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STRATEGIES AND PROGRESS IN STABILIZING INORGANIC PEROVSKITE SOLAR CELLS FOR LONG-TERM OPERATION

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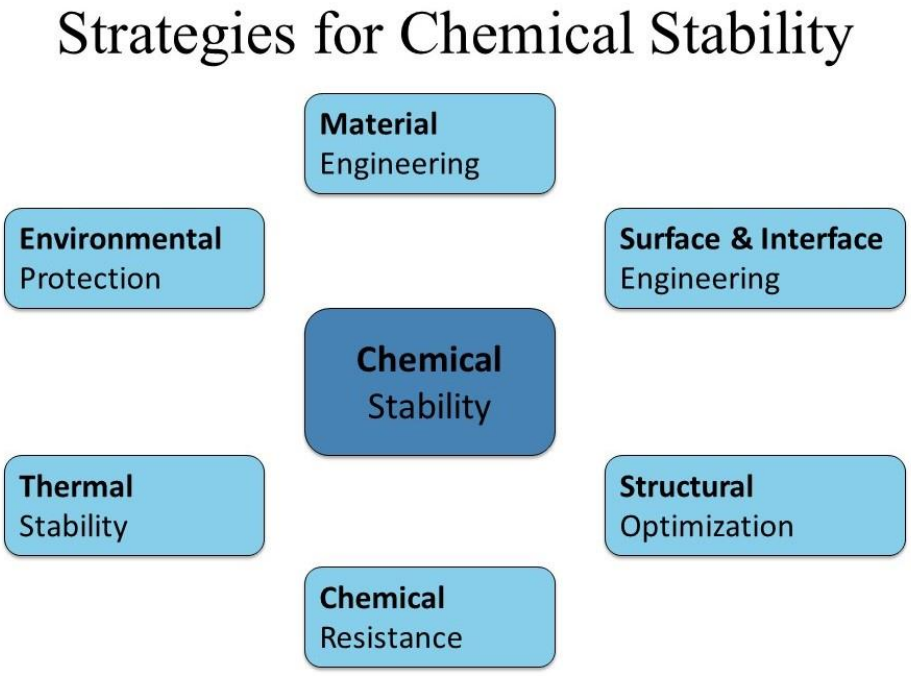
Abstract
Inorganic perovskite solar cells (PSCs) have attracted significant attention over the past six years due to their remarkable optoelectronic properties and potential for commercialization. Considerable progress has been made in developing advanced fabrication strategies to improve both the efficiency and stability of inorganic PSCs. Within a short time, the power conversion efficiency (PCE) of inorganic PSCs has increased from ~9.7% to over 20%, highlighting their promise as next-generation photovoltaic devices. However, their practical outdoor applications remain limited by intrinsic instability and degradation under environmental stresses such as oxygen, moisture, temperature fluctuations, ultraviolet irradiation, and processing solvents. These stability challenges must be addressed to achieve long-term durability, reproducibility, and reliable performance, which are essential for the successful transition of PSCs from laboratory research to industrial-scale commercialization. This review summarizes the current understanding of chemical stability in inorganic PSCs, focusing on degradation mechanisms under various conditions and highlighting potential strategies to enhance their stability for future applications.

1. INTRODUCTION

The global demand for sustainable and renewable energy has stimulated rapid advancements in photovoltaic (PV) technologies. Among various PV candidates, perovskite solar cells (PSCs) have emerged as one of the most promising due to their exceptional optoelectronic properties, solution process ability, and rapidly improving efficiencies. Since their first demonstration in 2009 with efficiencies of only 3.8%, PSCs have witnessed an unprecedented leap, now competing with traditional silicon solar cells in both performance and cost-effectiveness.[1] solar (based on cesium lead halides such as $CsPbI_3$, $CsPbBr_3$, and their mixed-halide derivatives) have drawn extensive attention over the past six years. Unlike hybrid organic–inorganic perovskites that contain volatile cations such as methyl ammonium (MA^+) and formamidinium (FA^+), inorganic perovskites rely on inorganic cations (Cs^+) that provide superior thermal and structural stability. This makes them attractive candidates for commercial solar cell applications, especially in regions with high temperatures where organic counterparts are prone to rapid degradation[2].



The field has seen remarkable efficiency progress: the power conversion efficiency (PCE) of inorganic PSCs has surged from ~9.7% in 2016 to over 20% in recent years. This achievement demonstrates their competitive edge as low-cost, high-performance photovoltaic devices. However, despite these gains, stability remains the central challenge**.** Inorganic PSCs (UV) irradiation, thermal stress, and ion migration.

The intrinsic instability of the black perovskite α-phase (photoactive phase) toward the yellow δ-phase (non-perovskite) under ambient conditions further complicates their reliability[3]. These stability issues severely limit their outdoor operation and hinder their transition from laboratory demonstrations to industrial applications.

