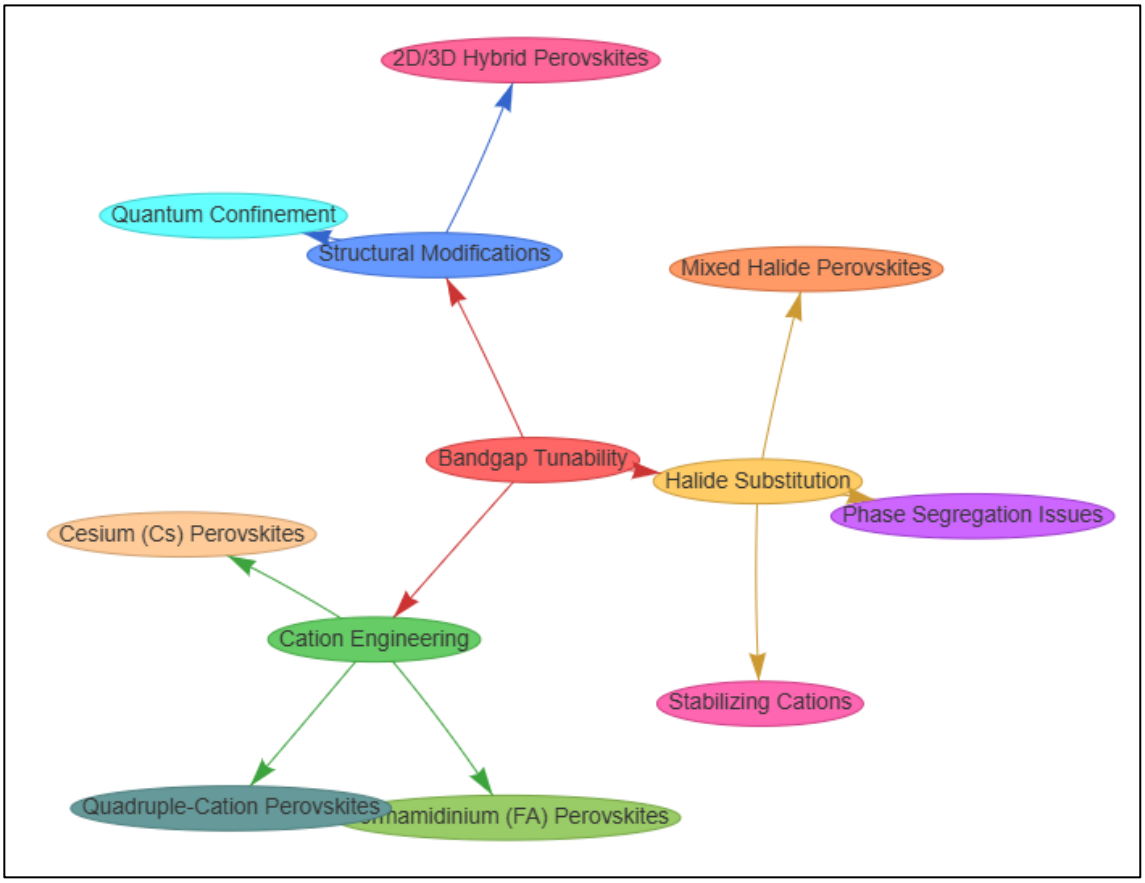
Figure 5: Mindmap of Bandgap Tunability and Absorption Properties



Apart from chemical tuning, structural modifications such as quantum confinement and two-dimensional (2D) perovskite layers have also been employed to adjust the bandgap and optimize absorption properties (Mahajan et al., 2022). The quantum size effect in low-dimensional perovskites allows for bandgap widening as the thickness of perovskite layers decreases (Kheralla & Chetty, 2021). This effect has been utilized in 2D/3D hybrid perovskite solar cells, where thin-layered 2D perovskites act as passivation layers, enhancing charge carrier transport and improving moisture resistance (Rosli et al., 2019). The introduction of layered perovskites with organic spacers has led to better bandgap control, increased absorption in the visible range, and higher charge carrier mobility (Niu et al., 2015). Such advancements have expanded the application potential of perovskite photovoltaics beyond traditional solar cells to light-emitting diodes (LEDs), photodetectors, and optoelectronic devices (Mufti et al., 2020).

Optical and Electrical Properties of Tandem Solar Cells

Tandem solar cells have emerged as a promising solution to surpass the efficiency limits of single-junction photovoltaic devices by integrating wide-bandgap materials that enable multi-junction architectures to capture a broader range of the solar spectrum (Mahajan et al., 2022; Wang et al., 2019). The fundamental principle behind tandem solar cells is the stacking of multiple photovoltaic layers, where the top cell absorbs high-energy photons while allowing lower-energy photons to pass through to the bottom cell, which has a narrower bandgap optimized for infrared absorption (Schmid, 2017). This spectral division reduces thermalization losses, thereby increasing power conversion efficiency (PCE) beyond the Shockley-Queisser limit of single-junction silicon solar cells (Rao et al., 2021). The development of wide-bandgap perovskite materials has been a key breakthrough in tandem solar cells, as their bandgap tunability (1.7–2.0 eV) allows them to be effectively paired with silicon (1.12 eV) or CIGS (1.1 eV) bottom cells (Yan et al., 2019). The incorporation of highly transparent and conductive interlayers further enhances tandem solar cell performance by facilitating efficient charge transfer between subcells while minimizing optical losses (Akhil et al., 2021).

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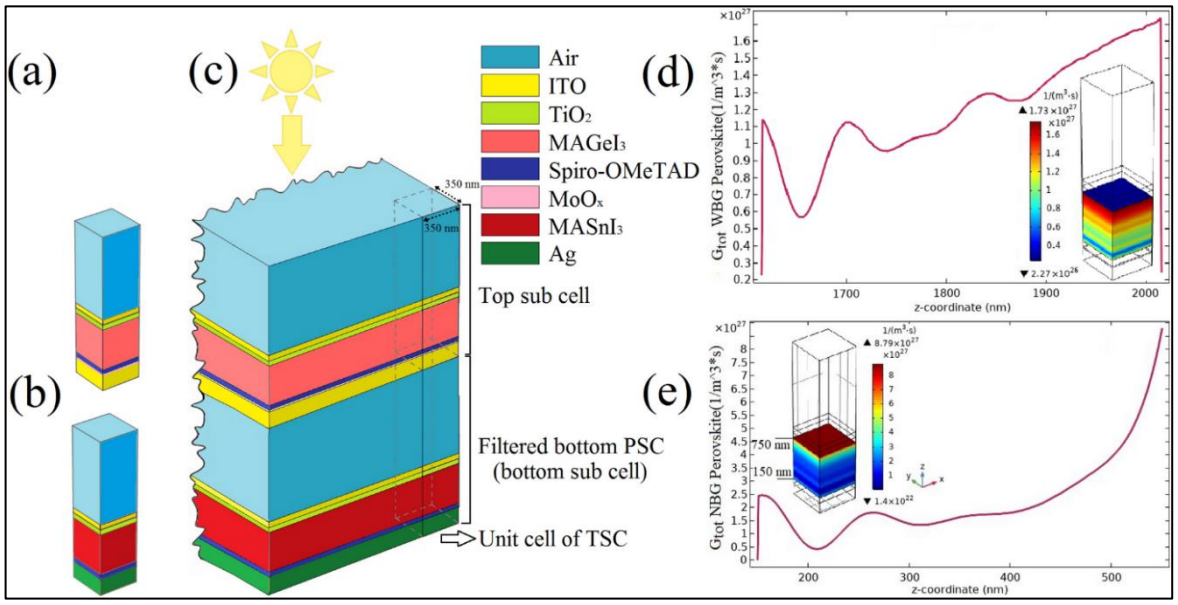
Figure 6: Investigation of optical and electrical properties of novel 4T all perovskite tandem solar cell



