The Academic
International Journal of Multidisciplinary Research

An Online Peer Reviewed / Refereed Journal
Volume 4 | Issue 2 | February 2026
ISSN: 2583-973X (Online), SJIF IF: 5.6
Website: www.theacademic.in

Perovskite Solar Cells: Progress, Challenges, and Future Prospects

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DOI : https://doi.org/10.5281/zenodo.18950492

ARTICLE DETAILS

Research Paper

Accepted: 25-02-2026

Published: 10-03-2026

Keywords:

Perovskite Solar Cells, Solar Energy, Optoelectronics, Photovoltaic Technology.

ABSTRACT

Metal halide perovskite solar cells (PSCs) are a new type of solar cell, having been around for less than 10 years. The unique optoelectronic properties of these materials made this big step forward possible. Some of these are the ability to process solutions at low temperatures, long carrier diffusion lengths, tolerance for defects, and strong light absorption. PSCs have a lot more work to do to keep their operations stable, make sure the environment is safe because of lead content, cut down on losses from interfacial recombination, and make their products scalable for use in industry, in addition to these successes. Another issue is making production in factories scalable. This review talks about the technical progress that has been made in the chemistry of perovskite materials, device architectures, fabrication strategies, interface engineering, and ways to make them more stable. It has a lot of facts about these new things. This study is only looking at a few places. Some of these areas include how perovskite-silicon and all-perovskite tandem solar cells perform in real-world conditions, the most recent improvements in these types of solar cells, and the technical and economic factors that affect their large-scale use.

1. Introduction

Perovskite solar cells (PSCs) have shown an unprecedented rise in power conversion efficiency since the first report of perovskite materials as light absorbers in dye-sensitized solar cells in 2009(Fig. 1). This is because they have great optoelectronic properties, a tunable bandgap, long carrier diffusion lengths, and can be made in solution at low temperatures. [1–5] Researchers from all over the world are interested in PSCs. The swift advancement of device architectures, compositional engineering, and interface passivation has enabled the attainment of efficiencies akin to those of crystalline silicon photovoltaics [3, 4, 11, 18, 21]. The fact that major issues like long-term operational stability, sensitivity to moisture and temperature, ion migration, lead toxicity, and scalable manufacturing have not been solved, even though progress has been made, makes it hard to sell the product on a large scale [12,24,34,38,40]. This review looks closely at how perovskite solar cells have come along, what problems they face, and what their future looks like. We carefully look at the chemistry of materials, the physics of devices, the ways that things break down, and the steps that make industrial use easier [7,10,37,40].

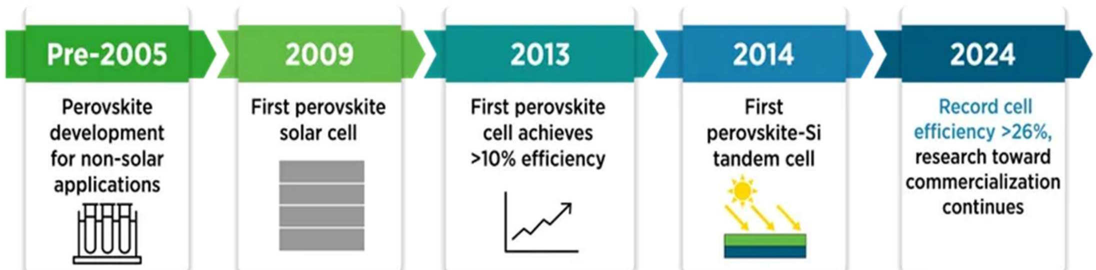

Fig. 1. Schematic timeline of key breakthroughs in perovskite solar cell development, from non-photovoltaic applications to high-efficiency tandem devices.

2. Perovskite materials: structure and optoelectronic properties

The ABX_3 crystal structure is what most metal halide perovskites used in solar devices have. The A-site cation, which is usually methylammonium, formamidinium, or cesium, is in a big space made up of BX_6 octahedra that share corners [8,10,17]. This simple but flexible structure is very helpful for figuring out how stable and well-performing perovskite materials work.

The Goldschmidt tolerance factor is a common way to see if a certain composition can make a stable perovskite phase. It is also common in perovskite research to make structures more stable so that they don't break apart into different phases [4,9,19].