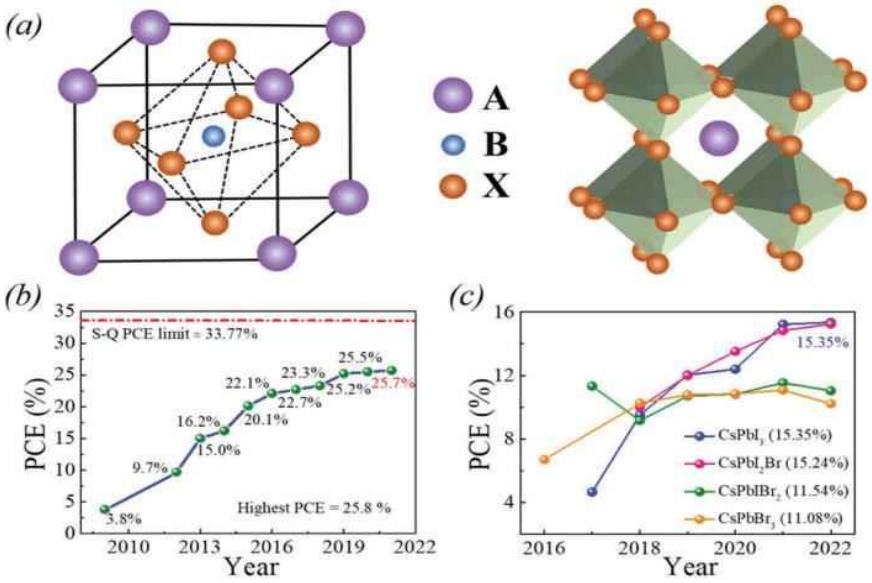
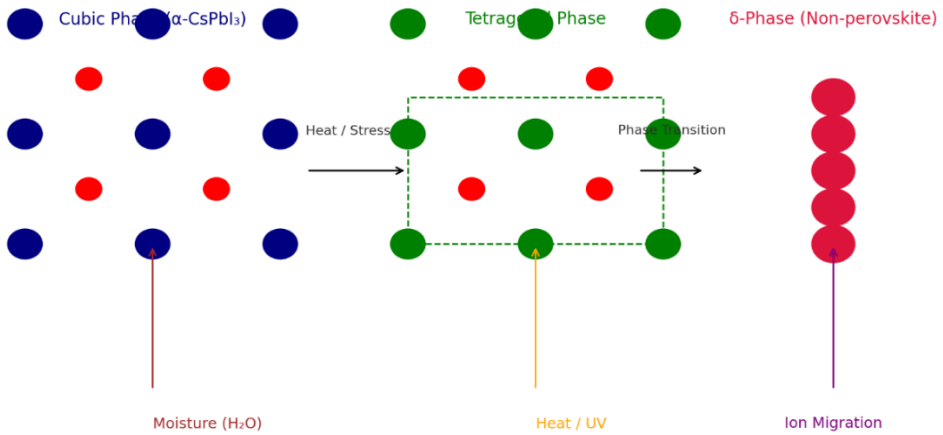


Figure 1 a) 3D crystal structure with the ABX_3 formula; PCE evolution for b) hybrid PSCs and c) Pb-based carbon inorganic PSCs. (Zhang, Xiang, et al., *Recent Progress of Carbon-Based Inorganic Perovskite Solar Cells: From Efficiency to Stability, Advanced Energy Materials*, 2022, 2201320).

Addressing the chemical stability of inorganic PSCs is, therefore, not only scientifically intriguing but also crucial for their commercial viability. Researchers worldwide have been exploring multiple approaches—including compositional engineering, surface passivation, interface modification, encapsulation, and doping strategies—to mitigate degradation pathways[4]. Moreover, recent studies emphasize the importance of understanding how environmental factors such as humidity, oxygen, and temperature interact with perovskite materials to trigger decomposition.[5]

Figure 1. Crystal Structures of $CsPbI_3$ Phases and Degradation Pathways



This review focuses on the chemical stability of inorganic PSCs, summarizing degradation mechanisms under different environmental conditions and evaluating the strategies that have been developed to counteract these challenges. Special emphasis is placed on linking stability improvements with the remarkable efficiency gains achieved in the past few years. Finally, perspectives are provided on the future directions required to transition inorganic PSCs from the research stage toward large-scale, industrial-level commercialization[6].

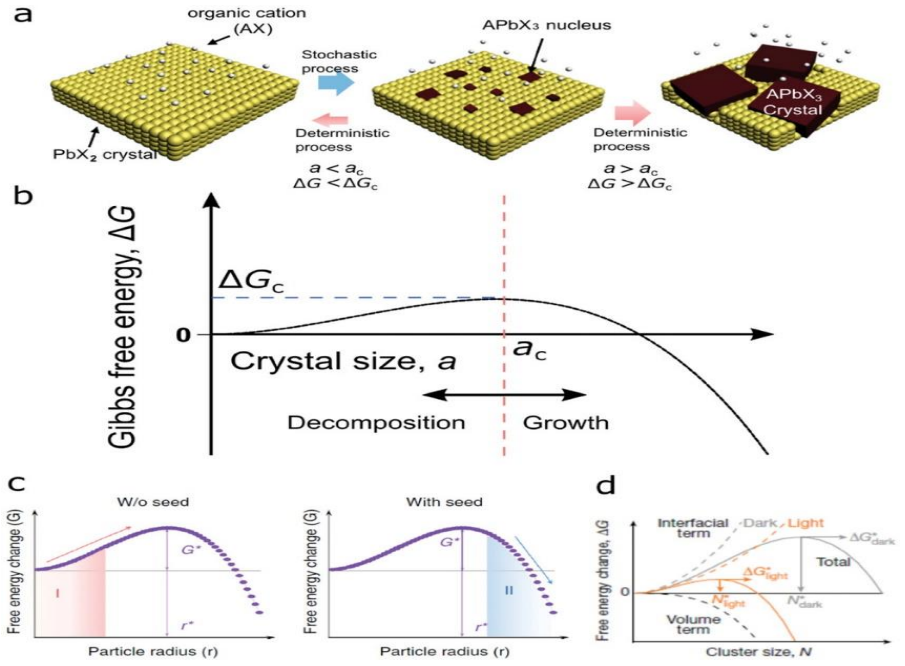
2. Degradation Mechanisms in Inorganic Perovskite Solar Cells