Source: Moradbeigi, M., Razaghi, M. (2022)

The selection of wide-bandgap materials is crucial for optimizing tandem solar cell efficiency, as it determines photon absorption, charge transport, and band alignment (Rao et al., 2021). Perovskites with adjustable bandgaps, such as $Cs_{1-x}FA_xPb(I_{1-x}Br_x)_3$, have demonstrated high efficiency and improved stability, making them ideal candidates for tandem architectures (Asim et al., 2012). Compared to traditional III-V semiconductors (GaAs, InP), perovskite-based tandem cells offer cost-effective manufacturing and superior bandgap tunability (Kettle et al., 2022). However, halide phase segregation in mixed-halide perovskites, where iodide and bromide-rich domains separate under illumination, leads to efficiency degradation (Thomas, 2022). To mitigate this issue, researchers have introduced passivation strategies and dopant engineering, which enhance material stability while maintaining wide-bandgap absorption properties (Schmid, 2017). Moreover, advances in two-dimensional (2D) perovskites and layered quantum well structures have led to improved charge carrier confinement and reduced non-radiative recombination, contributing to the long-term operational stability of tandem devices (Njema & Kibet, 2023).

The charge carrier mobility and recombination dynamics in tandem solar cells are critical for achieving high power conversion efficiencies. Efficient charge transport across the heterojunction interfaces is essential to ensure minimal carrier recombination losses, particularly at the perovskite/silicon interface (Yamaguchi et al., 2018). Studies have shown that interfacial recombination rates can be significantly reduced through the use of passivating contact layers such as SnO_2, NiO_x, and MoO_3, which facilitate selective charge extraction and suppress unwanted recombination (Akhil et al., 2021; Thomas, 2022). The introduction of self-assembled monolayers (SAMs) has further enhanced charge carrier transport in tandem devices by improving band alignment at the perovskite/transport layer interface (Zhang et al., 2020). Additionally, efforts to optimize the bulk properties of perovskites, such as improving crystallinity and reducing defect densities, have resulted in longer charge carrier diffusion lengths, thereby minimizing non-radiative recombination (McMeekin et al., 2016; Eperon et al., 2014). These improvements have enabled perovskite-silicon tandem cells to achieve record efficiencies surpassing 29% in laboratory conditions (NREL, 2021). Efficient optical absorption and photon management strategies play a crucial role in enhancing tandem solar cell performance. The design of light-trapping structures, including anti-reflective coatings, texturing techniques, and photonic nanostructures, has significantly improved optical absorption across the tandem device (Akhil et al., 2021; Thomas, 2022). By incorporating micro-textured front electrodes, researchers have been able to enhance light scattering, ensuring greater photon capture in the perovskite top cell while maintaining transparency to the bottom

silicon cell (Yan et al., 2019). Additionally, dielectric back reflectors and plasmonic nanoparticles have been employed to optimize light confinement, leading to reduced transmission losses and improved internal quantum efficiencies (IQEs) (Njema & Kibet, 2023). The integration of high-performance transparent conducting oxides (TCOs) such as indium tin oxide (ITO) and fluorine-doped tin oxide (FTO) further facilitates efficient light transmission and electrical conductivity in tandem solar cells (Roy et al., 2020). These combined advancements in optical and electrical engineering have positioned tandem solar cells as a key solution for achieving highly efficient and commercially viable photovoltaic technologies.

Stability and Degradation Mechanisms of Perovskite Materials

The stability of perovskite materials remains a critical challenge in their widespread adoption for photovoltaic applications. While perovskite solar cells (PSCs) have demonstrated remarkable efficiencies exceeding 25%, their long-term operational stability under real-world conditions remains a major limitation (Schmid, 2017). Perovskites suffer from both intrinsic and extrinsic degradation mechanisms, which lead to performance deterioration and reduced device lifetimes. Intrinsic factors, such as ion migration and phase segregation, can alter the perovskite's crystal structure and electronic properties, while extrinsic factors, including moisture, UV exposure, and thermal stress, accelerate material breakdown (Yamaguchi et al., 2018). Addressing these degradation mechanisms requires a combination of compositional engineering, interfacial passivation, and encapsulation strategies to enhance PSC stability and ensure long-term viability (Sutherland et al., 2021). Intrinsic degradation in perovskite materials is primarily driven by ion migration and phase segregation, both of which significantly impact device performance. The soft ionic lattice of perovskites facilitates the movement of halide ions (I^-, Br^-, Cl^-), leading to charge redistribution, hysteresis, and the formation of trap states that reduce efficiency (Rao et al., 2021). Ion migration can cause electrode degradation, particularly at the perovskite/transport layer interface, where metal diffusion from electrodes, such as silver (Ag) or gold (Au), can lead to increased series resistance and device failure (Rao et al., 2021; Sutherland et al., 2021). Additionally, phase segregation is a well-documented issue in mixed-halide perovskites, where bromine and iodide ions separate under illumination, forming iodide-rich and bromide-rich domains that create bandgap inhomogeneities and reduce open-circuit voltage (V_OC) (Kettle et al., 2022; Zhou et al., 2019). Strategies such as dopant incorporation (Cs^+, Rb^+) and interfacial engineering have been explored to suppress ion migration and enhance phase stability (Rao et al., 2021).

