INFORMATICS JOURNALS
The Journal of Electrochemical Society of India, Volume 75, Issue (1&2), January-March 2026; pp. 12–31
ISSN (Print) : 0013-466X
ISSN (Online) : xxxx-xxxx
DOI: 10.18311/JESCI/2026/55809

Next Generation Photovoltaics: A Review of Perovskite Fabrication, Degradation, and Future Avenues

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Abstract

In just over ten years, Perovskite Solar Cells (PSCs) have gone from a lab experiment to a massive breakthrough in clean energy. Their efficiency numbers have climbed so fast that they are now a real threat to traditional silicon panels. This review breaks down that progress, explaining how these cells actually work, the different ways we can build them in a lab, and the big hurdles, like stability and toxic materials, that we still need to clear. It's a straightforward look at where the technology stands today and what it will take to get these panels onto our roofs finally. It begins with the key milestones that shaped PSC evolution, highlighting the unique properties of perovskite materials, progress in device architecture, and compositional modifications that enhanced performance. The fundamental chemistry and structure of perovskites and the representative PSCs with regular mesoscopic structure, planar structure, and inverted (planar) structure are also discussed, along with commonly used synthesis approaches such as spin coating, doctor blading, inkjet printing and screen printing. The review further emphasises the major challenges limiting PSC commercialisation, particularly their poor long-term stability caused by exposure to humidity, light, and heat. Finally, this paper outlines future directions in perovskite research and explains how continued innovation could enable highly efficient, low-cost, and flexible solar devices capable of transforming the renewable energy landscape.

Keywords: Band Gap Tuning, Efficiency Stability, Fabrication Techniques, Interfacial Engineering, Power Conversion Efficiency (PCE)

1. Introduction

Due to rapid population growth, industrial development, and technological progress, it has been a major challenge for energy sources in the 21st century. Because of this, traditional sources like fossil fuels have been used for a long time as a source of power. However, the excessive use of fossil fuels led to various serious problems like air pollution, global warming and depletion of natural resources. So, to overcome this, we can shift towards cleaner and more sustainable energy sources, as they are the best way to prevent various issues that have arisen due to traditional energy sources. Among all the alternatives, solar energy stands out as one of the best options because sunlight is abundant, renewable, and nearly endless. In recent decades, the solar energy field, especially the PV industry, has developed rapidly. Silicon-based solar cells have become the most widely used because of their high efficiency and reliability. Over time, PV technologies have gone through different generations, each using new materials, improved manufacturing methods, and achieving higher efficiency levels[1].

1.1 Milestones: A Decade of Unprecedented Progress

The development of PSC technology has its roots in the 19th century, beginning with the discovery of naturally occurring perovskite minerals. In 1839, Gustav Rose identified the mineral calcium titanate ($CaTiO_3$), which was later named "perovskite" in Honor of the Russian mineralogist Lev A. Perovski[2]. Later studies revealed

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that several other inorganic metal oxides, such as barium titanate ($BaTiO_3$), lead titanate ($PbTiO_3$), and strontium titanate ($SrTiO_3$), also shared this same crystal structure. These materials attracted great scientific interest because of their unique electrical and physical properties, such as ferroelectricity and piezoelectricity, which made them useful in devices like dielectrics and pyroelectrics. However, despite these advantages, they were not suitable for PV applications because of their poor semiconducting properties[3].

The next major step in the history of perovskites took place in 1893, when Wells and his team of researchers successfully synthesised lead halide compounds of the type $CsPbX_3$ (where X = Cl, Br, or I). Later, in 1957, C.K. Moller continued this research and reported that similar perovskite structures were also found in compounds such as $CsPbCl_3$ and $CsPbBr_3$, which drew further scientific interest toward the chemistry of perovskites[4]. A major breakthrough came in 1978 when D. Weber discovered that an organic ion, methylammonium ($CH_3NH_3^+$), could replace caesium (Cs^+) in these halide structures to form methylammonium lead halides ($CH_3NH_3MX_3$, where M = Pb or Sn, and X = I or Br). This finding introduced the concept of organic–inorganic hybrid perovskites[5].

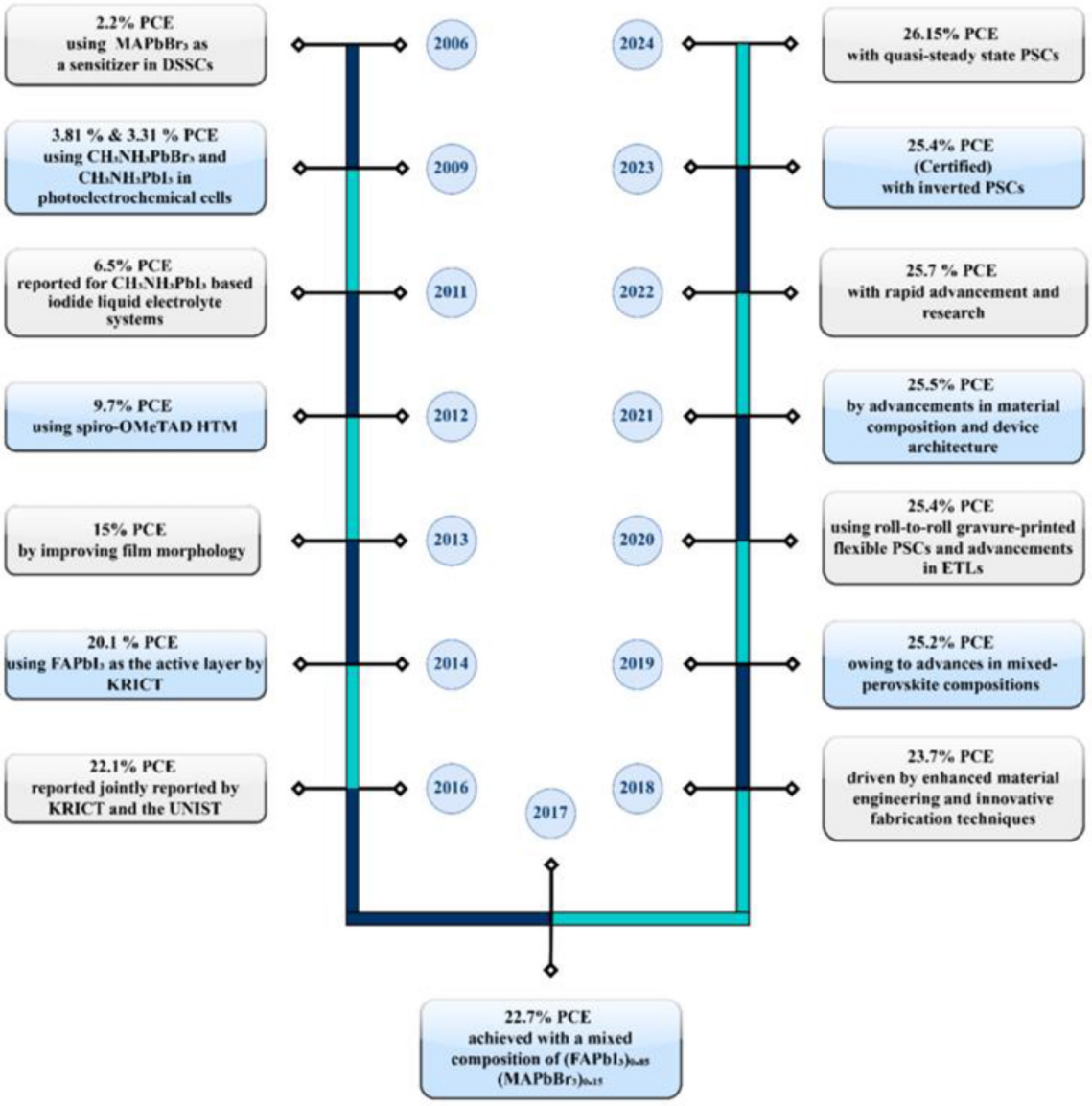


Figure 1. Timeline showing the advances in PCE of PSC from 2006 to 2024.

Source: Afroz *et al.*[64]

In the late 1990s, David Mitzi expanded this research by designing new halide perovskites containing both small and large organic cations, leading to the development of two-dimensional (2D) and three-dimensional (3D) perovskite structures. However, the true potential of perovskites for solar energy applications was not realised until the early 2000s. In 2005, initial studies on using perovskite materials for solar cells began in the laboratory of Tsutomu Miyasaka at Toin University, Japan. At that time, the term "perovskite" mainly referred to metal oxides known for their ferroelectric and piezoelectric behaviour. The turning point came in 2009 when Miyasaka and his team used an organic lead-halide perovskite, methylammonium lead iodide ($CH_3NH_3PbI_3$), as a light-absorbing material in a dye-sensitised solar cell. Although the initial power conversion efficiency was only about 3.8%, this achievement sparked global research interest and marked the beginning of the rapid advancement of perovskite-based solar technologies[6].

The progress of PSCs has been remarkable since their discovery, showing continuous improvement in Power Conversion Efficiency (PCE) and material design, as illustrated in Figure 1. The evolution of power conversion efficiency (PCE) in perovskite solar cells has been widely studied.

In 2006: The first reported PSC achieved a PCE of 2.2% using methylammonium lead bromide ($MAPbBr_3$) as a sensitiser in Dye-Sensitised Solar Cells (DSSCs). This result laid the foundation for future perovskite-based PV research[7].

By 2009: Kojima and colleagues demonstrated the use of organic lead halide perovskites—$CH_3NH_3PbBr_3$ and $CH_3NH_3PbI_3$ in photoelectrochemical cells, achieving efficiencies of 3.81% and 3.13%, respectively. This work officially introduced perovskites into solar energy studies[8].