The performance and durability of inorganic perovskite solar cells (PSCs) are strongly influenced by their chemical stability under different environmental and operational conditions. Although inorganic cations (Cs^+) provide greater thermal tolerance than organic ones (MA^+, FA^+), inorganic PSCs remain vulnerable to multiple degradation pathways that limit their long-term operation. The main degradation mechanisms include interactions with moisture, oxygen, temperature fluctuations, ultraviolet irradiation, ion migration, and chemical reactivity with charge transport layers and electrodes.[7-9]

2.1 Moisture-Induced Degradation

Moisture is one of the most detrimental external factors affecting the stability of PSCs. When exposed to humid air, $CsPbI_3$ and other halide perovskites tend to absorb water molecules, which disrupt hydrogen bonding and halide coordination within the perovskite lattice. This leads to the hydrolysis of the perovskite phase and its decomposition into lead iodide (PbI_2) and volatile species (HI, I_2). Furthermore, moisture accelerates the undesirable transformation of the black photoactive α-phase of $CsPbI_3$ into the non-perovskite δ-phase, which is optically inactive and drastically reduces device efficiency.[10] The situation worsens when devices are not encapsulated, as water molecules can easily penetrate through grain boundaries and interfaces, initiating rapid degradation.

Achieving Long-Term Stability in Perovskite Solar Cells: Understanding Degradation and Strategies for Stabilization. The formation of perovskite crystals begins when organic halides (AX) and lead halides (PbX_2) react in a stochastic manner, leading to the nucleation of $APbX_3$ crystals.[11]



2.2 Oxygen-Induced Degradation

Inorganic PSCs are also susceptible to oxygen-related degradation[12], especially under illumination. Oxygen can diffuse into the perovskite lattice and react with photo excited electrons to form superoxide species (O_2^-). These reactive oxygen species attack the Pb–I framework, resulting in halide vacancy formation and lattice collapse. The combined effect of oxygen and moisture often leads to synergistic degradation, where perovskites decompose much faster in ambient air than in controlled, dry conditions.[13, 14]

2.3 Thermal Instability and Phase Transition

Although inorganic PSCs show better tolerance to heat compared to hybrid perovskites, they are still subject to phase instability. The black cubic α-$CsPbI_3$ phase, which is photoactive, is metastable at room temperature and tends to spontaneously convert to the non-perovskite yellow δ-$CsPbI_3$ phase, especially when exposed to prolonged thermal stress. This phase transition is thermodynamically driven and represents one of the most fundamental challenges to the chemical stability of inorganic perovskites. Moreover, repeated thermal cycling during outdoor operation exacerbates lattice strain, ion migration, and interfacial reactions with transport layers, accelerating device degradation.[15, 16]

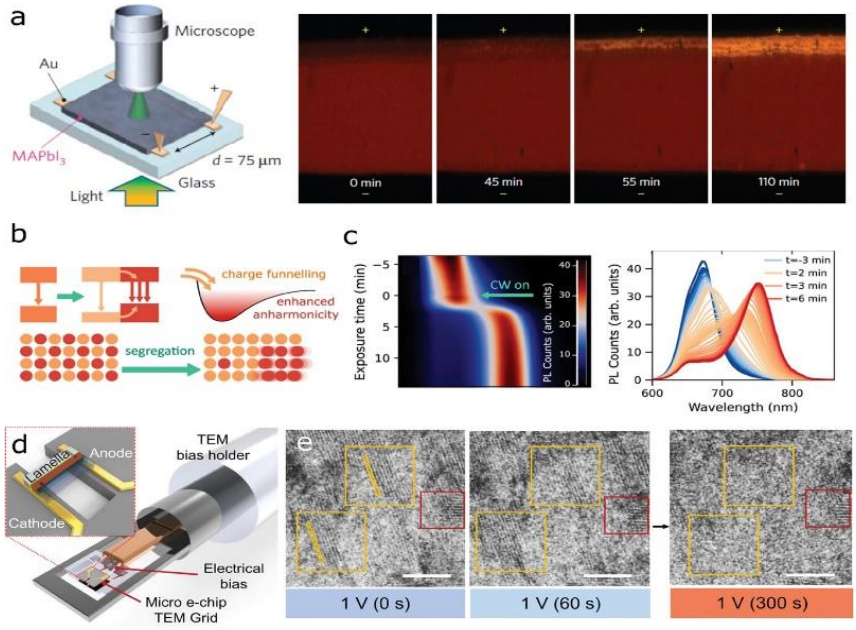
2.4 Ultraviolet (UV) Light-Induced Degradation

Ultraviolet irradiation contributes significantly to instability in PSCs. High-energy photons can break Pb–I bond, generate defect states, and accelerate photo-oxidation reactions in the presence of oxygen and moisture. UV light also destabilizes organic transport layers (such as Spiro-OMeTAD or polymers) when used in combination with inorganic perovskites, producing reactive intermediates that attack the perovskite surface. In addition, UV-induced heating can increase the rate of ion migration and accelerate the α- to δ-phase transformation.[17, 18]

2.5 Ion Migration and Lattice Defects

Ion migration is an intrinsic degradation pathway in PSCs. Mobile halide ions (I^-, Br^-) and, to some extent, cations (Cs^+, Pb^{2+}) can migrate within the perovskite lattice or across interfaces under electric fields, light, or thermal gradients. This migration leads to hysteresis in current–voltage characteristics, interfacial chemical reactions, and irreversible breakdown of device performance. Vacancies and grain boundaries act as pathways for ion migration, making polycrystalline films particularly vulnerable. Over time, this contributes to permanent structural distortion and efficiency loss.[19, 20]

Towards Long-Term Stable Perovskite Solar Cells: Understanding Degradation and Strategies for Stabilization