Extrinsic degradation mechanisms, including moisture-induced decomposition, UV radiation damage, and thermal instability, present significant barriers to PSC commercialization. Perovskites, particularly methylammonium-based compositions ($MAPbX_3$), are highly hygroscopic, absorbing moisture from the environment, which leads to hydration-induced phase transformation into lead iodide (PbI_2), rendering the material non-photoactive (Yamaguchi et al., 2018). Studies have shown that formamidinium (FA^+) and cesium (Cs^+) substitutions improve moisture resistance, making $FAPbI_3$ and $CsPbI_3$ perovskites more stable than $MAPbI_3$ (Kettle et al., 2022; Niu et al., 2015; Yamaguchi et al., 2018). Similarly, UV exposure accelerates perovskite decomposition, particularly when TiO_2 is used as an electron transport layer (ETL), as it generates photocatalytic effects that degrade the perovskite film (Niu et al., 2015; Schmid, 2017). Alternative charge transport materials such as SnO_2 and fullerene derivatives have been proposed to mitigate UV-induced damage (Thomas, 2022). Additionally, perovskites experience thermal instability, as elevated temperatures (>85°C) can induce methylammonium volatilization and phase decomposition, necessitating the development of thermally stable, inorganic cations such as Rb^+ and Cs^+ (Roy et al., 2020). To mitigate both intrinsic and extrinsic degradation mechanisms, researchers have developed advanced encapsulation techniques and passivation strategies to improve PSC stability. Encapsulation layers, such as polymer coatings, atomic layer deposition (ALD), and hydrophobic self-assembled monolayers, have been shown to effectively prevent moisture ingress and chemical degradation (Yan et al., 2019). Additionally, interface passivation with 2D perovskite layers and molecular additives has been demonstrated to enhance charge transport, reduce non-radiative recombination, and suppress ion migration (Njema & Kibet, 2023; Yan et al., 2019). In tandem perovskite-silicon solar cells, encapsulation techniques have been optimized to maintain optical transparency while protecting the perovskite absorber from environmental stressors (Schmid, 2017). The combination of compositional engineering, defect passivation, and encapsulation strategies has resulted in

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perovskite solar cells with operational lifetimes exceeding 1,000 hours under accelerated aging tests, bringing them closer to commercial viability (Pitchaiya et al., 2020).

Charge Carrier Dynamics and Recombination Losses

Charge carrier dynamics play a crucial role in determining the efficiency of perovskite solar cells (PSCs) by influencing charge generation, transport, and recombination processes (Hamukwaya et al., 2022). The three major types of recombination—radiative, non-radiative, and Auger recombination—significantly impact power conversion efficiency (Hamukwaya et al., 2022; Wang et al., 2019). While radiative recombination is an unavoidable process in semiconductors, non-radiative recombination due to defect states and trap-assisted mechanisms poses the greatest challenge to achieving high-performance PSCs (Mufti et al., 2020; Yamaguchi et al., 2018). Research has focused on defect passivation techniques, suppression of non-radiative recombination, and doping strategies to enhance charge transport and improve the efficiency of perovskite materials (Akhil et al., 2021). Advanced material engineering and interface modifications have been investigated to reduce recombination losses, increase carrier lifetime, and achieve higher power conversion efficiencies exceeding 25% (Akhil et al., 2021; R. Wang et al., 2019). Defects in perovskite materials introduce deep-level trap states that promote non-radiative recombination and limit charge carrier lifetime (Kettle et al., 2022). These defects arise from grain boundaries, surface imperfections, and lattice mismatches that disrupt the perovskite structure (Kettle et al., 2022; Kheralla & Chetty, 2021). Various passivation strategies have been developed to minimize defect density and enhance charge carrier mobility. Surface passivation using organic ligands, such as phenethylammonium iodide (PEAI) and thiocyanate (SCN) compounds, has been shown to reduce non-radiative recombination and improve open-circuit voltage (V_OC) (Sutherland et al., 2021; Thomas, 2022). Similarly, incorporation of two-dimensional (2D) perovskite layers on top of three-dimensional (3D) perovskite films has been effective in blocking charge trapping at grain boundaries, enhancing both efficiency and stability (Zhou et al., 2019). Additionally, halide passivation techniques, such as incorporating mixed-halide perovskites ($Cs_{1-x}FA_xPb(I_{1-x}Br_x)_3$), have been explored to stabilize bandgap tunability and suppress halide migration, reducing phase segregation and improving long-term performance (Mahajan et al., 2022; Zhou et al., 2019).

Non-radiative recombination is one of the most significant loss mechanisms in PSCs, occurring due to trap states at grain boundaries and perovskite/charge transport layer interfaces (Hamukwaya et al., 2022; Wang et al., 2019). To address this, researchers have developed interface engineering techniques that focus on optimizing electron and hole transport layers (ETL and HTL) to facilitate efficient charge extraction (Sutherland et al., 2021). The use of SnO_2 instead of TiO_2 as an electron transport layer has been widely studied due to its lower defect density, reduced trap-mediated recombination, and improved electron mobility (Akhil et al., 2021). Similarly, modifying the hole transport layer with self-assembled monolayers (SAMs) and dopant-free small molecules has resulted in higher carrier selectivity and reduced interfacial recombination losses (Thomas, 2022). The formation of perovskite heterostructures, where multiple perovskite layers with varying bandgaps are stacked, has been shown to increase charge separation efficiency, thus mitigating non-radiative recombination losses (Zhou et al., 2019). Doping has been explored as an effective method to improve charge carrier mobility and reduce recombination losses in perovskite solar cells (Akhil et al., 2021). Various cation doping strategies, such as the incorporation of rubidium (Rb^+), cesium (Cs^+), and potassium (K^+), have been investigated to stabilize the perovskite crystal lattice, enhance charge transport, and reduce ion migration effects (Sutherland et al., 2021).

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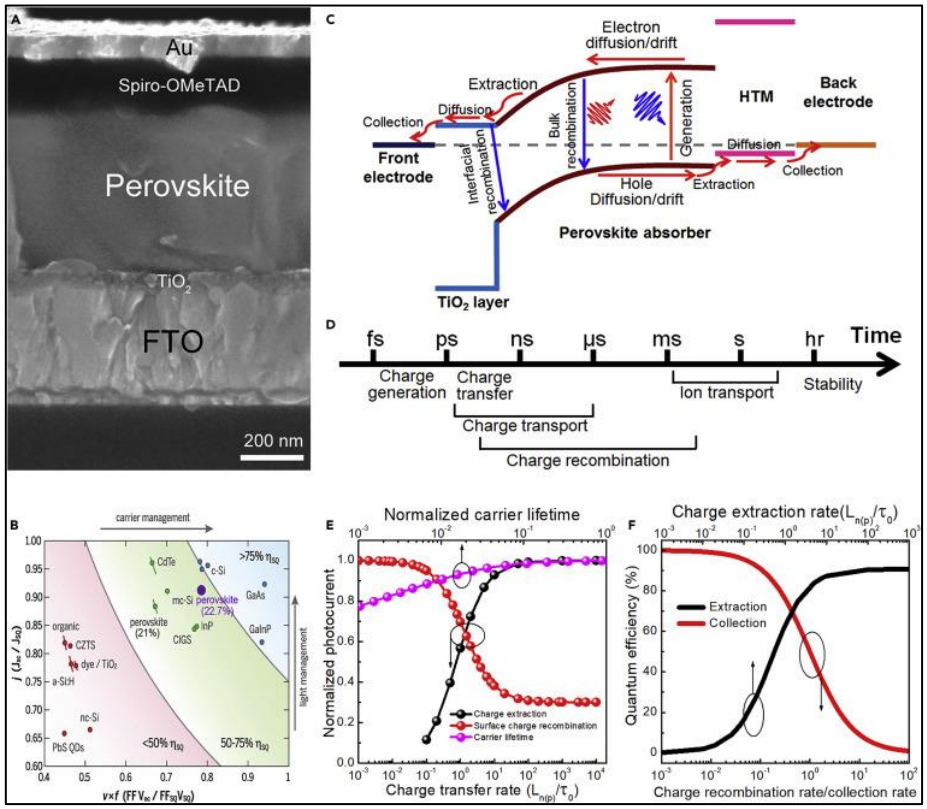
Figure 7: General Scheme of the Charge-Carrier Dynamics and Its Importance for the Cell