In 2012: A major leap occurred when solid-state DSSCs were developed, pushing the PCE to 9.7%. The improvement came from using spiro-O Me TAD as a Hole Transport Material (HTM), which offered better stability than traditional liquid electrolytes[9].

By 2014: Researchers at the Korean Research Institute of Chemical Technology (KRICT) achieved a certified efficiency of 20.1% using Formamidinium lead iodide ($FAPbI_3$) as the light-absorbing layer. This breakthrough was verified by the National Renewable Energy Laboratory (NREL) and marked a major milestone in PSC development[10].

In 2018: The record efficiency rose to 23.7%, driven by advancements in material chemistry and fabrication techniques such as caesium doping, which improved both performance and long-term stability[11].

By 2019: Further innovations in mixed-perovskite compositions enhanced light absorption and charge movement, raising the record PCE to 25.2%[11].

In 2020: Progress in roll-to-roll gravure printing and new Electron Transport Layer (ETL) designs led to flexible PSCs with a record PCE of 25.4%, showing potential for large-scale manufacturing[12].

By 2021: The highest verified efficiency increased slightly to 25.5%, supported by improved material compositions and advanced heterojunction device structures, bringing PSCs closer to their theoretical limits[13].

In 2023: Inverted PSCs reached a certified PCE of 25.4%, with continued progress in mini-modules and large-area device fabrication[14].

By 2024: The quasi-steady-state PSC achieved an impressive 26.15% PCE, maintaining 95% of its original efficiency after 1200 hours of continuous operation, showing great advancements in both efficiency and stability[15].

Overall, these milestones reflect the tremendous progress achieved in PSC research over the past decade. The steady rise in efficiency is a result of innovations in material composition, interface engineering, transport layers, and fabrication processes. The transition from liquid to solid-state devices, along with the optimisation of electron and hole transport layers, has greatly improved both performance and durability. With ongoing progress in mixed perovskite materials, dopant-free layers, and scalable production methods, PSCs are now among the most promising technologies for next-generation solar energy.

1.2 What are PSC?

Perovskite Solar Cells are the 3rd generation solar cells that have attracted widespread research and commercialisation because of their high efficiency, tunable bandgap and low production cost. The term 'Perovskite' was specifically originated to describe the natural mineral having the chemical formula *'$CaTiO_3$'*. However, today it represents a broad class of materials that share a similar crystal structure, known as the *ABX_3 structure*[16]. Figure 2 shows the schematic of the ABX_3 perovskite structure, with representative as a PSCs.

In this structure:

- The **A-site** is usually occupied by a monovalent cation such as $CH_3NH_3^+$ (methylammonium or MA^+), $NH_2CH{=}NH_2^+$ (Formamidinium or FA^+), Cs^+, or Rb^+.
- The **B-site** contains a divalent metal cation, typically Pb^{2+}, Sn^{2+}, or Ge^{2+}.
- The **X-site** is filled by a halide anion such as I^-, Br^-, or Cl^-.

In the perovskite crystal, the B-site metal ion is surrounded by six halide ions, forming an octahedral (BX_6) structure. These octahedra share corners with one another, while the A-site cations occupy the spaces between them. This arrangement gives perovskites their distinctive three-dimensional crystal structure, where each A-site cation is surrounded by twelve halide ions[17,18].

Perovskite Solar Cells (PSCs) are capable of transporting both electrons and holes, which allows them to be designed in three main configurations based on their application needs: the conventional *(n–i–p) mesoporous structure*, the *(n–i–p) planar structure*, and the *inverted (p–i–n) planar structure.*

The *mesoporous structure* of PSCs is inspired by the traditional design of DSSCs. In this design, the mesoporous layer usually acts as the ETL and is commonly made from materials like Titanium Dioxide (TiO_2). Sometimes, insulating materials such as Aluminium Oxide (Al_2O_3) or Zirconium Oxide (ZrO_2) are also used[19]. The mesoporous ETL forms close contact with the perovskite layer, helping in the efficient transfer of photogenerated electrons. It also serves as a framework that supports the crystallisation and uniform growth of the perovskite film.

When insulating materials are used as the mesoporous layer, they can reduce unwanted charge recombination by blocking the movement of charges between the perovskite and the transport layer. This helps improve the *open-circuit voltage* (Voc) of the device. Although mesoporous PSCs have achieved PCEs above 25%, their fabrication process is quite complex, especially the formation of dense and mesoporous TiO_2 layers, which increases production costs and makes them less suitable for flexible or wearable applications. Additionally, TiO_2 shows strong photocatalytic activity under UV light, which can degrade the device over time and reduce its stability[20,21].

In contrast to mesoporous designs, Planar PSCs do not include a mesoporous layer. Instead, they use a thin and compact ETL often made of oxide materials onto which the perovskite layer is directly deposited. This structure reduces the thickness of the underlying transport layer, which helps shorten the distance that charge carriers need to travel. As a result, there is less energy loss from unwanted light absorption, and the perovskite layer can more effectively capture incident light. Planar structures also produce smoother perovskite films, which improves the interface contact between layers. Because of their advantages, Planar n-i-p PSCs are widely used configurations, and because of their design, many record-breaking efficiencies have been achieved[22].

In *Inverted (p–i–n) PSCs*, the Hole Transport Layer (HTL) is put on the bottom first, meaning it sits underneath the Perovskite absorber. Because of its compatibility, this design is popular. A diverse set of HTL materials researchers can use because of this setup. Organic compounds such as PEDOT: PSS and Poly(triphenylamine) (PTAA) can be used, and inorganic materials like NiOx, CuO and CuSCN can be used. A very popular choice right now is Nickel oxide (NiOx). Because it doesn't break down easily, and it works perfectly if you want to stack a perovskite cell on top of a traditional

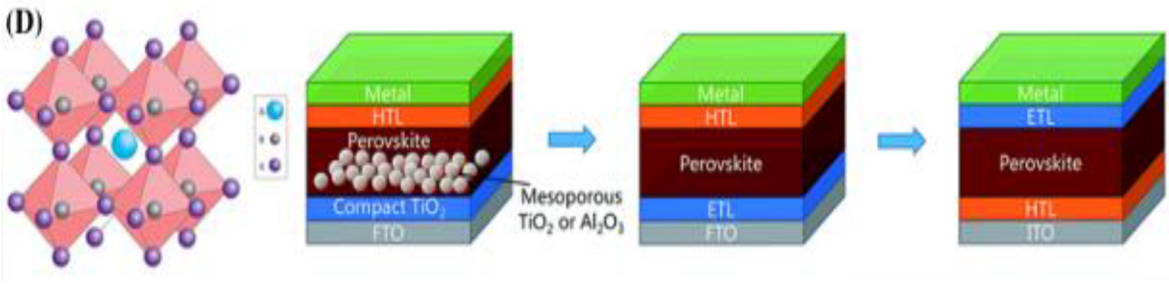


Figure 2. Schematic of the ABX_3 perovskite structure and the representative PSCs with regular mesoscopic structure, planar structure, and inverted (planar) structure.
Source: Ju *et al.*[65]

silicon cell to make a highly efficient Tandem device. Hence, researchers love to work with it[23,24].

Even though these cells are getting more efficient day by day, we still have some serious problems to solve. First, these cells use Lead for better performance, which is poisonous and hazardous to the environment if it leaks. Second, these cells are considered very 'sensitive', meaning if they get too hot, too wet or stay in the sun for a longer time, they can fall apart. So, this makes them lose their power very quickly. To improve the stability and efficiency of perovskite materials, this has become one of the core research areas that can be studied by researchers for making PSCs more reliable and also making them safer for planet[25].

1.3 Fundamental Properties of PSC

Because of their various unique properties (Figure 3) makes Perovskite is special. Making them excellent for PCE and for producing maximum voltage. These include a high light absorption coefficient (greater than $10^4 cm^{-1}$), long charge-carrier diffusion lengths, moderate carrier mobility, high defect tolerance, and slow charge recombination rates. Research indicates that these exceptional features may be linked to factors such as the material's intrinsic ferroelectric properties, bulk PV effects, surface electric fields, carrier-lattice interactions, and the formation of large polarons[26]. To fully understand the outstanding performance of PSCs, it is important to study the fundamental crystal structure, chemical composition, and intrinsic material properties of perovskites, as these aspects are key to explaining their remarkable optoelectronic behaviour.

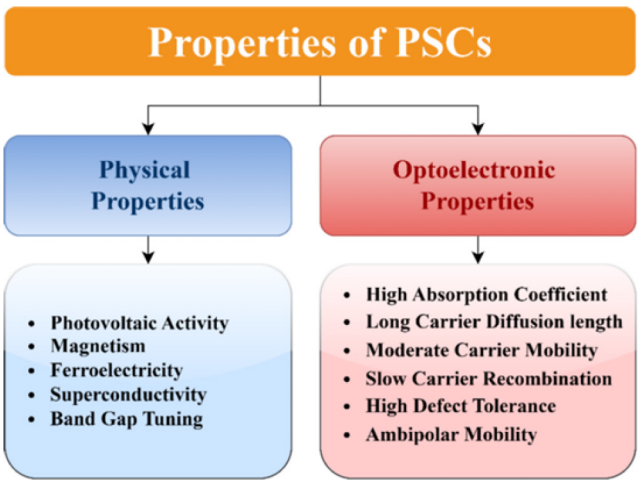


Figure 3. Fundamental properties of PSCs.
Source: Afroz *et al.*[64]

1.4 Working of PSCs

In the early stages of research, PSCs were thought to function similarly to DSSCs. Initially, perovskite materials were deposited onto a mesoporous TiO_2 layer within a liquid electrolyte setup. It was believed that when light struck the perovskite layer, electrons would become excited and then transfer into the TiO_2 layer, following a pathway similar to that observed in DSSCs[27]. Because perovskites were so new at that time, everyone assumed they needed this specific structure to work, not realising yet that Perovskites were far more powerful.