Ion movements in halide perovskites: a) In situ microscopic measurement of ion migration in a $MAPbI_3$ film (left) with real-time images showing ion movement over 110 minutes. Adapted with permission from ref. [54b], ©2014 Springer Nature Limited. b) Schematic illustration of halide segregation. c) Direct observation of halide segregation through the time evolution of photoluminescence (PL) spectra using 400 nm pulsed irradiation..[21]

2.6 Chemical Instability with Charge Transport Layers

Inorganic perovskites often interact unfavorably with charge transport layers (CTLs). For example, the acidic dopants used in hole transport materials (HTMs) can corrode perovskites, while reactive metal oxides (e.g., TiO_2) in electron transport layers can catalyze perovskite decomposition under illumination. In addition, direct contact with metallic electrodes (e.g., Ag, Al) can result in interfacial diffusion and undesirable reactions, forming insulating by-products (e.g., AgI), which degrade electrical contact and reduce efficiency.[22, 23]

2.7 Processing Residues and Solvent Effects

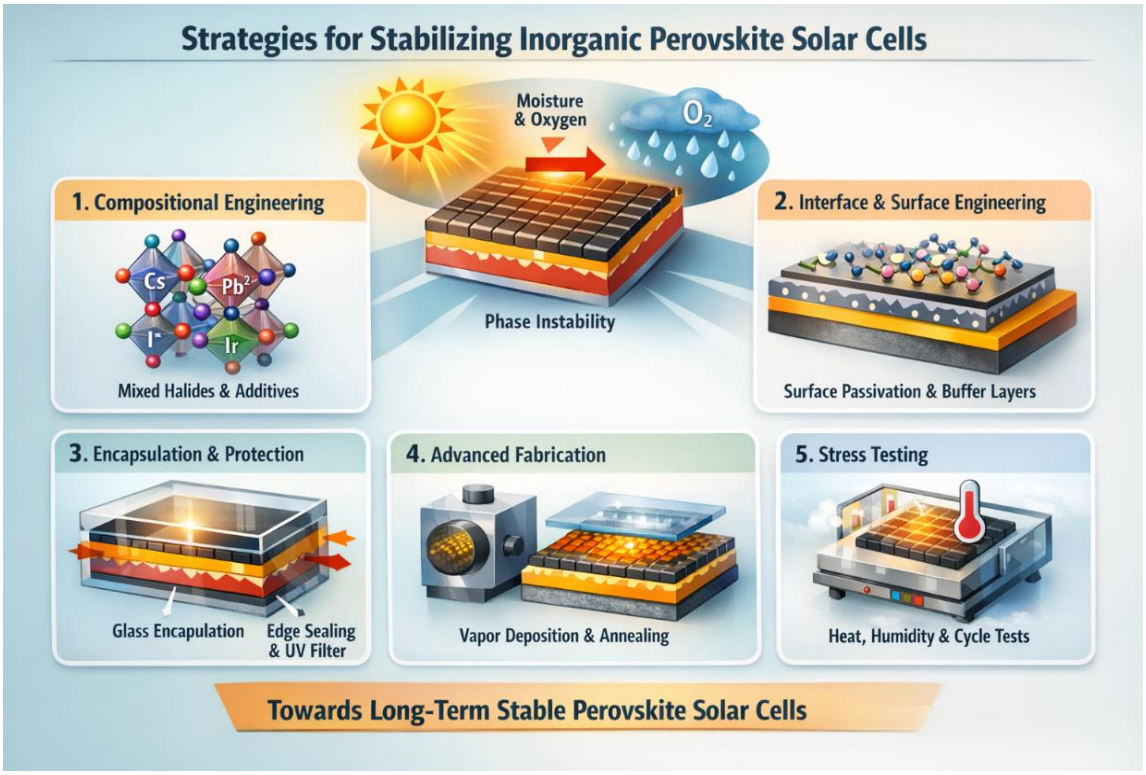
Incomplete removal of precursor solvents (e.g., dimethylformamide, dimethyl sulfoxide) or additives can leave behind chemical residues that destabilize the perovskite structure. Such impurities promote trap formation, interfacial recombination, and sensitivity to humidity. Similarly, fabrication conditions (annealing temperature, solvent engineering, and film crystallization speed) can greatly influence long-term stability.[24-26]

Table 1. Summary of Chemical Degradation Pathways in Inorganic Perovskites

Mechanism	Cause	Effect on Device	Example Material	Key Reference
Phase instability	$CsPbI_3$ transforms to δ-phase at room T	Loss of bandgap absorption, drop in PCE	$CsPbI_3$	Jin et al., 2024[27]
Ion migration	Halide vacancies migrate under light/bias	Hysteresis, bandgap shifts	$CsPbI_2Br$	Lee et al., 2023[28]
Halide segregation	Mixed I/Br compositions under illumination	Phase separation, reduced PL	$CsPbIBr_2$	Gui et al., 2024[29]
Moisture degradation	Water uptake → PbI_2 formation	Film decomposition	$CsPbI_3$	Reddy et al., 2024[30]
Interfacial reactions	Metal diffusion, redox reactions	Contact instability	Ag electrode with $CsPbBr_3$	Igbari et al., 2025[31]

3. Strategies for Enhancing Chemical Stability in Inorganic Perovskite Solar Cells

To overcome the inherent instability of inorganic perovskite solar cells (PSCs), researchers have developed various strategies aimed at suppressing degradation pathways, enhancing lattice stability, and improving device encapsulation. The following approaches are among the most effective and widely investigated.