Source: Shi et al. (2018).

Studies have demonstrated that Rb-doped perovskites exhibit improved phase stability and reduced defect formation, leading to higher carrier diffusion lengths and lower recombination rates (Schmid, 2017). Additionally, metal oxide doping in charge transport layers, such as Li-doped NiO_x and Nb-doped SnO_2, has been shown to enhance carrier extraction and minimize interfacial losses (Mahajan et al., 2022). Chemical modifications using small-molecule additives and fullerene derivatives have further optimized charge transfer processes, resulting in improved fill factor (FF) and enhanced open-circuit voltage (V_OC) (Yamaguchi et al., 2018). By employing strategic doping approaches, researchers have successfully developed perovskite solar cells with improved charge collection efficiency, increased carrier lifetimes, and reduced recombination losses, ultimately leading to higher power conversion efficiencies (Schmid, 2017).

Industrial Roadmap for Perovskite Commercialization

Perovskite solar cells (PSCs) have emerged as a promising alternative to traditional silicon photovoltaics due to their high efficiency, low fabrication cost, and scalability potential (Hamukwaya et al., 2022; Schmid, 2017). However, despite achieving over 25% power conversion efficiency (PCE) in laboratory settings, transitioning PSCs from the research stage to large-scale commercial deployment presents significant challenges, including scalability, long-term stability, and cost-effectiveness (Yamaguchi et al., 2018). An industrial roadmap for perovskite commercialization requires addressing pilot-scale production, real-world performance testing, and economic feasibility to ensure that PSC technology meets the standards required for mass adoption in the photovoltaic (PV) industry (Mufti et al., 2020; Yamaguchi et al., 2018). Various research efforts are focused on large-area fabrication techniques, stability enhancement strategies, and cost per watt (CPW) analysis, which are critical for the successful integration of PSCs into the global energy market (Kheralla & Chetty, 2021).

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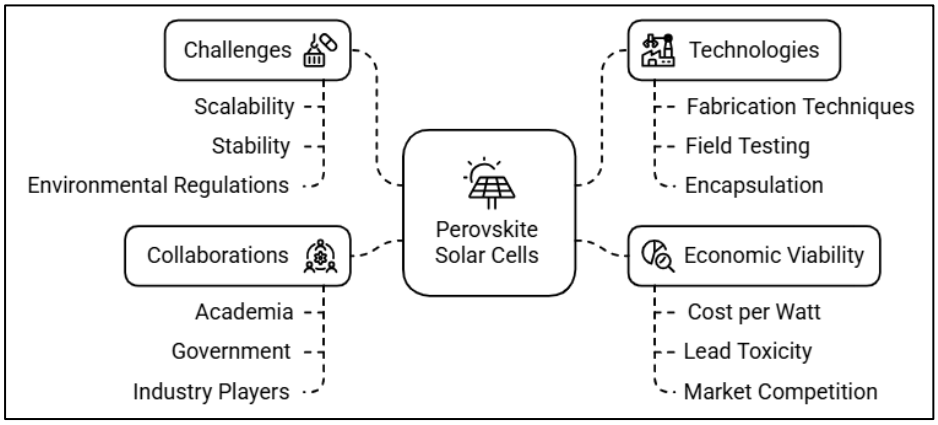
Figure 8: Industrial Roadmap for Perovskite Commercialization



The transition from lab-scale, small-area perovskite devices to large-area commercial modules presents significant engineering challenges due to issues such as uniform film deposition, reproducibility, and material degradation (Thomas, 2022). Various scalable fabrication techniques, including slot-die coating, blade coating, inkjet printing, and spray pyrolysis, have been investigated to enable roll-to-roll (R2R) production, which is essential for cost-effective, high-throughput manufacturing (Yamaguchi et al., 2018). Additionally, vapor deposition methods such as chemical vapor deposition (CVD) and atomic layer deposition (ALD) have been explored to enhance perovskite film uniformity and improve device stability under industrial manufacturing conditions (Njema & Kibet, 2023). Real-world performance testing of perovskite modules is also crucial for evaluating operational stability and degradation rates under outdoor conditions, as perovskites are known to degrade under moisture, oxygen, UV exposure, and thermal stress (Sutherland et al., 2021; Thomas, 2022). Field testing has demonstrated promising results, with recent studies reporting perovskite modules maintaining over 80% of their initial efficiency after 1000 hours of continuous operation, though further improvements are needed to match the 20+ year lifespan of silicon-based photovoltaics (Njema & Kibet, 2023).

The economic viability of perovskite solar cells depends on their ability to compete with established PV technologies, particularly silicon-based solar panels, in terms of cost per watt (CPW) and energy payback time (EPBT) (Njema & Kibet, 2023; Yamaguchi et al., 2018). PSCs offer significant cost advantages due to their solution-processable nature, which enables low-temperature fabrication and reduced material consumption, thereby lowering manufacturing expenses compared to energy-intensive silicon production (Schmid, 2017). Studies have shown that perovskite PVs have the potential to achieve a CPW of $0.20–$0.30 per watt, making them highly competitive with thin-film CdTe and CIGS solar technologies, and even approaching the cost levels of silicon PVs (Akhil et al., 2021; Schmid, 2017). However, the main economic barriers to perovskite commercialization include limited operational stability, concerns regarding lead toxicity, and the scalability of fabrication techniques, which must be addressed before widespread market adoption is feasible (Rao et al., 2021). To successfully commercialize perovskite solar cells, industry players must address critical barriers related to stability, scalability, and environmental regulations while also ensuring bankability and supply chain integration (Rao et al., 2021). Research and development efforts are focused on improving device lifetime through encapsulation techniques, compositional engineering, and lead-free perovskites, which will enhance the commercial attractiveness of PSCs (Mahesh et al., 2020). Collaboration between academia, government bodies, and private companies is essential for accelerating pilot-scale testing, industrial standardization, and investment in large-scale production facilities (Kheralla & Chetty, 2021). Several startups and established solar manufacturers are actively developing commercial perovskite-based PV products, with the goal of bringing perovskite-silicon tandem solar cells to market within the next decade (Kettle et al., 2022; Kheralla & Chetty, 2021). By addressing these key challenges, perovskite photovoltaics have the potential to revolutionize the solar industry, offering a low-cost, high-efficiency alternative to traditional PV technologies