However, as research progressed, scientists realised that PSC work in a very different way. Unlike older cells, PSCs don't actually need a TiO_2 structure to move electrons. Instead, the Perovskite material is so efficient in such a way that electrons and holes travel freely on their own (Figure 4). This shifted the entire field's perspective, and this is exactly what allowed researchers to push their efficiency to the record-breaking levels we see today.

Another remarkable characteristic of PSCs is their high Voc. In conventional solar cells, Voc is primarily determined by the difference in the work functions of

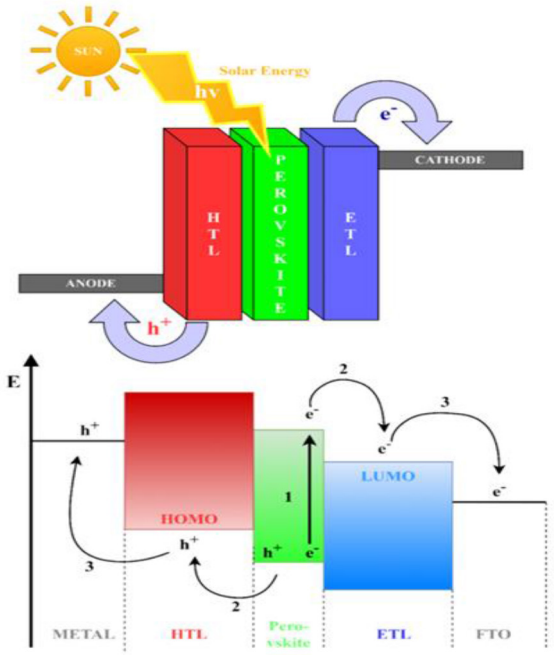


Figure 4. Basic working of a perovskite solar cell. Hole Transport Layer (HTL), Electron Transport Layer (ETL), Fluorene doped Tin Oxide (FTO), Highest Occupied Molecular Orbital (HOMO), Lowest Unoccupied Molecular Orbital (LUMO).
Source: Afroz *et al.*[64]

the contact materials. However, PSCs display high Voc and impressive efficiency due to their intrinsic material properties, including strong optical absorption, long charge-carrier diffusion lengths, and very low rates of electron-hole recombination. These exceptional features distinguish PSC from other PV technologies[28].

2. Materials for PSC

Choosing the right materials is the most important step in building a high-performance PSC. Beyond just efficiency, the choice of materials not only dictates the device's durability but also determines if the cell will last for years and how much it will cost to manufacture. If we look closely at each layer, we can understand how much material choice matters to improve long-term performance.

2.1 Charge Transport Layers (CTLs)

The Charge Transport Layers (CTLs) are vital components that manage the flow of electricity. When light hits the Perovskite layer, it creates charge carriers (electrons and holes). This Charge Transport Layer act as a specialised pathway that extracts these charges and helps them move to the electrodes.

To work well, the Charge Transport Layer must have high electrical conductivity and needs to be 'transparent' so that light can easily pass through it. If the energy levels don't match up with the Perovskite layer, it will significantly reduce the efficiency[29].

These are categorised based on two types of electrical charges (electrons and holes) they create:

(i) Electron Transport Layer (ETL)

(ii) Hole Transport Layer (HTL)

(i) Electron Transport Layer (ETL)

In a PSC, the ETL is responsible for extracting negatively charged electrons and moving them towards the electrode.

For this to work, the energy level of the conduction band should align perfectly with the Perovskite layer so that electrons can slide across easily. Figure 5 shows the Energy level representation of some of the most commonly used ETLs.

So, ETL should be in such a way that it needs to be tough and environmentally stable, meaning that it can prevent it from degradation due to heat, oxygen, or moisture. It should also be 'solvent resistant' so that it doesn't dissolve while building up the solar cell.

Using a good ETL can even fix 'J-V Hysteresis', which is a common glitch that makes it hard to measure how much power a cell can actually produce. While there are many different materials to choose from, the goal is always to find thin and smooth ETL to keep the cell efficient and prevent recombination[30].

The materials used as Electron Transport Layers (ETLs) are generally classified into two categories: Inorganic and organic materials. Each type has its own unique properties, advantages and applications. Table 1 enlists the Common Electron Transport Layer (ETL) materials used in PSC.

(a) *Inorganic ETLs*

Many scientists prefer using metal oxides as Inorganic ETLs due to their unique properties. Because of their toughness, it provides higher electrical charge so that electrons can move easily. These materials are well-suited for long-lasting and efficient solar cells.

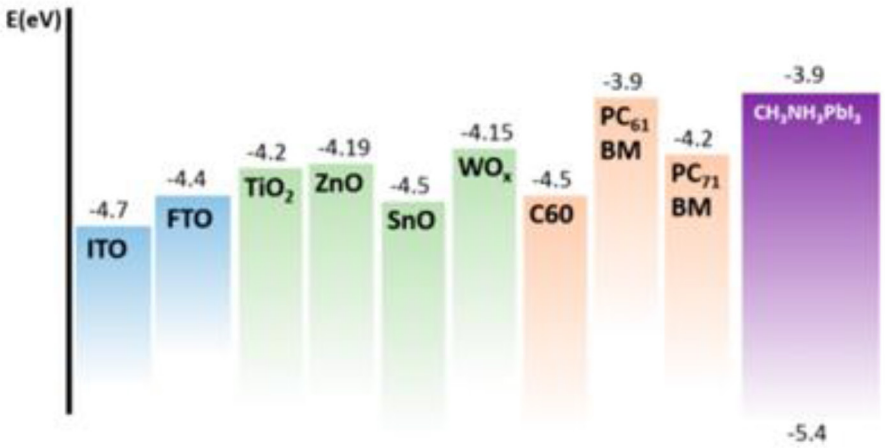


Figure 5. Energy level representation of some most commonly used ETLs.

Source: Kim *et al.*[66]

(b) *Organic ETLs*

Organic ETLs have gained attention because they can be easily processed at low temperatures and their electronic properties can be tuned through chemical modification. Depending on their molecular structure, they are generally classified into fullerene-based and non-fullerene-based materials. These organic ETLs are lightweight, flexible, and compatible with a variety of fabrication methods, making them ideal for flexible and printable solar cell applications[31].

(ii) Hole Transport Layer (HTL)

In PSCs, Hole Transport Materials (HTMs) form an important connection between the perovskite layer and the anode. Their main role is to collect holes (positive charge carriers) generated in the perovskite layer and transfer them efficiently to the anode, while also preventing electrons from recombining with holes. Table 2 lists Common HTL materials used in PSC.

Types of HTMs

HTMs are generally grouped into three main types based on their composition:

(a) Organic materials
(b) Inorganic materials
(c) Carbon-based materials

Each type has distinct properties that affect the efficiency, stability, and cost of PSCs.

Organic HTMs

Organic HTMs are widely used in PSCs because they can be easily customised at the molecular level, have adjustable energy levels, and are compatible with solution-based, low-temperature fabrication methods. These materials are mainly divided into small-molecule HTMs and polymer-based HTMs, each with its own advantages and drawbacks[32].

(i) Small-Molecule Organic HTMs

These are like engineered building blocks. Because of their well-defined chemical structures, scientists find them much easier to purify and characterise. When applied to solar cells, they form a smooth and uniform layer. This is what allows the cell to pull 'holes' out of Perovskite so easily. The most common examples are 'Spiro- OMeTAD' and 'PTAA', which are widely used in cells to enhance stability and efficiency[33].

(ii) Polymer-based HTMs

These are like long, flexible chains. Most common examples are P3HT and PEDOT: PSS. Because of their flexible nature, they can act as a protective layer for PSCs by preventing their interfacial defects and improving mechanical strength. And this flexibility allows researchers to explore and find better Hole Transport Materials (HTMs)[34].

(a) *Inorganic HTMs*

From the name itself, we can conclude that they are made from Inorganic minerals or metal oxides. They are highly stable under heat, oxygen or moisture, meaning they cannot break down easily. Despite their advantages, it has some challenges, such as being a bit stubborn to work

Table 1. Common Electron Transport Layer (ETL) materials used in PSC.

Material	Advantages	Limitations	Typical processing temp.	Remarks/Notes
TiO_2 (Titanium Dioxide)	Stable, good band alignment, widely studied	Requires high sintering temp (~450–500°C), slower electron mobility	High (~450–500°C)	Early benchmark ETL, mostly mesoporous PSCs
SnO_2 (tin oxide)	High electron mobility, smooth interface, low-temperature processable	Sensitive to surface defects	Low (<150°C)	Popular in planar PSCs; enables flexible devices
ZnO (zinc oxide)	Easy to synthesise, transparent, and low temperature	Reacts with perovskite, causing degradation	Low (~100°C)	Often modified or doped to improve stability
PCBM (phenyl-C_{61}-butyric acid methyl ester)	Excellent for low-temperature processing, compatible with organic layers	Costly, less stable under heat	Room temp/ solution process	Common in inverted (p–i–n) architectures
TiO_2– SnO_2 composite	Combines the stability of TiO_2 and the mobility of SnO_2	Complex synthesis	Moderate (~200°C)	Hybrid ETL improves charge extraction and device lifetime

with. It is often harder to get them to form a perfectly smooth layer, which is why their energy levels can differ from the Perovskite layer. Figure 6 shows the energy level representation of some of the most common inorganic HTMs used in PSCs.