3.1 Compositional Engineering of the Perovskite Layer

The choice of composition is critical for chemical stability. Compositional engineering is a powerful strategy to enhance the chemical stability of inorganic perovskite solar cells. Mixed-halide systems such as CsPb(I/Br) have been shown to stabilize the photoactive cubic phase of $CsPbI_3$ by

alleviating lattice strain and improving moisture tolerance; however, they are often limited by phase segregation under continuous illumination. Another approach involves doping with small ions, where the incorporation of alkali cations (Rb^+, K^+, Na^+) passivates lattice defects and suppresses ion migration, while transition-metal dopants such as Mn^{2+} or Sn^{2+} further enhance electronic stability and reduce defect density.[32-34] Additionally, alloying with Sn-based perovskites, through partial substitution of Pb^{2+} with Sn^{2+}, offers improved phase stability, although it requires precise control to mitigate the inherent oxidation of Sn^{2+}. Collectively, these compositional modifications contribute to stabilizing the perovskite structure and prolonging device lifetime.

3.2 Surface Passivation and Interface Engineering

Surface defects and grain boundaries are major sites for degradation. Various passivation methods have been proposed. Surface passivation plays a critical role in mitigating non-radiative recombination and enhancing the environmental stability of inorganic perovskite solar cells. The use of organic molecules, including long-chain ammonium salts, polymers such as PMMA, and alkylphosphonic acids, can form protective interfacial layers that prevent moisture ingress while reducing defect density. In parallel, inorganic passivation strategies—notably atomic-layer-deposited (ALD) oxides like Al_2O_3 and TiO_2—create ultrathin diffusion barriers that effectively block oxygen and water penetration. Moreover, 2D/3D hybrid perovskite structures, in which 2D perovskite layers are introduced atop 3D $CsPbI_3$, not only stabilize the photoactive black phase but also passivate surface defects, thereby yielding significantly improved device lifetime and operational reliability.[35-37]

3.3 Encapsulation Techniques

Effective encapsulation is indispensable for protecting inorganic perovskite solar cells (PSCs) against moisture, oxygen, and thermal stress under ambient and outdoor conditions. Conventional glass encapsulation, employing glass covers sealed with epoxy adhesives, offers excellent long-term stability but increases cost and weight, limiting flexibility. In contrast, polymer-based films such as PET and PEN enable lightweight and flexible device designs, making them suitable for portable and wearable applications. Furthermore, barrier coatings, typically consisting of alternating organic and inorganic layers, provide superior resistance against environmental ingress.[38, 39] Recently, self-healing encapsulation systems, incorporating moisture-absorbing additives and UV blockers, have emerged as an advanced strategy to actively protect perovskite films during operation, thereby extending device lifetime and reliability.

3.4 Stabilization of the Perovskite Phase

The thermodynamically unstable α-phase $CsPbI_3$ requires effective stabilization strategies to preserve its superior optoelectronic properties and achieve long-term operational performance. Nanocrystal engineering, by reducing grain size, provides kinetic stabilization of the black phase at room temperature. Additionally, strain engineering, through substrate-induced strain or lattice confinement, can effectively suppress the undesirable $\alpha \rightarrow \delta$ phase transition. Moreover, additive incorporation and alloying approaches, such as introducing halogen species (Cl^-, F^-) or intercalating organic molecules at grain boundaries, serve to pin the perovskite in its photoactive phase, thereby extending device lifetime and improving efficiency.[40-42]

3.5 Improving Charge Transport Layers (CTLs)

Instability often arises at the interfaces between perovskite and CTLs. Replacing conventional TiO_2 electron transport layers, which catalyze perovskite decomposition under UV illumination, with alternatives such as SnO_2 or ZnO has proven effective in suppressing interfacial photocatalysis and enhancing device durability. Similarly, the development of stable hole transport materials (HTMs) is crucial, as the widely used Spiro-OMeTAD suffers from poor moisture resistance and requires dopants that accelerate chemical degradation. In contrast,

inorganic HTMs such as NiOx, CuSCN, or carbon-based layers offer superior stability and cost-effectiveness. Furthermore, the introduction of interfacial buffer layers (e.g., MoO_3, graphene oxide) can effectively block ion migration and protect electrodes from unfavorable reactions with halides, thereby prolonging the operational lifetime of inorganic perovskite solar cells.[43-45]

3.6 Defect and Ion Migration Suppression

Ion migration remains one of the most detrimental degradation mechanisms in inorganic perovskite solar cells, as it accelerates phase instability and performance loss under operational conditions. Several strategies have been proposed to mitigate this challenge. Defect passivation using small molecules such as fullerenes, Lewis bases, or ionic liquids effectively suppresses halide vacancies, thereby lowering ion mobility within the perovskite lattice. In addition, lattice doping with stable cations like K^+ or Rb^+ fills defect sites and hinders halide migration, improving structural robustness. Another promising approach is grain boundary engineering, where solvent-engineering techniques are employed to enlarge perovskite grain size, thus reducing the density of grain boundaries that typically serve as fast diffusion channels for migrating ions. Collectively, these strategies provide viable pathways to limit ion migration and enhance the long-term stability of inorganic perovskite solar cells.[19, 46, 47]

3.7 Device Architecture Innovation

Novel device designs also contribute to long-term stability:

The stability of inorganic perovskite solar cells can be significantly improved through advanced device-level strategies. One effective approach is the use of carbon-based electrodes**,** which replace reactive silver or aluminum contacts and thereby prevent metal diffusion and halide corrosion. In parallel, the adoption of HTM-free architectures not only simplifies device design but also enhances intrinsic stability while reducing fabrication costs by eliminating the need for expensive and often unstable organic hole-transport materials.[48-50] Moreover, the development of tandem configurations**,** where inorganic perovskites are integrated with silicon or CIGS absorbers, offers a dual advantage of mitigating thermal stress and extending spectral utilization, ultimately improving both device longevity and efficiency.