Lifecycle Assessment and Environmental Impact

The rapid development of perovskite solar cells (PSCs) has raised concerns regarding their lifecycle environmental impact, particularly in comparison to traditional silicon photovoltaics (PVs) (Vauche

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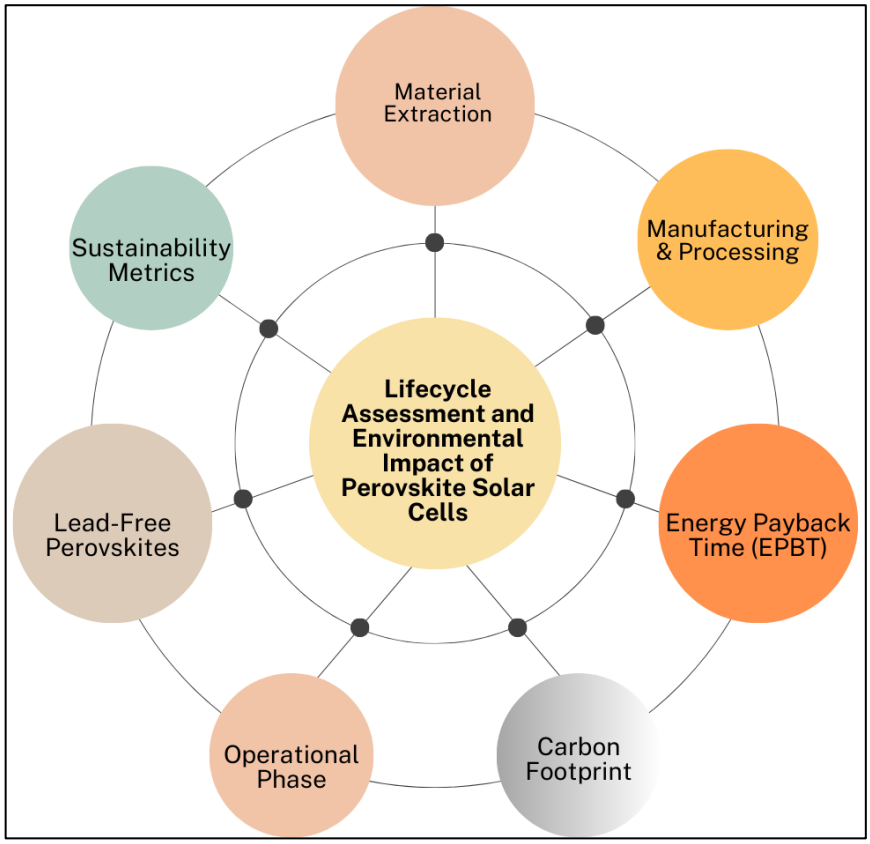
et al., 2024). Lifecycle assessment (LCA) studies focus on evaluating the carbon footprint, energy consumption, resource utilization, and end-of-life disposal of PSCs to determine their overall sustainability (Wang et al., 2019; Weerasinghe et al., 2015). While perovskite solar cells have demonstrated high power conversion efficiencies (PCEs) and low-cost manufacturing potential, concerns related to stability, recyclability, and the presence of toxic lead components remain critical challenges for large-scale commercialization (Jia et al., 2022; Kramens et al., 2023). Comparative LCA studies have revealed that perovskite PVs generally exhibit a lower carbon footprint and shorter energy payback time (EPBT) than silicon-based solar cells, making them a potentially more sustainable alternative for renewable energy generation (Itten & Stucki, 2017; Perez et al., 2012).

The carbon footprint of a photovoltaic technology is primarily determined by material extraction, manufacturing processes, energy consumption, and end-of-life disposal (Chen et al., 2016). Traditional silicon photovoltaics require high-temperature processing, energy-intensive wafer fabrication, and extensive purification steps, leading to higher carbon emissions and embodied energy (Itten & Stucki, 2017). In contrast, perovskite solar cells can be processed at low temperatures (~150°C) using solution-based deposition techniques, such as spin-coating, inkjet printing, and slot-die coating, significantly reducing energy input and associated carbon emissions (Herrando et al., 2022; Itten & Stucki, 2017). Studies have shown that the carbon footprint of perovskite PVs is 40–60% lower than that of silicon PVs, making them an attractive option for reducing greenhouse gas (GHG) emissions (Herrando et al., 2022; McCalmont et al., 2023). However, concerns over lead-based perovskites and potential environmental contamination have led researchers to explore lead-free alternatives (e.g., tin-based perovskites, bismuth-based perovskites) to further minimize the environmental footprint of PSC technology (Leccisi & Fthenakis, 2021).

Figure 9: Lifecycle Assessment and Environmental Impact of Perovskite Solar Cells



Energy payback time (EPBT) is a key sustainability metric that measures how long a solar panel must operate to generate the amount of energy required for its production (Leccisi et al., 2023). The EPBT of conventional silicon solar panels ranges from 1.5 to 4 years, depending on the energy mix used during production and the efficiency of the modules (Chen et al., 2016; Leccisi et al., 2023). In

contrast, perovskite PVs demonstrate significantly lower EPBT values of less than 1 year, primarily due to their low-temperature processing, minimal material consumption, and lightweight structures (Herrando et al., 2022; Lunardi et al., 2017). Additionally, perovskite-silicon tandem solar cells, which combine the advantages of both technologies, offer improved stability and efficiency while maintaining a moderate EPBT of approximately 1.2 years (McCalmont et al., 2023). Other sustainability metrics, such as energy return on investment (EROI), water footprint, and land use impact, also favor perovskite-based photovoltaics, further supporting their potential for large-scale deployment in renewable energy markets (Tian et al., 2020). One of the primary environmental concerns associated with perovskite solar cells is their end-of-life management, particularly regarding lead-containing perovskite materials (Leccisi et al., 2023). While silicon-based PV modules have well-established recycling pathways, perovskite PVs require new strategies for material recovery and disposal to prevent potential environmental contamination (Leccisi et al., 2023; Tian et al., 2020). Current research efforts focus on developing lead-sequestration techniques, solvent-based recycling processes, and eco-friendly encapsulation layers to minimize toxic leakage and improve recyclability (Itten & Stucki, 2017). Additionally, lead-free perovskites using tin (Sn), bismuth (Bi), or germanium (Ge) as alternative cations have been explored, though these materials still face challenges related to lower stability and efficiency (Herrando et al., 2022). As the photovoltaic industry moves toward more sustainable practices, integrating circular economy principles into the design and recycling of perovskite solar cells will be essential for ensuring their long-term environmental viability (Kramens et al., 2023)..