Inorganic HTMs are grouped into two categories:

(i) Metal-based HTMs

(ii) Non-metal-based HTMs

(i) Metal-Based Inorganic HTMs

Common examples include NiOx, CuSCN, CuI, and $CuCrO_2$. Because of their high stability and great electrical conductivity, they are widely used. Due to its toughness, it can withstand environmental conditions, preventing degradation. But some of these materials require high temperature, and some don't dissolve easily in liquids. Hence, this makes them a bit challenging[35].

(ii) Non-Metal-Based Inorganic HTMs

Non-metal-based HTMs, like MoOx, WOx, and V2Ox, are promising and emerging HTMs. Unlike some other materials, they are transparent and absorb very little light and can easily pass through the Perovskite layer where it is needed. They also dissolve quickly and provide a smooth layer. On the downside, these materials usually have lower hole mobility and higher trap densities, meaning that they can slow down charge transport and reduce the device's performance[36].

(b) *Carbon-Based HTMs*

Carbon-based materials are another interesting group of HTMs because they are highly conductive, have a large surface area, and show excellent compatibility with the perovskite layer. These materials are also low-cost, stable, and environmentally friendly, making them a strong alternative to traditional HTMs. The most commonly used carbon-based materials in PSCs are carbon black, graphene, and Carbon Nanotubes (CNTs). Each of these has unique advantages: for instance, graphene provides fast charge transport, while CNTs offer mechanical flexibility and durability[37].

3. Fabrication Methods for PSCs

Perovskite Solar Cells (PSCs) have gained a lot of attention because of their high PCE and low manufacturing cost. To make these solar cells, different deposition techniques are used to form smooth and uniform perovskite layers. These methods are mainly divided into solution-based and vapour-based techniques, although some other methods like sol–gel synthesis, electrodeposition, and laser ablation are also used to produce efficient and cost-effective PSCs. The chosen method plays a major role in determining the structure, crystallinity, and smoothness of the perovskite layer, which in turn affects the efficiency, durability, and large-scale production potential of the devices.

3.1 Solution-Based Deposition Techniques

Among all available fabrication methods, solution-based techniques are the most widely used because they are simple, affordable, and suitable for large-scale manufacturing. Some of the most common solution-based deposition methods include spin coating, doctor blading, screen printing, slot-die coating, spray coating, and inkjet printing (Figure 7)[38].

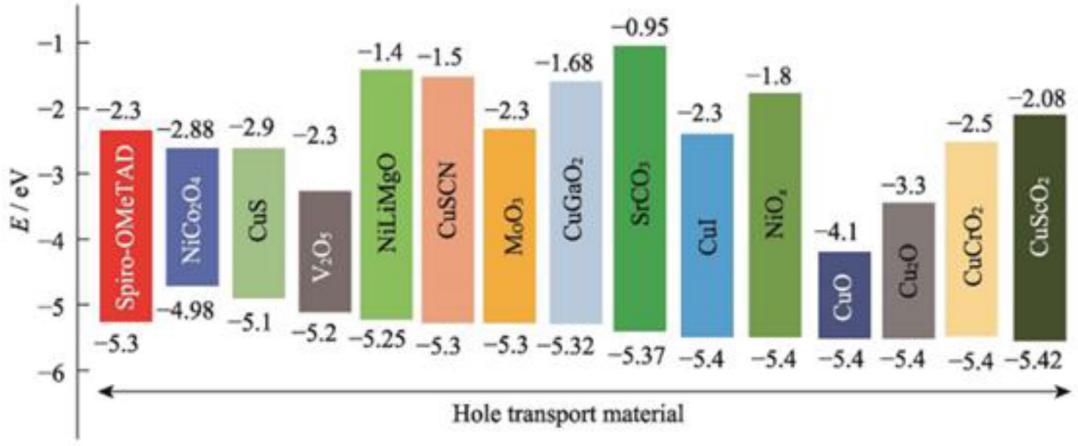


Figure 6. Energy level representation of some of the most common inorganic HTMs used in PSCs. Source: Chen *et al.*[67]

Table 2. Common Hole Transport Layer (HTL) materials used in PSC.

Material	Advantages	Limitations	Typical processing temp.	Remarks/notes
Spiro-O Me TAD	Widely used, good energy alignment, high efficiency	Expensive, requires dopants, hygroscopic	Low (~100°C)	Standard HTL in high-efficiency PSCs
PTAA (Poly[bis(4-phenyl) (2,4,6-trimethylphenyl) amine])	Good stability, solution-processable, compatible with flexible devices	Costly, lower conductivity without doping	Low (~100°C)	Often used in inverted (p–i–n) architectures
NiO (Nickel Oxide)	Inorganic, thermally stable, low-cost	Lower hole mobility requires annealing	Moderate (~200°C)	Used in inverted PSCs for better long-term stability
CuSCN (Copper Thiocyanate)	Transparent, low-cost, high hole mobility	Sensitive to moisture, interface issues	Low (~80–100°C)	Promising for low-temperature, flexible devices
PEDOT: PSS (Poly(3,4-ethylenedioxythiophene) polystyrene sulfonate)	Easy to process, flexible, low-temperature	Acidic, can degrade perovskite	Room temp/ solution process	Common in inverted planar PSCs

3.1.1 Spin Coating

Spin Coating is the most reliable and easiest technique for fabricating solar cells on a small scale. In this method, a precursor solution is deposited onto a substrate. Then the machine is rotated at high speed to achieve a uniform thin layer using centrifugal force[39]. After spinning, the coated film undergoes a process called 'annealing', meaning it is heated at high temperature. Due to this heating, it actually grows crystals on the surface and drives off solvents. As film thickness is highly sensitive to parameters like RPM, acceleration and time, researchers can control it by adjusting its speed.

There are two main ways by which we can perform this:

(a) One-Step Spin Coating

In this method, a single precursor solution contains both lead halide (PbI_2) and methylammonium halide (MAI), and it is deposited onto a substrate and spun to create a film. Although it is a simple process, it can be tricky sometimes to get a uniform film because it usually ends up with tiny holes or patches, which makes solar cells less efficient[40].

(b) Two-Step Spin Coating

In this method, we first put a layer of Lead halide (PbI_2) onto the base. Once it is dried, we add a layer of Methylammonium halide (MAI) onto the top. Because of this, it can produce more uniform and high-quality film[31]. Despite their advantages, the first layer doesn't fully react with the second, leaving behind the presence of unreacted material, which can affect the cell's efficiency.

Even though this method helped researchers to reach an amazing efficiency above 22%, it isn't perfect. Because a large amount of material is wasted during spinning[39].

3.1.2 Doctor Blading

Doctor blading, sometimes just called *blade coating,* is one of the simplest ways to scale up solar cell production. In this process, a sharp, flat blade moves across the surface and drags the perovskite solution along with it to create a perfectly thin, even film. The best part about this method is how efficient it is with materials. Because the blade only uses exactly what it needs to cover the area, you aren't wasting expensive chemicals like you might with other methods. Since it's a continuous process, it fits perfectly into roll-to-roll manufacturing. This makes it a great option for moving PSCs out of the lab and into a real factory. Recent improvements, such as ambient blade coating, have helped improve the film's crystallinity and PCE. However, one major challenge is maintaining film uniformity, especially when coating large substrates[41].

3.1.3 Slot-die Coating

Slot-die coating is another roll-to-roll compatible method used for continuous film deposition. In this technique, the perovskite solution is fed through a narrow slit (die) to form a uniform layer on the substrate. Since the solution stays enclosed inside the system, there is less

risk of contamination. A great example of this in action is the work by *Hwang and his team*. They used a two-step coating process but they used high-pressure nitrogen to basically achieve the film into a smoother state. This little trick helped them get rid of any rough spots and push their efficiency up to around 11.9%. Similarly, Di Giacomo et al. achieved a 16.4% PCE on larger PSC modules (12.5 × 13.5 cm^2), which is close to the efficiency obtained using spin coating. However, controlling solvent evaporation and crystal formation during coating is still critical to ensure high-quality films[42].

3.1.4 Inkjet Printing

Inkjet printing is a digital, contactless technique that allows precise deposition of perovskite precursor solutions onto substrates. It uses very little material, making it cost-efficient with almost no wastage. Specific patterns can be printed directly, removing the need for masks or extra processing steps. Researchers have used inkjet printing to improve PSC performance, for example, adding carbon to the precursor solution enhanced mechanical stability and lifetime, while optimising the substrate temperature improved film morphology and quality[43]. A key challenge in this method is controlling droplet size and merging, as uneven spreading can cause variations in film thickness. Inkjet printing is mainly classified into two types[44]:

Continuous Inkjet (CIJ): It is a high-speed fabrication method where the perovskite solution is pumped in a non-stop, steady stream rather than waiting for a command to spray. To create a pattern, the machine vibrates the nozzle at a very high frequency, which breaks that solid stream into millions of identical, tiny droplets. As these drops fall, a computer gives a specific electrical charge to only the ones needed for the solar cell.

These charged drops are then steered by an electric field to land exactly where they belong on the substrate. Meanwhile, any droplets that aren't needed simply fall straight down into a collection gutter, where they are sucked back into the main tank and recycled. Due to this, it has been a huge advantage for perovskite research because it prevents the chemicals from drying out and clogging the nozzle, a common problem in other printing methods. Plus, by recycling the unused solution, researchers can avoid wasting expensive materials during large-scale production.

Drop-on-Demand (DoD): Unlike the continuous method, *Drop-on-Demand (DoD)* inkjet printing only ejects a droplet when the computer specifically tells it to. Instead of a non-stop stream, the printer stays quiet until it passes over a spot that needs a layer of perovskite. At that exact microsecond, a small pulse of pressure usually created by a tiny vibrating crystal (piezoelectric) or a quick burst of heat pushes a single drop out of the nozzle and onto the surface[44].