3.8 Operational Stability Enhancements

Environmental protection strategies are increasingly essential for extending the operational lifetime of inorganic perovskite solar cells. The integration of UV filters, such as UV-absorbing coatings or down-conversion layers, effectively mitigates UV-induced degradation by reducing high-energy photon exposure. Similarly, the use of moisture-scavenging additives within encapsulant materials provides an active defense mechanism, as hygroscopic components trap residual water molecules before they reach the perovskite layer. In addition, thermal management approaches, including heat-dissipating substrates or phase-change materials, help prevent overheating under continuous sunlight exposure, thereby reducing thermally induced degradation pathways.[51-53] Together, these strategies complement intrinsic material engineering efforts and play a critical role in ensuring long-term device stability under real-world operating conditions.

Table 2. Strategies to Improve Chemical Stability

Strategy	Approach	Example	Impact
Compositional Engineering	A-site alloying with Rb^+, K^+	$Cs_{0.9}Rb_{0.1}PbI_3$	Phase stabilization
	B-site doping with Mn^{2+}, In^{3+}	Mn-doped $CsPbI_3$	Reduced strain
	Halide mixing (I/Br)	$CsPbI_2Br$	Bandgap tuning + stability
Phase Stabilization	Strain engineering	Lattice-matched substrates	Stabilized black phase
	Nanocrystals with ligands	$CsPbI_3$ QDs	δ-phase suppression
Passivation	Grain boundary salts (KCl, NaF)	$CsPbI_3$ + KCl	Reduced ion migration
	Hydrophobic molecules (PEA^+)	$CsPbI_3$/PEA	Improved moisture tolerance
Interface Engineering	Inorganic ETL (SnO_2, ZnO)	SnO_2/$CsPbI_3$	Minimized reactions
	Buffer layers	Al_2O_3 interlayer	Ion blocking
Encapsulation	Glass/polymer laminates	$CsPbI_3$/Encap	>1,000 h stability
	ALD barriers	Al_2O_3 coating	Excellent moisture barrier

Table 3. Lead-Free Double Perovskites

Composition	Bandgap (eV)	Stability	Limitation	Research Direction
$Cs_2AgBiBr_6$	1.9–2.2	High moisture stability	Indirect bandgap	Bandgap engineering
$Cs_2AgSbCl_6$	2.0–2.5	Chemically stable	Wide gap, low absorption	Doping/Alloying
Cs_2TiBr_6	~1.8	Strong structural stability	Deep defects	Surface passivation

4. Recent Progress in Efficiency and Stability of Inorganic Perovskite Solar Cells

Over the past decade, inorganic perovskite solar cells (PSCs) have demonstrated remarkable improvements in both power conversion efficiency (PCE) and operational stability. While early devices suffered from poor reproducibility and rapid degradation, continuous research into material design, interface engineering, and device encapsulation has brought inorganic PSCs closer to commercial viability. Below, we summarize the key milestones and strategies that have driven this progress.

4.1 Early Developments (2014–2017): From Discovery to Proof-of-Concept

The development of fully inorganic perovskite solar cells (PSCs) has progressed through several key stages. Initial reports of $CsPbX_3$ (X = I, Br) devices achieved modest efficiencies of only ~2–3%, yet they were significant in proving the feasibility of organic-free perovskite photovoltaics. An efficiency breakthrough during 2015–2016 highlighted the potential of the α-phase $CsPbI_3$, which theoretically promised high power conversion efficiency (PCE).[54, 55] Through controlled crystallization and optimized

deposition processes, researchers achieved efficiencies approaching 9.7%. However, these advances also brought critical challenges to light, as devices suffered from rapid degradation within hours to days due to phase transitions from the black photoactive α-phase to the non-perovskite δ-phase, alongside moisture sensitivity and interfacial instability[56, 57]. These early findings laid the groundwork for subsequent stability-focused research that continues to drive progress in the field.

4.2 Mid-Stage Progress (2017–2020): Material and Interface Engineering

During this period, focused efforts on phase stabilization, defect passivation, and new charge transport layers resulted in significant performance gains. Following the early challenges of inorganic perovskite solar cells (PSCs), significant advances were made through targeted material and interface engineering. Phase stabilization strategies, such as the incorporation of bromide ions in mixed-halide $CsPb(I/Br)_3$ compositions, effectively suppressed phase transitions and prolonged device lifetimes. At the same time, defect passivation approaches employing fullerenes,[31] alkylammonium halides, and ionic liquid s reduced non-radiative recombination losses and enhanced both efficiency and stability. Improvements in charge transport layers—particularly the replacement of TiO_2 with SnO_2 as the electron transport layer and the adoption of NiOx as a stable hole transport material—further enhanced device reproducibility and resistance to UV-induced degradation. Collectively, these efforts culminated in a major efficiency milestone, with $CsPbI_3$- and $CsPbBr_3$-based devices surpassing 15% power conversion efficiency by 2018 and achieving operational stability of more than 500 hours under controlled conditions.[58, 59]