Metal halide perovskites have a special set of optoelectronic properties that make them great at turning light into electricity. They are also good for the building. These materials are good at absorbing light, have low exciton binding energies that make it easier to separate charges, and can move holes and electrons over long distances. These are the main reasons why the efficiency of perovskite solar cells' power conversion went up so quickly [10,16,18,29]. In addition, the precise bandgap tunability in the range of approximately 1.2–2.3 eV that can be achieved through halide and cation substitution makes it possible to optimize perovskite absorbers for applications in single-junction as well as tandem solar cell applications [11,18,20,22].

Mixed-cation and mixed-halide compositions, such as FA/Cs/MA and I/Br alloyed systems, have demonstrated the ability to prevent phase segregation while enhancing thermal and operational stability [8,9,33,35,39]. Still, intrinsic point defects, ion migration phenomena, and phase instability are big problems at the material level. These things cause current-voltage hysteresis and make devices less stable and reliable over time [12,19,36].

3. Device architectures and charge transport layers

In spite of the fact that there are numerous approaches to the production of perovskite solar cells, the most prevalent designs are planar and mesoporous. Both the standard design (n–i–p) and the flipped design (p–i–n) for these devices are the two primary variants that are available [2,3, 25]. There is a difference in the order of the layers that are responsible for moving the charge. The n–i–p arrangement requires electrons to first pass through an electron-transport layer, which could be made of a material such as TiO_2 or SnO_2. Material such as spiro-OMeTAD or PTAA is then penetrated by holes. When it comes to moving electrons, inverted perovskite solar cells make use of materials such as NiO_2 or PEDOT: PSS. On the other hand, PCBM, which originates from fullerene, is applied to move holes [13,23,41]. Depending on the particular device architecture that is utilized, the performance of perovskite solar cells is highly dependent. The ability to create devices employing low-temperature processing methods, hysteresis in the current-voltage connection, and charge recombination at the interfaces are all some of the major things that are impacted by this phenomenon [23,25].

The energy at the interface of the transport layers, the choice of carriers, and the chemical stability have a big effect on the open-circuit voltage and fill ratio. These three pieces are very similar. Recent studies have concentrated on developing transport layers that eliminate the necessity for dopants by utilizing inorganic materials instead. Later studies looked into how to make monolayers that put themselves together. The goal of these projects is to improve the system and help it move forward [13,26,31,41,46].

4. Fabrication method and film formation

In labs, people often use solution-based methods like spin coating with antisolvent dripping to make perovskite thin films that work very well [14,30]. Researchers have been able to make small films with fewer pinholes and much lower defect densities by using solvent engineering, adding chemicals, and controlling the temperature [14,17,30]. This has been made possible by carefully controlling how crystals grow and nucleate.

People are looking into scalable deposition methods like inkjet printing, roll-to-roll processing, blade coating, and slot-die coating as ways to make things bigger than just small-area devices (Fig. 2). These techniques work well for making things in big spaces and with a lot of throughput [7,47]. Also, vapor-based methods like dual-source evaporation and hybrid vapor deposition make films very even and let you control exactly what goes into them. They are great for making things in factories, but it costs more to set them up and run them [6,40].