This approach is excellent for creating very complex, detailed patterns without needing a recycling system for leftover solution. Because it only fires when necessary, it is much more efficient for printing specific shapes or grids on a solar cell. However, because the ink sits still inside the nozzle between shots, researchers have to be careful that the perovskite doesn't dry out and cause a blockage. To prevent this, special solvents are often added to the mix to keep the solution fluid and ready to spray at a moment's notice.

3.1.5 Spray Coating

Spray coating is a simple and efficient method used to create large-area perovskite films. In this process, the perovskite precursor solution is converted into tiny droplets (atomised) and sprayed onto a heated substrate, where it spreads and forms a thin film. This technique is highly suitable for mass production because it offers fast processing, good reproducibility, and low material wastage. Spray coating mainly consists of three parts: an atomising nozzle, an injection pumping system and a heating plate. Based on the type of nozzle and spraying mechanism, spray coating can be divided into three types - Pneumatic spraying, Ultrasonic spraying, Electro spraying[45].

For achieving high-quality and uniform perovskite films, it is important to carefully control parameters such as the solution flow rate, nozzle-to-substrate distance, and temperature/crystallisation conditions during the process.

3.1.6 Screen Printing

Screen printing is a simple and low-cost method used to fabricate certain layers of PSC, especially electrodes and transport layers. In this technique, a patterned screen is placed over the substrate, and a paste or ink is pressed through the screen to form the desired layer. One of the main advantages of screen printing is that it is suitable for large-area fabrication and mass production, making it attractive for commercial applications.

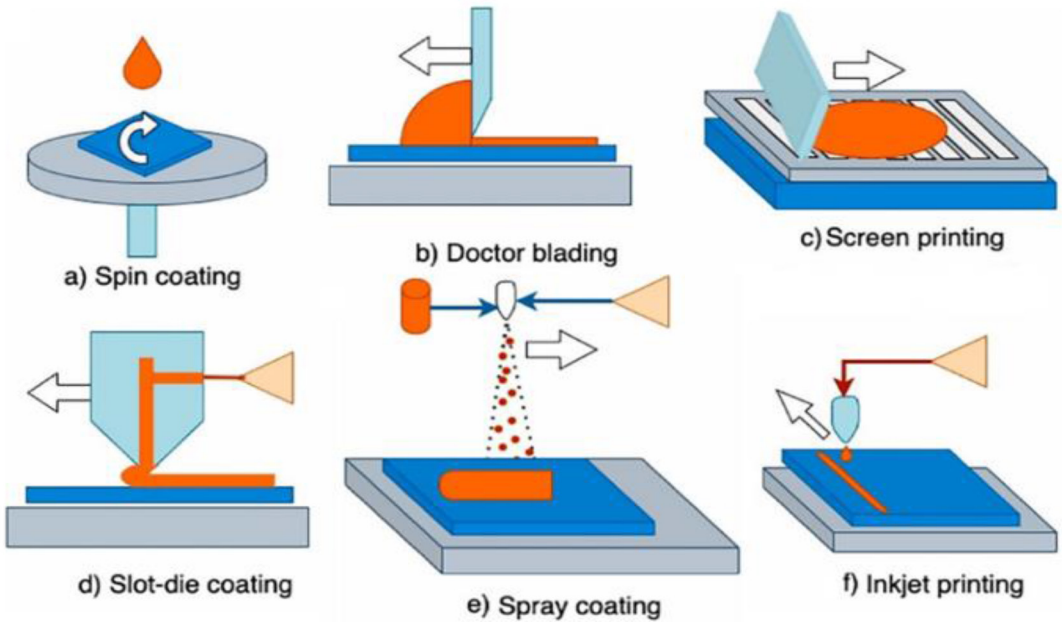


Figure 7. Different solution-based techniques.

Source: Becker and Wark[38]

However, controlling the thickness and uniformity of the printed layers can be difficult, which may affect device performance. Therefore, screen printing is often used along with other deposition techniques to improve the overall efficiency and stability of PSC[46].

4. Key Factors Influencing Efficiency in PSCs

The efficiency of PSCs depends on the careful optimisation of both the materials used and the overall device structure. Several key factors influence their performance (Figure 8).

4.1 Material Properties and Optoelectronic Characteristics

The optoelectronic properties of the materials used in different layers, especially the perovskite absorber layer, play a major role in determining the performance of PSCs. To understand these properties better, scientists often use theoretical methods like Density Functional Theory (DFT). DFT helps in studying how defects form, how they affect charge movement, and how the electronic structure of the perovskite behaves. These studies are very helpful because they guide researchers in choosing suitable materials and fabrication methods, ensuring that the perovskite film maintains good structure and electrical properties over time, which improves the long-term stability of the device.

Crystal, they create trap states that cause charge recombination, meaning that electrons and holes recombine before producing electricity. This reduces the overall PCE of the solar cell. Hence, reducing or passivating defects is a crucial step in improving PSC performance[47].

4.1.1 Carrier Transport and Extraction in PSCs

Efficient charge transport and extraction are key to achieving high-performance PSCs. Improving these processes ensures that the charges generated in the perovskite layer are quickly collected at the electrodes before they recombine, which helps boost the overall PCE.

4.1.2 Carrier Recombination in PSCs

Recombination is one of the main loss processes in PSC and has a strong effect on their efficiency. When recombination occurs, charge carriers combine before they can be collected, which reduces the overall power output of the device. To understand how recombination affects performance, it is important to study how charge carriers behave inside the perovskite layer. For this

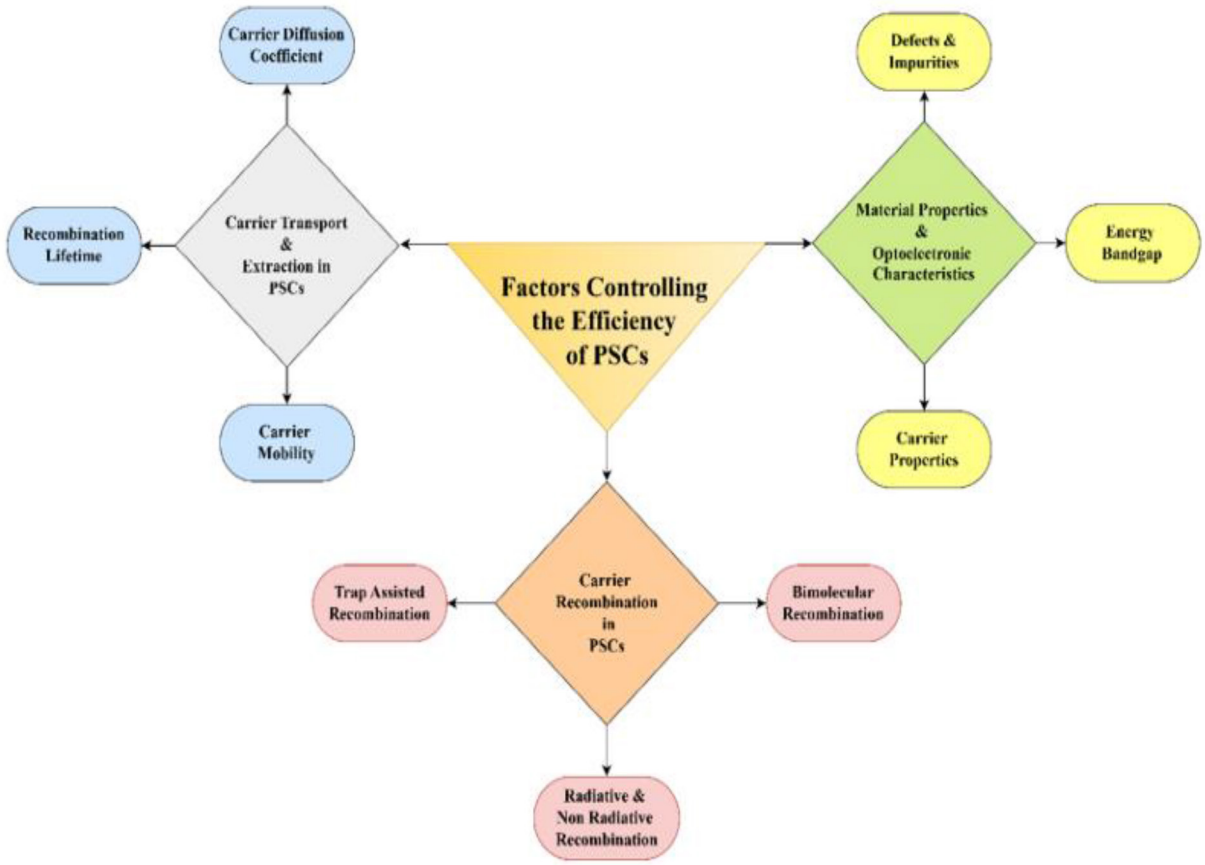


Figure 8. Efficiency controlling factors for PSCs (The diagram presents a general overview; not all topics are discussed in equal detail).
Source: Afroz *et al.*[64]

purpose, advanced techniques like transient photovoltage and transient photoconductivity measurements were widely used. These techniques tell us if the problem is a messy layer of perovskite or if the charges are just getting stuck at the edges of the cell[48].

5. Challenges in Attaining High Efficiency in PSCs

Perovskite Solar Cells (PSCs) have rapidly moved to the forefront of PV research, with efficiencies now climbing past 25%. However, translating these laboratory successes into a commercial product remains difficult. The core issue is that while the cells perform well initially, they face significant hurdles regarding long term environmental stability and large-scale manufacturing. This section identifies the primary mechanisms behind material degradation and evaluates the current engineering strategies being used to bridge the gap between the lab and the market.