4.3 Recent Advances (2020–2023): Towards 20% Efficiency and Beyond

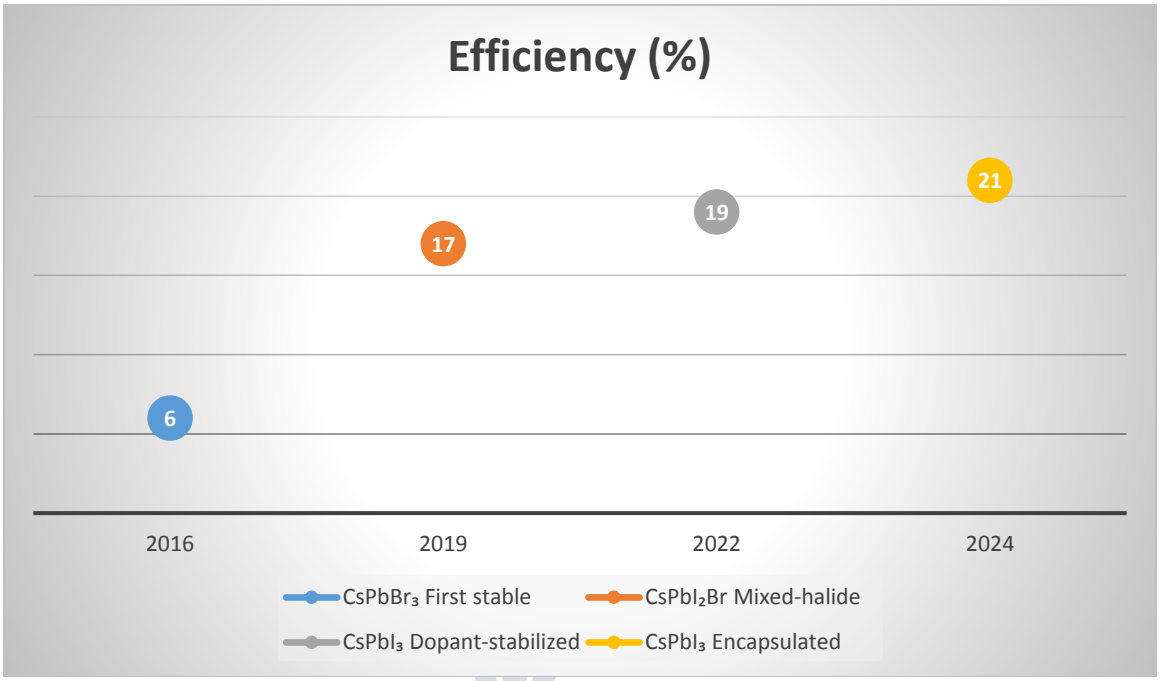
From 2020 onward, inorganic PSCs entered a new stage of development characterized by record efficiencies and improved operational lifetimes. In recent years, inorganic perovskite solar cells (PSCs) have achieved remarkable milestones that bring them closer to commercial viability. A major efficiency breakthrough was realized as power conversion efficiencies (PCEs) surpassed 20%, with $CsPbI_3$-based devices exceeding 19–20% through advanced nanocrystal engineering and interface optimization, placing them on par with hybrid perovskite counterparts. Equally important, operational stability has improved significantly, with encapsulated inorganic PSCs demonstrating over 1,000 hours of continuous illumination stability while maintaining performance. Beyond single-junction devices, tandem applications integrating inorganic PSCs with silicon and CIGS solar cells have achieved combined efficiencies exceeding 25%, highlighting their potential for high-efficiency photovoltaic modules. Furthermore, innovative phase stabilization techniques, including Nano confinement, quantum dot incorporation, and strain engineering, have successfully suppressed phase degradation, extending device lifetimes and ensuring reliable operation under practical conditions.[60-62]

4.4 Current Trends (2023–2025): Commercial Prospects and Industrial Relevance

The most recent research emphasizes scalability, outdoor stability, and commercialization pathways:

Recent advances in scalable fabrication and industrial deployment have further strengthened the potential of inorganic perovskite solar cells (PSCs) for commercial applications. Techniques such as blade coating, slot-die coating, and inkjet printing have enabled the production of large-area $CsPbI_3$ modules achieving efficiencies above 18%. In terms of outdoor stability, these devices retain more than 80% of their initial power conversion efficiency after over 2,000 hours of operation, marking a significant step toward practical deployment.[63] Encapsulation innovations, including advanced barrier layers and self-healing materials, are being developed to meet industrial stability requirements, such as IEC standards. Additionally, the inherently low-cost precursors and HTM-free architectures of inorganic PSCs contribute to competitive

manufacturing costs relative to silicon solar cells.[64] Finally, several industrial roadmaps are exploring perovskite–Si tandem modules, with inorganic PSCs serving as durable top cells capable of combining high efficiency with long-term stability.[65, 66]



Recent Progress on the Long-Term Stability of Perovskite Solar Cells

5. Future Perspectives

Future research on inorganic perovskite solar cells (PSCs) should focus on several critical directions. Phase stabilization of $CsPbI_3$ remains a top priority to ensure long-term operational stability. Simultaneously, strategies that enhance outdoor durability, addressing challenges such as humidity, UV exposure, and thermal stress, are essential for real-world deployment. The development of scalable and eco-friendly manufacturing processes will be key to industrial adoption, while the exploration of Pb-free alternatives and effective recycling strategies will support environmental sustainability. Finally, the pursuit of new applications, including building-integrated photovoltaics (BIPV), flexible and wearable devices, and hybrid energy-harvesting systems, has the potential to expand the commercial and societal impact of inorganic PSC technology.