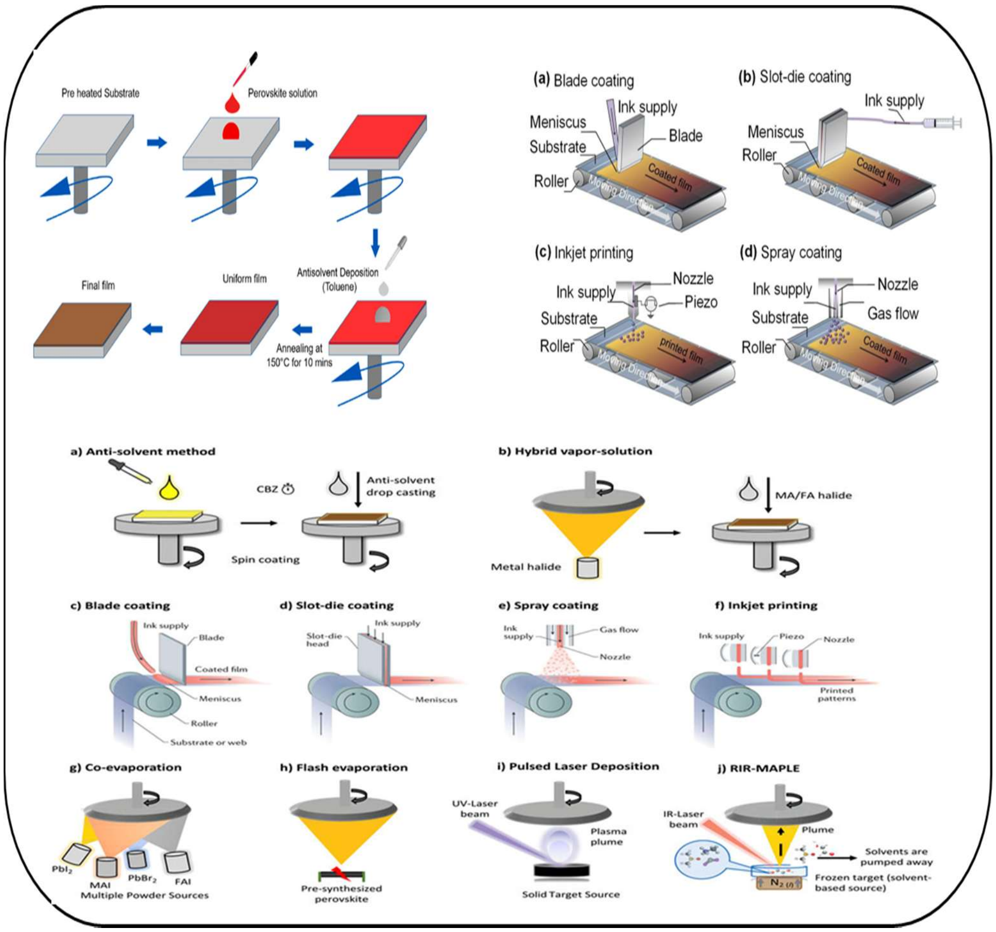

Fig. 2. (a) Solution-processed perovskite thin-film deposition using spin coating and antisolvent engineering for high-quality small-area devices; (b) Scalable printing and coating suitable for large-area and high-throughput manufacturing; (c) Vapor-based deposition approaches providing excellent uniformity and compositional control for industrial fabrication.

5. Photovoltaic performance: Efficiency record and trends

Independent labs [1,6,21] say that the power conversion efficiency of perovskite solar cells has gone up a lot, from about 3.8% in 2009 to more than 25% for single-junction devices. This progress is due to recent changes in the composition of materials, interface passivation, and the reduction of non-radiative recombination losses [11,26,41].

The Shockley–Queisser limit of single-junction cells has been surpassed by tandem structures that combine perovskites and silicon. These architectures have achieved efficiencies that are greater than thirty percent in laboratory demonstrations [20,44,48]. The translation of laboratory performance into steady module operation continues to be a key challenge [38,40], despite the fact that record efficiency has been achieved.

6. Degradation mechanism and stability strategies

There are a number of factors that might cause perovskite solar cells to degrade, including moisture, oxygen, heat, UV light, and electrical bias [20,34]. While the perovskite lattice is hydrolyzed when exposed to moisture, ion migration and interfacial processes are accelerated when exposed to thermal stress and light [32,36]. Furthermore, deterioration in conventional designs is made worse by the photocatalytic activity of TiO2 that is caused by ultraviolet light [34].

The insertion of two-dimensional perovskite capping layers, defect passivation, and enhanced encapsulation methods are some of the advanced stability enhancement strategies [9,31,34,38]. Compositional engineering, also known as combining Cs and FA, is another strategy. [38] In order to provide an accurate performance evaluation, standardized stability testing techniques, such as ISOS (International Summit on Organic Solar Cells), are becoming increasingly popular.

7. Interface engineering and defect passivation

At grain boundaries, interfacial recombination and defect states are two of the most important loss routes in perovskite solar cells [12,26]. The use of Lewis bases and acids, fullerene derivatives, polymers, and self-assembled monolayers by means of chemical passivation has been demonstrated to be successful in lowering trap densities and increasing carrier lifetimes [26,31,43,46].