5.1 Stability Challenges

Perhaps the most difficult work is to prevent the commercial rollout of PSCs and their limited long-term stability. While laboratory performance is high, these devices are really sensitive to their surroundings. This degradation is rarely caused by a single factor; instead, it is a complex combination of environmental exposure, internal material breakdowns, and the physical design of the cell itself. Furthermore, the interfaces between different layers in the device architecture often act as 'weak points' where defects can accumulate, eventually leading to a complete loss of power output. To move from a lab-scale experiment to a reliable consumer product, these stability issues must be solved through better encapsulation and material engineering.

5.2 Environmental Sensitivity

Perovskite materials break down into *Inorganic- Organic Hybrids (OHPs)* when exposed to factors like UV light, temperature, and moisture. When these cells are operated in real-world conditions, even minor exposure to humidity or oxygen can trigger a chain reaction that can physically affect the material's structure. Because of this, ensuring that PSCs can survive the harsh conditions is still most of the most difficult challenge today[49].

5.3 Material Degradation

Even if we keep a solar cell perfectly dry, the perovskite material itself can still fall apart over time just from being warm. This happens because of the way the atoms are held together inside the crystal. There is something called *hydrogen bonding* that acts like the 'glue' between the centre piece A-site cation and the BX6 octahedra. The problem is that these bonds are actually pretty weak.

When the solar cell sits in the sun and gets hot, that heat is enough to start shaking these weak bonds until they eventually snap. Once those bonds break, the perfect crystal shape is ruined, and the solar cell stops working. This is the main reason why perovskite cells don't last nearly as long as the old-fashioned silicon ones. For us as researchers, the big challenge is finding a way to make this bond stronger so the cells can survive the heat for years, not just months[50].

5.4 Structural Stability

You can think of a perovskite crystal as a 3D puzzle where the atoms (A, B, and X) must be in the exact right size to fit. Scientists use the *tolerance* and *octahedral factors* to calculate this 'fit.' The issue with many hybrid perovskites is that they use large iodine atoms with weak bonds, which makes the whole structure defective and easy to breaking[1]. To solve this, researchers are mixing 3D crystals with 2D layers. These 2D layers act like a 'protective skin' that shields the 3D core, keeping the cell efficient while making it much tougher against the environment[51].

5.5 Defect Structures and their Effect on Efficiency

Defects in the perovskite layer are one of the biggest reasons for losing efficiency. They act as traps for the electricity. Normally, electrons and holes should move freely to create power, but these defects cause them to crash into each other and cancel out before they can do their job. This is called *non-radiative recombination*[52]. When this happens, it directly pulls down the open-circuit voltage (Voc) and the fill factor, which limits the cell's overall performance. We usually split these defects into two groups: *Intrinsic defects* and *Extrinsic defects*.

5.5.1 Intrinsic Defects

Intrinsic defects are basically natural flaws that happen inside the crystal as it forms. They are like missing or misplaced pieces. Sometimes an atom is just gone, leaving behind *vacancies*, when a pair of atoms is missing, it is called a *Schottky defect*, or when an atom is squeezed into the wrong spot, it is called a *Frenkel defect*. These gaps act like speed bumps that slow down the flow of electricity. A bigger problem is ion migration, where atoms like iodide or bromide start wandering around inside the lattice instead of staying put. This constant movement is a major headache because it makes the cell unstable and causes the power to drop over time[53].

5.5.2 Extrinsic Defects

Extrinsic defects are even worse because they come from the outside, usually from dirt or impurities during the making of the film. Most of these outside issues gather at the Grain Boundaries (GBs), which are basically the cracks between the tiny crystals. Instead of moving through the cell to create power, electrons and holes get stuck in these boundaries and cancel each other out. This process, called *recombination*, is a huge energy killer that drags down the cell's performance. On top of that, if the film's surface is messy or distorted with molecular irregularities, making the whole device less reliable[53].

5.6 Processing Methods and Scalability

Making a high-quality solar cell is all about control. If the perovskite layer isn't perfectly smooth or if the crystals don't grow right, the efficiency drops immediately. The real headache starts when we try to move from small lab samples to large-scale manufacturing. It's incredibly tough to get a uniform coating over a big surface without any dry spots or bumps. On top of that, you have to make sure the material gets combined with different types of substrates. If we can't figure out how to keep the quality consistent across large panels, these cells will never make it out of the lab and into the real world[54].

5.7 Carrier Transport Mechanisms

For a solar cell to actually work, the electrons and holes have to move fast. So, carriers need to reach the electrodes before they get stuck. The biggest obstacle here is trap-assisted recombination. Think of these traps as dead ends or potholes caused by messy defects in the material. If a charge carrier falls into one, it just recombines and vanishes instead of turning into electricity. To stop this, we have to clean up the material to get rid of these traps. By lowering the defect density, we're essentially paving a smooth highway for the charges. If they can travel without hitting these roadblocks, the cell hits a much higher efficiency and doesn't break down as easily[55].

5.8 Rear Electrode Work Function

The work function of the back electrode is basically what creates the 'push' or 'pull' inside the solar cell. If the work function is set correctly, it creates a steep enough hill for the electrons and holes to roll down toward the right collectors. If this electric field is too flat, the charges won't move fast enough and the cell's power drops. By picking the right material for the back electrode, we can fine-tune this pull to make sure charge extraction is as smooth as possible. When the charges can exit the cell easily, you get a much stronger current and a more efficient device overall[56].

6. Major Degradation Mechanism in PSCs

Right now, the biggest hurdle for PSCs isn't their power; it's how fast they break down. The instability of PSCs comes mainly from two sources: intrinsic and extrinsic factors (as shown in Figure 9). Intrinsic instability comes from the internal properties of the perovskite materials themselves and how they behave under working conditions. Factors such as temperature, humidity, and Ultraviolet (UV) light can easily break down the perovskite structure or cause unwanted reactions between layers. Over time, this leads to a loss of efficiency and faster degradation of the solar cell. Extrinsic instability, on the other hand, is caused by external environmental factors. If the protective layers or sealing around the solar cell are damaged or poorly made, moisture and oxygen from the air can enter. This exposure can speed up the chemical decomposition of the perovskite material and reduce the performance of the device. The main factors that cause perovskite degradation include[57]:

Humidity, which leads to the breakdown of the perovskite structure.

Sunlight (UV radiation), which accelerates chemical reactions and causes phase changes.

Even a little bit of oxygen or air can oxidise the perovskite and totally ruin its crystal structure, which kills the power output. To stop this from happening, researchers are attacking the problem from three different angles.

First, there is *encapsulation,* which is basically like putting the solar cell inside a high-tech protective layer. By sealing it with stable materials, we can physically block out the moisture and UV light that cause the most damage[57].

Second, there is *material engineering*, where we actually change the structure of the perovskite itself. Instead of just trying to hide the material from the air, we're trying to build a new version that is naturally tougher and doesn't fall apart the moment it gets stressed by the environment. The use of additives and dopants helps strengthen the material and improve the interfaces between layers.

Third, there is *Device Architecture Modification,* where we adjust the layer structure or configuration of the PSC, which can also reduce degradation. For example, improved interfacial layers can minimise unwanted reactions and enhance the overall stability of the device.

6.1 Extrinsic Instability

Extrinsic instability in PSCs mainly arises due to external environmental conditions that directly affect the stability and performance of the device. Factors like humidity, oxygen, temperature, and Ultraviolet (UV) light exposure can significantly speed up the degradation process[25]. In addition, damage to the encapsulation layers or mechanical stress during device packaging can also cause external instability[57].

6.1.1 Moisture and Oxygen-Induced Degradation

Among all the environmental factors, moisture and oxygen are the most harmful to PSCs. When water vapour enters the perovskite layer, it reacts with the perovskite material, especially with methylammonium lead iodide ($MAPbI_3$) and weakens its structure[26]. Water molecules form hydrogen bonds with the methylammonium (MA^+) ions, breaking their connection to the $[PbI_6]^{4-}$ framework. And this triggers a chemical reaction called *hydrolysis* that basically dissolves the material from