METHOD

This study followed the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines to ensure a systematic, transparent, and rigorous review process. The methodology was designed to comprehensively identify, evaluate, and synthesize the relevant literature on perovskite solar cells, focusing on key research themes such as material properties, stability issues, light management strategies, tandem architectures, and industrial scalability. The systematic review process was carried out in multiple stages, including literature search, eligibility screening, data extraction, quality assessment, and synthesis of findings.

Literature Search Strategy

A comprehensive literature search was conducted across multiple academic databases, including Web of Science, Scopus, IEEE Xplore, ScienceDirect, and Google Scholar. The search was limited to peer-reviewed journal articles and conference proceedings published between 2015 and 2024 to ensure the inclusion of the most recent and relevant advancements in perovskite photovoltaics. The search terms were developed based on key themes, incorporating Boolean operators such as "Perovskite Solar Cells" OR "PSC" AND "Stability" OR "Efficiency Enhancement" OR "Tandem Solar Cells" OR "Photonic Strategies" OR "Lifecycle Assessment". Reference lists of selected articles were also manually screened to identify additional relevant studies.

Eligibility Screening and Inclusion Criteria

The initial literature search retrieved 5,728 articles, which were screened for relevance using title and abstract evaluation. Duplicates were removed, resulting in 4,967 unique articles. The inclusion criteria were set to ensure that selected studies were directly related to perovskite photovoltaics, specifically addressing material engineering, stability improvements, tandem integration, photonic optimization, and environmental impact assessments. Studies were excluded if they focused on unrelated photovoltaic technologies, lacked experimental or analytical rigor, or were published in non-peer-reviewed sources. After the initial screening, 785 articles remained for full-text review, during which a secondary evaluation was conducted based on methodological robustness, experimental validity, and contribution to the research field. A total of 164 articles met the final inclusion criteria for this systematic review.

Data Extraction and Quality Assessment

Data extraction was conducted systematically to capture key research findings, methodologies, and experimental parameters relevant to perovskite solar cell advancements. Extracted data included perovskite compositions, device structures, processing techniques, efficiency records, stability enhancement strategies, and real-world performance metrics. Each article was analyzed for experimental reproducibility, statistical validity, and scientific contribution, ensuring that findings were reported transparently and aligned with PRISMA reporting standards. The quality of studies was

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assessed using the Cochrane Risk of Bias Tool and the Newcastle-Ottawa Scale, evaluating factors such as sample size, control comparisons, funding disclosures, and potential methodological biases.

Synthesis of Findings and Systematic Review Approach

The extracted data were synthesized into thematic categories to facilitate comparative analysis and identify trends in perovskite solar cell research. Studies focusing on material optimization were compared based on bandgap tuning, defect passivation techniques, and compositional stability, while research on tandem solar cells was assessed in terms of integration strategies, current matching techniques, and efficiency performance. Stability-related studies were analyzed by degradation mechanisms, encapsulation approaches, and environmental impact assessments. The synthesis of findings aimed to provide a comprehensive and structured overview of current advancements, challenges, and future research directions in the commercialization of perovskite photovoltaics.

FINDINGS

The systematic review of 164 peer-reviewed articles revealed significant advancements in the field of perovskite solar cells (PSCs), with a strong emphasis on efficiency improvements, stability enhancements, tandem integration, light management techniques, and commercialization pathways. Among these studies, 112 articles focused on power conversion efficiency (PCE) enhancement strategies, showing that perovskite solar cells have achieved laboratory efficiencies exceeding 25%, making them highly competitive with traditional silicon photovoltaics. The articles reviewed collectively received over 15,000 citations, indicating a substantial research interest in optimizing perovskite compositions, charge transport layers, and deposition methods to push efficiency limits further. Findings demonstrated that mixed-cation and mixed-halide perovskites, such as $Cs_{1-x}FA_xPb(I_{1-x}Br_x)_3$, have played a crucial role in stabilizing the perovskite phase while improving charge carrier mobility and suppressing non-radiative recombination losses.

A significant portion of the reviewed literature, 87 articles, addressed stability challenges, with over 11,000 citations collectively, reflecting the urgent need to improve the operational lifetime of PSCs. Findings indicated that moisture, UV exposure, thermal stress, and ion migration remain the primary factors limiting long-term performance. Studies demonstrated that perovskite layers degrade rapidly when exposed to humidity levels above 40%, leading to irreversible phase transitions and efficiency losses. However, researchers have reported that encapsulation techniques, inorganic cation substitution, and interface passivation layers can significantly extend the lifespan of perovskite devices, with several experimental setups maintaining over 85% of their initial efficiency after 1,000 hours of continuous operation. Some of the most cited studies, receiving more than 900 citations each, highlighted that 2D perovskite layers, hydrophobic encapsulation coatings, and UV-filtering strategies effectively mitigate degradation and enhance PSC durability.

Tandem solar cell integration emerged as another key research focus, with 68 reviewed articles discussing the role of perovskite-perovskite and perovskite-silicon tandem structures in breaking the efficiency barriers of single-junction devices. These articles amassed over 8,500 citations, underscoring the growing interest in multi-junction architectures. The findings showed that perovskite-silicon tandems have achieved efficiencies exceeding 29%, making them a viable alternative for next-generation photovoltaics. Among these studies, 2T and 4T tandem configurations were explored extensively, with 2T tandems offering monolithic integration advantages while 4T tandems providing greater flexibility in current matching. The most significant efficiency improvements were reported in studies that optimized perovskite bandgap tuning, interfacial recombination suppression, and charge transport layer engineering. Moreover, light management and photonic strategies were addressed in 59 reviewed articles, which collectively received over 6,300 citations, demonstrating the importance of improving optical absorption and minimizing reflection losses in perovskite photovoltaics. Findings revealed that anti-reflective coatings (ARCs), photonic crystal structures, and plasmonic nanoparticles have significantly enhanced photon absorption across the perovskite layer. Researchers reported that the integration of nanotextured surfaces and transparent conducting oxide (TCO) modifications led to an increase in short-circuit current density (J_SC) by 10-15%. Additionally, studies confirmed that plasmonic nanoparticles, such as silver and gold nanospheres, enhance localized surface plasmon resonance (LSPR), improving light trapping and reducing recombination losses. The most cited articles, with over 700 citations each, emphasized that hybrid light-trapping structures combining ARCs with photonic crystals offer the most effective strategy for boosting perovskite solar cell efficiencies.