Open-circuit voltage and operational stability are greatly improved by optimized interfaces [13,41,46]. Optimized interfaces also make energy levels more aligned, stop non-radiative recombination, and raise power levels by a lot. Because of this, interface engineering is considered to be an essential component of a PSC design that maximizes efficiency and maintains stability [11,37].

8. Tandem and multijunction devices

Perovskite materials are great for use in tandem photovoltaics because they can be made at low temperatures and have a wide range of band gaps [20,44]. But all-perovskite tandems could lead to applications that are light and flexible [44,48]. Perovskite–silicon tandems are presently the most common type of tandems in research. Current matching, stability in the interconnection layer, and long-term reliability are three of the most important difficulties [20,45].

9. Lead toxicity, environmental impact, and lead-free alternatives

The inclusion of lead in high-performance perovskites modifies the fundamental principles and their surroundings. Numerous concerns stem from defective devices and products that must be disposed of upon failure. Numerous persons assert that lead-sequestering layers, recycling methods, and encapsulation can inhibit lead from leaching [27, 38, 40].

Despite the fact that there have been investigations into lead-free alternatives that make use of tin, germanium, and double perovskites, these alternatives now exhibit lower levels of efficiency and worse stability in comparison to lead-based systems [28,29]. Continuous innovation in materials is an absolute requirement if we are going to be able to close this performance gap [27,37].

10. Scale-up, module fabrication, and manufacturing

Perovskite solar cells have several problems when transitioning from laboratory devices to large-area modules that must be addressed. Film uniformity, fault tolerance, and yield are among the issues addressed here. Current investigations are actively focusing on methodologies such as laser scribing, enhanced encapsulation, and scalable coating techniques for the purpose of module integration, for example [7,47].

Researchers have shown that perovskite photovoltaics could help cut the cost of electricity over time. This will happen if the appropriate conditions are satisfied for long-term stability. The published observations [6,40] demonstrate that the industry is exhibiting an increasing interest in pilot production lines.

11. Characterization techniques and standards

A comprehensive characterization of perovskite solar cells utilizes structural, optical, and electrical methodologies, including X-ray diffraction (XRD), scanning electron microscopy (SEM), photoluminescence/transient photovoltage (PL/TRPL), impedance spectroscopy, and transient photovoltage evaluations [19,29,41]. Standardized tests for performance and stability are necessary to ensure that results are reproducible and comparable among laboratories [21,38].

12. Commercialization landscape and techno-economic considerations

Several companies and industrial organizations are working to make perovskite photovoltaics usable in buildings, portable devices, and other places [40]. Techno-economic studies show that production costs may not be very high, but problems with stability and certification could make things harder [6,40].

13. Challenges and Research Priorities

Perovskite solar cells could be very useful, but there are still a lot of basic and technical issues that need to be fixed before everyone can use them. At the material level, ion migration, phase instability, and defect-mediated non-radiative recombination make devices less reliable over time, especially when they are under stress from heat, light, and electrical bias [12,24,36,38].

One of the main reasons why performance gets worse over time is that the interface between the perovskite absorber and the charge transport layers is unstable [13, 41, 46].

From the standpoint of devices and production, primary research objectives include verifying the product's compatibility with diverse substrates, augmenting its durability to endure processing variations, and formulating encapsulation techniques that preserve its stability over time [7,40]. We need to find a way to make perovskite absorbers that work just as well as the ones we already have, but without lead, which is bad for the environment and against the law [27,28,37]. We need to make progress in a lot of areas at once, like life-cycle evaluation, standardized testing methods, materials chemistry, and device engineering, to fix these problems.

14. Future Prospects and Outlook

In the near future, perovskite solar cells are expected to enter niche markets, such as building-integrated applications and indoor photovoltaics [42,49]. Perovskite-silicon tandems are likely to be very important for the next generation of high-efficiency photovoltaics in the medium to long term, as long as problems with durability and the environment are solved [44,48,49,50].

15. Conclusion

Using perovskite solar cells could help us learn more about science and technology in a unique way. Photovoltaic (PV) systems, especially powered solar cells (PSCs), are going to be very important for the world's energy needs. They can be used as lightweight, low-cost modules in some cases, or as high-efficiency tandem combinations with silicon. It is possible to use both. This is because there is more research being done on making things in a way that is safe for the environment, scalable, and consistent.

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