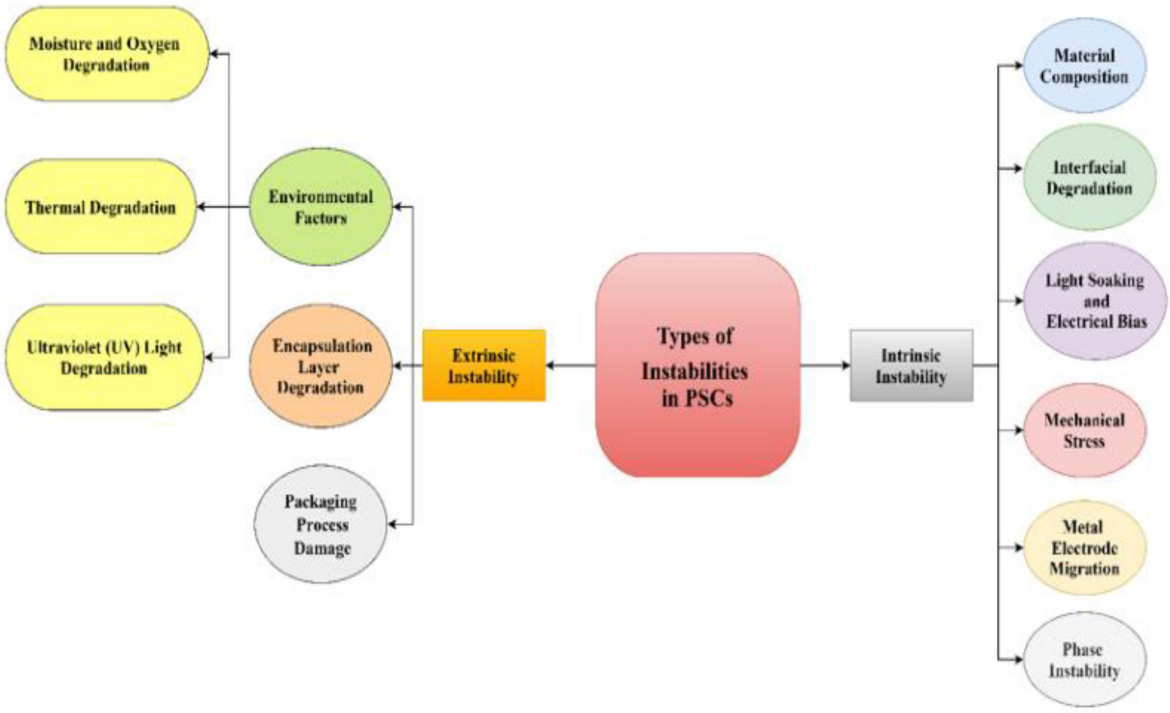


Figure 9. Types of Instabilities in PSCs (The figure illustrates the major degradation pathways in PSC. Not all mechanisms are discussed in equal detail.)
Source: Afroz *et al.*[64]

within. The perovskite starts to rot and turns into gases like *methylamine* and *hydroiodic acid*. Because these are volatile, they literally float away and escape into the air, leaving the solar cell looking like a hollowed-out shell.

Oxygen is just as bad, especially when the sun is hitting the cell. The light creates excited electrons that react with oxygen to form *superoxide*. These superoxides are very aggressive and attack the perovskite layers, breaking down the chemistry and dragging the efficiency down until the cell can't produce power anymore[58].

6.1.2 Thermal Degradation

Heat is one of the major problems for PSCs. Even though these materials don't fully fall apart until they hit 250°C, they start to 'leak' much earlier. In the real world, a solar panel on a roof can easily hit 85°C, which is enough to start a slow decay. At these temperatures, the organic parts like MA^+ and FA^+ basically begin to evaporate from the crystal lattice.

As these pieces leave, the perfect perovskite structure is ruined and turns into *lead iodide* (PbI_2), which is just a yellow, non-functional byproduct. It's like a brick wall where the mortar starts to crumble the whole thing eventually loses its ability to catch sunlight and generate electricity. This is why a cell that works perfectly in a cool lab might fail after just a few weeks of sitting in the hot summer sun[58].

6.1.3 Degradation of the Encapsulation Layer

Even the best protective layers won't last forever. Over time, the encapsulation, which is supposed to be the cell's main defense can start to crack from the constant stress of heat and weather.

As this layer gets brittle and develops tiny cracks, it basically opens the door for moisture and oxygen to sneak back in. Once that happens, the inner layers of the perovskite aren't protected anymore. This doesn't just make the cell look old; it actually speeds up the chemical breakdown of the materials inside. It's a chain reaction, actually once the outer seal fails, the whole device's stability and power output start to drop much faster than they should[59].

6.1.4 Damage During Packaging Process

Even after the solar cell is made, the final packaging step can actually be one of the most dangerous. During this

stage, any rough handling or mechanical pressure can create tiny cracks or pinholes that you can't even see with your eyes. These aren't just cosmetic; they can let moisture and oxygen walk right into the device.

Once these cracks are there, the damage starts to spread. It messes with the charge transport layers and the metal electrodes, which basically cuts off the electricity's path. Even worse, these small structural breaks make it much easier for ions to start wandering around inside the perovskite, causing it to fall apart from the inside out. If the packaging isn't perfect, a cell that looked great in the lab will fail the moment it hits the real world.

6.2 Intrinsic Instability

Intrinsic instability is actually a fight happening inside the material itself. Even if you seal the cell perfectly, the perovskite can still start to break down just from doing its job. This internal decay happens because of how the chemicals react to light soaking or the constant electrical stress of generating power. It's not just one thing; it's a mix of problems like the layers peeling apart, causing *interfacial degradation* or atoms literally drifting out of place, which we call *metal ion migration*. Whether it's the crystal structure changing shape or the physical 'strain' of heating up and cooling down, these internal shifts can slowly kill the cell's efficiency from the inside out[59].

6.2.1 Material Composition

The biggest problem with PSCs is that the process we use for the most efficient cells (like $MAPbI_3$) is actually quite fragile. These hybrid materials have organic parts that just can't handle the stress of being outside in the sun. When it gets too hot, the organic cations like MA^+ or FA^+ basically start to break apart and turn into gases like ammonia or methylamine. some of the pieces just decide to evaporate into thin air. Once those organic pieces are gone, there's only lead iodide (PbI_2) left and other junk phases that don't belong there. These leftover phases stop electricity from moving through the cell. This is why a new cell can lose its power so quickly; it's literally falling apart at the atomic level[60].

6.2.2 Light Soaking and Electrical Bias

Light soaking happens when PSCs are exposed to continuous light for a long time. If you leave a $MAPbI_3$ cell under the sun for too long, the energy from the light actually starts to tear the molecules apart. It is where the metal halides break down into bits of neutral lead and iodine, which then messes up the system. An even weirder problem happens in mixed perovskites (the ones that use both iodine and bromine). When the light hits them, the iodine and bromine atoms form in different regions. This is called *halide segregation*. Even though these atoms sometimes move back to their original spots once you turn the lights off, the constant back-and-forth movement wears out the crystal structure, making it much harder for electricity to flow[61,62].

6.2.3 Mechanical Stress

Even though we don't usually move solar cells once they're installed, they still deal with a lot of slow ageing just from the weather. As the sun heats them and they cool down at night, the different materials in the cell expand and shrink at different rates. This constant pulling causes *delamination*, where the layers literally start to peel away from each other. Once the perovskite layer loses its tight grip on the charge transport layers, the electricity gets stuck and can't jump across the gap, which reduces performance. Eventually, this repeated stretching and shrinking creates tiny cracks throughout the structure. These cracks make it much easier for moisture and oxygen to get inside and finish off the cell[63].

7. Conclusion

In just over a decade, PSCs have transformed from a lab curiosity into a replacement for traditional silicon. We have seen PCE numbers climb past 26%, proving that these materials have the optical properties like incredible light absorption and easy charge movement to lead the next generation of energy. This article has covered that entire journey, from the basic physics of the crystal to the complex ways we now build these devices. We've seen how interface engineering and a new process for the perovskite layer have allowed us to push the limits of what a thin-film cell can actually do. However, the ultimate goal for commercial use is still a bit further off because we are currently facing a stability gap. While the power is there, we are still fighting to make these cells tough enough to survive twenty years of heat, heavy rain, and UV exposure. On top of that, we have to solve the lead problem by finding safer alternatives or perfect recycling methods, and we must figure out how to manufacture giant panels without losing the high quality we get in a tiny lab. Despite these massive hurdles, the progress is

steady and undeniable. If we can finally fix the remaining issues between high lab efficiency and long-term survival in the field, PSCs won't just be a research success; they will be the practical, low-cost solution that changes how the world uses clean energy.

8. Future Aspects

As we look toward the future, the to-do list for perovskite research is pretty clear. First, we have to deal with the lead problem. Moving toward tin or bismuth-based materials is the best way to make these cells safer for the environment without losing the power they're known for. At the same time, we need to keep working on the outer shell, improving encapsulation so that moisture simply can't get in. Inside the cell, we can use *passivation* and *compositional engineering* to basically overcome internal defects and stop atoms from wandering around, which is the only way to make these devices last for years instead of weeks.

For PSCs to actually hit the market, we have to stop thinking about tiny lab samples and start focusing on large-scale production. This means perfecting methods like *vapour deposition* that can coat giant surfaces smoothly and evenly. We are also seeing a huge push for tandem cells, where we pair perovskite with silicon to break the efficiency limits of a single-layer cell. Finally, there's the exciting world of flexible solar cells. If we can make these materials tough enough to bend without cracking, we could see solar power built right into our portable gadgets. It's a massive challenge, but the potential is even bigger. Furthermore, advancing computational modelling can help scientists understand degradation processes, predict material behaviour, and design better experiments. Finally, setting industry-wide testing and performance standards is crucial for accurately comparing results across laboratories and assessing the commercial readiness of PSCs.

9. Acknowledgement

The author gratefully acknowledges Dr. Shobha A. Waghmode and Dr. Ashwini P. Alegaonkar for their continuous encouragement, valuable insights, and constructive suggestions during the preparation of this review article. The author also extends her appreciation to the Department of Chemistry, MES Abasaheb Garware College, Pune, for providing institutional support and essential resources.