5.1 Addressing Phase Instability

Despite significant progress, the thermodynamic instability of the α-phase $CsPbI_3$ remains a major challenge for long-term device operation. While strategies such as Nano confinement, strain engineering, and halide mixing have successfully stabilized the black phase at laboratory scales, achieving reproducible performance at industrial scales remains elusive. Future research should focus on discovering novel phase stabilizers capable of suppressing δ-phase formation under real-world conditions, as well as designing multi-dimensional perovskite architectures—particularly 2D/3D hybrids—that inherently resist structural transitions.[67] Additionally, the application of in-situ characterization techniques will be critical for gaining a deeper understanding of dynamic phase transformations during device operation, thereby guiding the development of more robust and commercially viable inorganic perovskite solar cells.[68-70]

5.2 Long-Term Stability under Real-World Conditions

Laboratory testing under controlled conditions often fails to capture the full spectrum of real-world stresses experienced by inorganic perovskite solar cells (PSCs). To ensure long-term operational stability, devices must endure simultaneous humidity, UV exposure, temperature fluctuations, and mechanical stress.[71] Future research should therefore focus on developing accelerated lifetime testing protocols that more accurately emulate outdoor conditions. In parallel, the integration of self-healing materials capable of repairing moisture- or UV-induced defects could significantly extend device lifetimes.[63] Additionally, the design of smart encapsulation systems, which not only block oxygen and water ingress but also actively regulate thermal stress, will be essential for bridging the gap between laboratory performance and reliable field operation.[72]

5.3 Scalable and Low-Cost Manufacturing

For industrial applications, achieving long-term stability is necessary but not sufficient; fabrication techniques must also be scalable, reproducible, and cost-competitive with established silicon technologies. Key directions include the implementation of roll-to-roll processing, slot-die coating, and spray deposition methods for producing large-area perovskite modules. Equally important is the development of green, non-toxic solvents, which minimize environmental and health hazards during manufacturing.[73, 74] Finally, the standardization of reproducible fabrication protocols is essential to ensure batch-to-batch consistency, enabling reliable large-scale production and facilitating the transition of inorganic perovskite solar cells from the laboratory to industrial deployment.[75]

5.4 Interface and Device Architecture Innovation

Interfacial degradation continues to be a major bottleneck in achieving long-term operational stability for inorganic perovskite solar cells (PSCs). Future research should prioritize the design of inorganic charge transport layers, such as SnO_2, NiOx, or CuSCN, which combine chemical inertness with high conductivity. In parallel, the development of HTM-free architectures utilizing carbon-based electrodes offers a cost-effective route to enhanced stability.[49, 76] Additionally, the exploration of tandem architectures—including Si/perovskite, CIGS/perovskite, and perovskite/perovskite stacks—presents a promising pathway to exceed 30% power conversion efficiency while simultaneously maintaining long-term device durability.[77]

5.5 Environmental and Toxicity Concerns

Lead toxicity remains a critical challenge for the large-scale deployment of inorganic perovskite solar cells (PSCs). Although Pb-based perovskites currently achieve the highest efficiencies, environmental regulations and safety concerns may constrain their widespread adoption. Future research should focus on developing Pb-free alternatives, such as Sn-, Bi-, Sb-, or Ge-based perovskites, despite their current performance limitations. In parallel, efficient recycling and lead-sequestration strategies are needed to prevent environmental contamination from discarded modules.[78-80] Additionally, the establishment of eco-friendly life-cycle assessments for perovskite modules will be essential to ensure sustainable commercialization and regulatory compliance.[81]

5.6 Integration into Energy Systems

Beyond achieving single-device stability, inorganic perovskite solar cells (PSCs) must demonstrate their utility in integrated energy systems. Building-integrated photovoltaics (BIPV) benefit from the tunable bandgaps and aesthetic color options of inorganic perovskites, making them ideal for incorporation into windows and building facades. Additionally, flexible and wearable electronics can exploit thin-film PSCs fabricated on lightweight substrates, enabling portable and adaptable energy solutions. Finally, hybrid energy harvesting systems that couple PSCs with energy storage devices, such as batteries or supercapacitors, offer a pathway for direct solar-to-storage applications,[63, 68, 82] further

enhancing the versatility and value of inorganic perovskite technology in practical energy systems.

5.7 Roadmap to Commercialization

The inorganic perovskite solar cells (PSCs) to achieve meaningful market penetration, close collaboration among research institutions, industry stakeholders, and policymakers is essential. Critical milestones include achieving IEC stability standards, which demand operational lifetimes of 25 years or more, and addressing toxicity concerns through robust encapsulation strategies or the development of Pb-free perovskites. Additionally, scaling up from laboratory-scale cells to large-area modules while maintaining efficiencies above 18–20% is crucial for commercial viability.[65, 76, 83] Finally, the establishment of standardized testing protocols across laboratories will ensure reproducible performance metrics, thereby fostering confidence among manufacturers, investors, and regulators.

6. Conclusion

Inorganic perovskite solar cells (PSCs) have rapidly emerged as a promising class of photovoltaic devices due to their high power conversion efficiencies, excellent optoelectronic properties, and potential for low-cost fabrication. Over the past decade, their efficiency has advanced from below 10% to over 20%, bringing them closer to competing with established silicon technologies. At the same time, remarkable progress has been made in improving their chemical stability through compositional engineering, phase stabilization, interface optimization, defect passivation, and advanced encapsulation strategies.

Despite these achievements, challenges remain—particularly in mitigating phase instability, suppressing ion migration, and ensuring long-term durability under realistic environmental conditions. The thermodynamic instability of the α-phase $CsPbI_3$, moisture and oxygen sensitivity, and interfacial degradation continue to limit outdoor performance and large-scale deployment. Moreover, the reliance on lead raises environmental and health concerns, making Pb-free alternatives and recycling strategies an urgent research priority.

Looking ahead, the integration of inorganic PSCs into tandem solar architectures, flexible devices, and building-integrated photovoltaics presents exciting opportunities. For industrial commercialization, however, stability standards equivalent to 20–25 years of operation must be achieved, alongside scalable, reproducible, and eco-friendly manufacturing processes.

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