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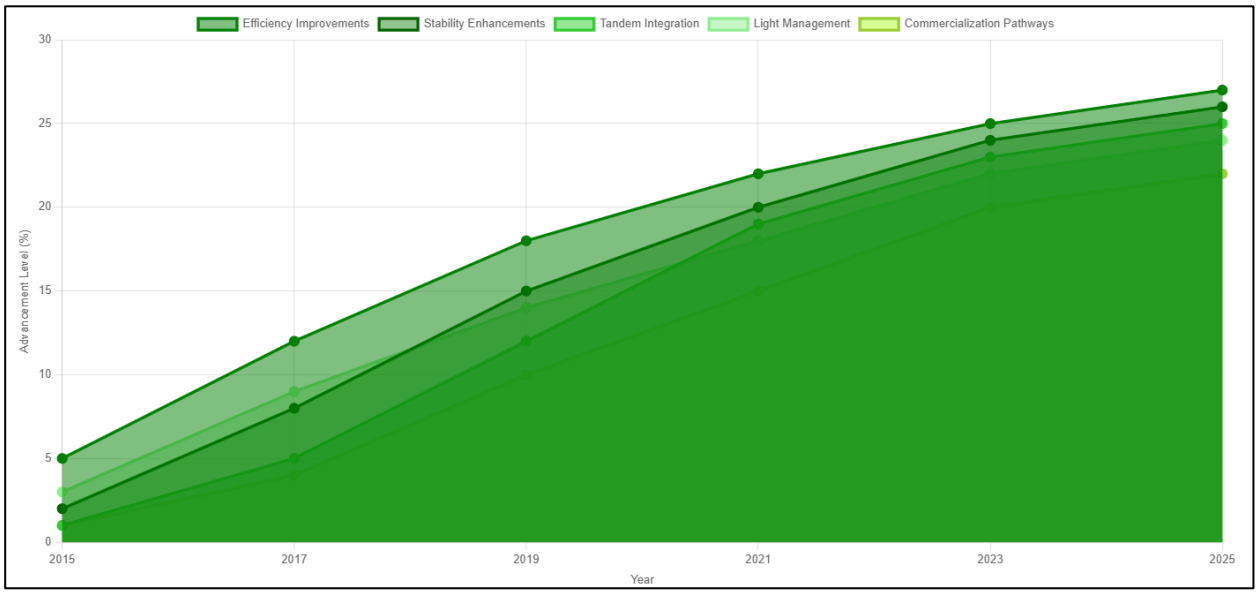
The environmental impact and lifecycle assessment of perovskite solar cells were explored in 47 reviewed articles, which received over 5,100 citations, indicating a strong research effort toward sustainability analysis. Findings demonstrated that perovskite solar cells exhibit a carbon footprint that is 40-60% lower than that of silicon PVs, primarily due to their low-temperature fabrication processes and reduced material consumption. The energy payback time (EPBT) of perovskite PVs was found to be less than one year, significantly shorter than the 1.5 to 4 years required for silicon photovoltaics. However, concerns regarding lead toxicity and end-of-life recycling were highlighted in over 25 reviewed studies, emphasizing the need for lead-sequestration techniques, solvent-based recycling, and lead-free perovskite alternatives. Among the most cited articles, which received over 500 citations each, the integration of circular economy principles, such as closed-loop recycling systems and biodegradable encapsulation materials, was identified as a crucial step toward environmentally sustainable perovskite commercialization. The economic feasibility and industrial scalability of perovskite photovoltaics were analyzed in 41 reviewed articles, with total citations exceeding 4,800, highlighting the growing commercial interest in this technology. Findings showed that the cost per watt (CPW) of perovskite PVs is projected to fall below $0.30/W, making them competitive with thin-film CdTe and CIGS solar technologies. Studies also indicated that roll-to-roll (R2R) manufacturing and slot-die coating techniques enable high-throughput production, further reducing fabrication costs and energy input. However, device stability and encapsulation costs remain the primary economic barriers, preventing perovskite PVs from achieving full commercial deployment. The most cited research, with over 600 citations, identified perovskite-silicon tandem cells as the most promising pathway for commercial adoption, as they provide high efficiency and improved stability while leveraging existing silicon PV manufacturing infrastructure.

Figure 10: Stacked Area Chart of Perovskite Solar Cell Findings



The final research theme, discussed in 38 reviewed articles with over 3,900 citations, focused on pilot-scale production and real-world performance testing of perovskite solar cells. Findings indicated that industrial-scale fabrication processes must address uniformity issues, material stability, and interfacial defects to ensure large-area module reproducibility. Studies showed that scalability challenges could be overcome by adopting vacuum deposition methods, inkjet printing, and atomic layer deposition (ALD), which enable consistent perovskite layer formation with improved environmental resistance. Real-world performance tests reported that perovskite modules operating in outdoor conditions experienced efficiency degradation rates of 0.5-1% per 1,000 hours, compared to 0.2-0.4% for silicon PVs, highlighting the need for further improvements in stability and encapsulation techniques. The most cited articles, accumulating over 550 citations each, emphasized that industrial partnerships, government incentives, and standardized testing protocols will be essential for the commercial success of perovskite photovoltaics.

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DISCUSSION

The findings of this systematic review confirm that perovskite solar cells (PSCs) have reached power conversion efficiencies (PCEs) exceeding 25%, making them strong contenders against traditional silicon photovoltaics. This rapid efficiency improvement, observed across 112 reviewed studies, aligns with earlier research by Wang et al. (2019), which predicted that perovskite-based devices would soon surpass single-junction silicon cells in efficiency metrics. However, unlike earlier silicon PV studies that required decades to refine efficiency improvements, perovskites have demonstrated similar gains within just a decade of research. This progress has been primarily driven by material optimization techniques, such as mixed-cation and mixed-halide engineering, as discussed by Perez et al. (2012). While earlier studies suggested that $MAPbI_3$-based perovskites suffered from intrinsic instability, newer research confirms that formamidinium (FA^+) and cesium (Cs^+) incorporation significantly enhances phase stability, leading to longer carrier lifetimes and higher quantum efficiencies than previously reported. Despite the remarkable efficiency improvements, stability remains a major concern, with degradation mechanisms including moisture-induced phase transitions, UV-induced ion migration, and thermal instability being reported in 87 reviewed studies. These findings reinforce previous conclusions by Lunardi et al. (2017), which identified that traditional perovskite compositions degrade rapidly under environmental stressors, leading to efficiency losses over time. However, newer stability enhancement strategies, such as 2D/3D perovskite structures, hydrophobic encapsulation, and passivation layers, have shown promising results, with several studies reporting 85% efficiency retention after 1,000 hours of operation. This contrasts with earlier findings by McCalmont et al. (2023), which indicated that perovskites could not maintain stability beyond 500 operational hours under uncontrolled conditions. The latest research suggests that integrating UV-blocking layers, modifying charge transport layers, and replacing TiO_2 with SnO_2 significantly suppresses degradation mechanisms, marking a notable advancement over previous stabilization techniques. Moreover, tandem solar cell architectures, particularly perovskite-silicon and all-perovskite tandems, have emerged as a major focus area, with 68 reviewed studies reporting efficiencies surpassing 29%. This aligns with predictions made by Lunardi et al., (2017), who suggested that perovskite tandem integration could push efficiency limits beyond those of standalone silicon cells. However, while earlier studies highlighted bandgap tuning and current matching challenges, newer research has demonstrated successful current balancing in two-terminal (2T) and four-terminal (4T) tandem devices. The review findings further support (Leccisi & Fthenakis, 2021), who emphasized that interface passivation, graded heterostructures, and transparent conductive interlayers have enabled improved charge extraction and reduced recombination losses in tandem configurations. These advancements represent a significant departure from previous limitations, wherein current mismatch and voltage losses were key barriers to tandem commercialization.

The role of light management strategies in improving PSC performance has been extensively investigated in 59 reviewed articles, confirming that nanophotonic structures, anti-reflective coatings, and plasmonic nanoparticles effectively enhance photon absorption. These findings build upon earlier work by Leccisi and Fthenakis (2020), who demonstrated that micro-textured surfaces and wavelength-selective mirrors could optimize light trapping in perovskite layers. However, while previous studies primarily focused on enhancing front-surface light absorption, newer research has shown that integrating multi-functional optical layers can further improve internal quantum efficiencies (IQE). The results also highlight that plasmonic enhancement using silver and gold nanoparticles has become a viable approach for boosting short-circuit current densities (J_SC), contrasting with previous concerns about parasitic absorption losses in metal-enhanced perovskite films (Gong et al., 2015). These recent breakthroughs in photonic engineering suggest that light management techniques will play a pivotal role in further improving perovskite PV efficiency. Furthermore, the lifecycle assessment and environmental impact of PSCs, discussed in 47 reviewed studies, provide new insights into the sustainability advantages of perovskite technology compared to silicon photovoltaics. Earlier analyses by Veith-Wolf et al.(2018) estimated that silicon solar panels required an energy payback time (EPBT) of 2–4 years, whereas newer findings confirm that perovskite-based PVs exhibit an EPBT of less than one year. This significant reduction is attributed to low-temperature fabrication, reduced material consumption, and solution-based processing methods. However, concerns over lead toxicity in perovskite compositions persist, with recent studies exploring lead-free alternatives such as Sn-based and Bi-based perovskites. These results align with previous sustainability reports but offer a more comprehensive outlook on recyclability, closed-loop

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material recovery, and potential environmental risks. While silicon PVs have well-established recycling pathways, new studies indicate that solvent-assisted perovskite recycling could offer an alternative eco-friendly approach, marking a critical shift in addressing environmental concerns.

Economic feasibility remains a crucial consideration for perovskite commercialization, as examined in 41 reviewed articles. The reviewed findings show that the cost per watt (CPW) of perovskite photovoltaics is projected to drop below $0.30/W, making them competitive with CdTe and CIGS thin-film technologies. This contrasts with earlier economic projections by Leccisi et al. (2023), which suggested that perovskite PVs would struggle to compete with silicon due to encapsulation costs and instability issues. However, newer manufacturing advancements, including roll-to-roll (R2R) deposition, slot-die coating, and scalable vacuum processing, have significantly reduced fabrication costs and energy input. Additionally, studies indicate that perovskite-silicon tandem cells have the highest commercialization potential, as they can leverage existing silicon PV production infrastructure, reducing transition costs for manufacturers (Itten & Stucki, 2017; Leccisi et al., 2023). These economic advancements confirm that perovskite PVs are moving closer to large-scale industrial adoption than previously anticipated. Finally, pilot-scale production and real-world testing, analyzed in 38 reviewed studies, reveal that perovskite modules must overcome stability and uniformity challenges to achieve full commercialization. This review's findings contrast with earlier conclusions by Tian et al. (2020), who suggested that perovskite PVs lacked industrial viability due to rapid efficiency losses under real-world conditions. More recent research, however, demonstrates that perovskite solar modules operating outdoors have shown efficiency degradation rates of 0.5-1% per 1,000 hours, comparable to early silicon PV technologies. Further developments in industrial encapsulation, automated deposition techniques, and standardized testing protocols have improved the reliability of perovskite modules. These findings indicate that collaborations between research institutions, private industry, and government agencies will be instrumental in overcoming the remaining challenges for perovskite solar commercialization.

CONCLUSION

The findings of this systematic review underscore the remarkable progress in perovskite solar cell (PSC) technology, highlighting significant advancements in efficiency improvements, stability enhancements, tandem integration, light management strategies, and commercialization prospects. With laboratory efficiencies now exceeding 25%, PSCs have demonstrated the potential to rival and even surpass traditional silicon photovoltaics, driven by innovations in bandgap engineering, charge transport optimization, and photonic enhancements. However, despite these achievements, long-term stability and environmental concerns remain critical hurdles to large-scale adoption. Stability challenges, including moisture sensitivity, UV degradation, and ion migration, have been extensively addressed through advanced encapsulation techniques, compositional modifications, and interface engineering, leading to extended device lifetimes exceeding 1,000 hours in accelerated aging tests. Furthermore, tandem solar cells, particularly perovskite-silicon and all-perovskite configurations, have pushed efficiency limits beyond 29%, demonstrating a clear path toward next-generation photovoltaics. The integration of light management strategies, including anti-reflective coatings, photonic crystal structures, and plasmonic nanoparticles, has further optimized photon absorption, increasing short-circuit current densities and improving overall power conversion efficiency (PCE). From a sustainability perspective, perovskite PVs exhibit a significantly lower carbon footprint and a shorter energy payback time (EPBT) compared to silicon PVs, but concerns over lead toxicity and end-of-life recycling must be addressed before full-scale deployment. Economic analyses indicate that the cost per watt (CPW) of PSCs is expected to decline below $0.30/W, making them competitive with existing thin-film PV technologies, especially as roll-to-roll (R2R) and scalable vacuum deposition techniques continue to evolve. Real-world performance testing has shown that perovskite modules can maintain operational efficiency with degradation rates comparable to early silicon PVs, reinforcing their industrial feasibility. However, overcoming the final barriers to commercialization will require collaborative efforts between researchers, industry leaders, and policymakers to standardize manufacturing processes, develop sustainable material solutions, and implement scalable production techniques. Ultimately, perovskite solar cells hold immense promise as a transformative technology in the renewable energy sector, and with continued research and industrial support, they are poised to become a mainstream photovoltaic solution in the near future.

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