7. References

1. Hayat MB, Ali D, Monyake KC, Alagha L, Ahmed N. Solar energy-A look into power generation, challenges, and a solar-powered future. Int J Energy Res. 2018; 43(3):1049–67. https://doi.org/10.1002/er.4252
2. Chakhmouradian AR, Woodward PM. Celebrating 175 years of perovskite research: A tribute to Roger H. Mitchell. Phy Chem Mineral. 2014; 41(6):387–391. https://doi.org/10.1007/s00269-014-0678-9
3. Snaith HJ. Perovskites: The emergence of a new era for low-cost, high-efficiency solar cells. J Phys Chem Lett. 2013; 4(21):3623–3630. https://doi.org/10.1021/jz402016b
4. Tiwari JP. Flexible perovskite solar cells: A futuristic IoTs powering solar cell technology, short review. Small Methods. 2024. https://doi.org/10.1002/smtd.202400624
5. ChrKn M. A phase transition in caesium plumbochloride. Nature. 1957; 180:981–982. https://doi.org/10.1038/180981a0
6. Weber D. $CH_3NH_3SnBr_3$ perovskite structure and related systems. Z Naturforsch B : Chem Sci. 1978; 33:862–865. https://doi.org/10.1515/znb-1978-0809
7. Jena AK, Kulkarni A, Miyasaka T. Halide perovskite photovoltaics: Background, status, and future prospects. Chem Rev. 2019; 119(5):3036-3103. https://doi.org/10.1021/acs.chemrev.8b00539
8. Mahmood K, Swain BS, Kirmani AR, Amassian A. Highly efficient perovskite solar cells based on a nanostructured WO_3–TiO_2 core–shell electron transporting material. J Mat Chem A. 2015; 3(17):9051-9057. https://doi.org/10.1039/C4TA04883K
9. Im JH, Lee CR, Lee JW, Park SW, Park NG. 6.5% efficient perovskite quantum-dot-sensitized solar cell. Nanoscale. 2011; 3(10):4088-4093. https://doi.org/10.1039/C1NR10867K
10. Niu G, Guo X, Wang L. Review of recent progress in chemical stability of perovskite solar cells. J Mat Chem A. 2015; 3(17):8970-8980. https://doi.org/10.1039/C4TA04994B
11. Tong X, Lin F, Wu J, Wang ZM. High performance perovskite solar cells. Adv Sci. 2016; 3(5):1500201. https://doi.org/10.1002/advs.201500201
12. Yang X, Wang W, Ran R, Zhou W, Shao Z. Recent advances in $Cs_2AgBiBr_6$-based halide double perovskites as lead-free and inorganic light absorbers for perovskite solar cells. Energy Fuel. 2020; 34(9):10513-1028. https://doi.org/10.1021/acs.energyfuels.0c02236
13. Kim YY, Yang TY, Suhonen R, Kemppainen A, Hwang K, Jeon NJ, *et al.* Roll-to-roll gravure-printed flexible perovskite solar cells using eco-friendly antisolvent bathing with wide processing window. Nat Commun. 2020; 11(1):5146. https://doi.org/10.1038/s41467-020-18940-5

14. Shao M, Bie T, Yang L, Gao Y, Jin X, He F, *et al*. Over 21% efficiency stable 2D perovskite solar cells. Adv Mat. 2022; 34(1):2107211. https://doi.org/10.1002/adma.202107211
15. Zhang S, Ye F, Wang X, Chen R, Zhang H, Zhan L, *et al*. Minimizing buried interfacial defects for efficient inverted perovskite solar cells. Science. 2023; 380(6643):404-409. https://doi.org/10.1126/science.adg3755
16. Chen H, Liu C, Xu J, Maxwell A, Zhou W, Yang Y, *et al*. Improved charge extraction in inverted perovskite solar cells with dual-site-binding ligands. Science. 2024; 384(6692):189-193. https://doi.org/10.1126/science.adm9474
17. Green MA, Ho-Baillie A, Snaith HJ. The emergence of perovskite solar cells. Nat Phot. 2014; 8(7):506-514. https://doi.org/10.1038/nphoton.2014.134
18. Park NG. Perovskite solar cells: An emerging photovoltaic technology. Mat Today. 2015; 18(2):65-72. https://doi.org/10.1016/j.mattod.2014.07.007
19. Zuo C, Bolink HJ, Han H, Huang J, Cahen D, Ding L. Advances in perovskite solar cells. Adv Sci. 2016; 3(7):1500324. https://doi.org/10.1002/advs.201500324
20. Di Giacomo F, Zardetto V, Lucarelli G, Cinà L, Di Carlo A, Creatore M, *et al*. Mesoporous perovskite solar cells and the role of nanoscale compact layers for remarkable all-round high efficiency under both indoor and outdoor illumination. Nano Energy. 2016; 30:460-469. https://doi.org/10.1016/j.nanoen.2016.10.008
21. Liu J, Chen X, Chen K, Tian W, Sheng Y, She B, *et al*. Electron injection and defect passivation for high-efficiency mesoporous perovskite solar cells. Science. 2024; 383(6688):1198-1204. https://doi.org/10.1126/science.adk1234
22. Xu D, Wang D, Liu J, Qi J, Chen K, Zhu W, *et al*. Dual defect passivation at the buried interface for printable mesoscopic perovskite solar cells with reduced open-circuit voltage loss. Small. 2024; 20(31):2311755. https://doi.org/10.1002/smll.202311755
23. Gao C, Zhang H, Ma S, Su H, Huang H, He L, *et al*. Quasi-conformal monolithic nip perovskite/c-Si tandem solar cells with light management strategies exceed 28% efficiency. Nano Energy. 2024; 129:110066. https://doi.org/10.1016/j.nanoen.2024.110066
24. Enkhbayar E, Otgontamir N, Kim S, Lee J, Kim J. Understanding of defect passivation effect on wide band gap pin perovskite solar cell. ACS Appl Mater Interfaces. 2024; 16(27):35084-35094.
25. Ahmed MI, Habib A, Javaid SS. Perovskite solar cells: potentials, challenges, and opportunities. Int J Photoenergy. 2015; 2015(1):592308. https://doi.org/10.1155/2015/592308
26. Stranks SD, Burlakov VM, Leijtens T, Ball JM, Goriely A, Snaith HJ. Recombination kinetics in organic-inorganic perovskites: Excitons, free charge, and subgap states. Phy Rev Appl. 2014; 2(3):034007. https://doi.org/10.1103/PhysRevApplied.2.034007
27. Zhang P, Li M, Chen WC. A perspective on perovskite solar cells: Emergence, progress, and commercialization. Front Chem. 2022; 10:802890. https://doi.org/10.3389/fchem.2022.802890
28. Chen Y, Zhang L, Zhang Y, Gao H, Yan H. Large-area perovskite solar cells – A review of recent progress and issues. RSC Adv. 2018; 8(19):10489-10508. https://doi.org/10.1039/C8RA00384J
29. Cheng M, Zuo C, Wu Y, Li Z, Xu B, Hua Y, *et al*. Charge-transport layer engineering in perovskite solar cells. Sci Bull. 2020; 65(15):1237-1241. https://doi.org/10.1016/j.scib.2020.04.021
30. Pan H, Zhao X, Gong X, Li H, Ladi NH, Zhang XL, *et al*. Advances in design engineering and merits of electron transporting layers in perovskite solar cells. Mat Horiz. 2020; 7(9):2276-2291. https://doi.org/10.1039/D0MH00586J
31. Lian J, Lu B, Niu F, Zeng P, Zhan X. Electron-transport materials in perovskite solar cells. Small Methods. 2018; 2(10):1800082. https://doi.org/10.1002/smtd.201800082
32. Urieta-Mora J, García-Benito I, Molina-Ontoria A, Martín N. Hole transporting materials for perovskite solar cells: A chemical approach. Chem Soc Rev. 2018; 47(23):8541-8571. https://doi.org/10.1039/C8CS00262B
33. Shariatinia Z. Recent progress in development of diverse kinds of hole transport materials for the perovskite solar cells: A review. Renew Sustain Energy Rev. 2020; 119:109608. https://doi.org/10.1016/j.rser.2019.109608
34. Raga SR, Jiang Y, Ono LK, Qi Y. Application of methylamine gas in fabricating organic–inorganic hybrid perovskite solar cells. Energy Technol. 2017; 5(10):1750-1761. https://doi.org/10.1002/ente.201700423
35. Yu Z, Sun L. Inorganic hole-transporting materials for perovskite solar cells. Small Methods. 2018; 2(2):1700280. https://doi.org/10.1002/smtd.201700280
36. Anoop KM, Ahipa TN. Recent advancements in the hole transporting layers of perovskite solar cells. Solar Energy. 2023; 263:111937. https://doi.org/10.1016/j.solener.2023.111937
37. Tountas M, Polyzoidis C, Loizos M, Rogdakis K, Kymakis E. Improved performance of hole-transporting material-free perovskite solar cells using a low-temperature printed carbon paste. ACS Appl Elect Mat. 2023; 5(11):6228-6235. https://doi.org/10.1021/acsaelm.3c01132
38. Bhati N, Nazeeruddin MK, Marechal F. Critical analysis of decision variables for High-Throughput Experimentation (HTE) with perovskite solar cells. Solar Energy. 2023; 262:111810. https://doi.org/10.1016/j.solener.2023.111810
39. Becker M, Wark M. Recent progress in the solution-based sequential deposition of planar perovskite solar cells. Cryst Growth Des. 2018; 18(8):4790-4806. https://doi.org/10.1021/acs.cgd.8b00686
40. Jeong I, Kim HJ, Lee BS, Son HJ, Kim JY, Lee DK, *et al*.

Highly efficient perovskite solar cells based on mechanically durable molybdenum cathode. Nano Energy. 2015; 17:131-139. https://doi.org/10.1016/j.nanoen.2015.07.025
41. Zhao J, Hou M, Wang Y, Wang R, Zhang J, Ren H, *et al*. Strategies for large-scale perovskite solar cells realization. Org Elect. 2023; 122:106892. https://doi.org/10.1016/j.orgel.2023.106892
42. Gong C, Tong S, Huang K, Li H, Huang H, Zhang J, *et al*. Flexible planar heterojunction perovskite solar cells fabricated via sequential roll-to-roll microgravure printing and slot-die coating deposition. Solar Rrl. 2020; 4(2):1900204. https://doi.org/10.1002/solr.201900204
43. Li SG, Jiang KJ, Su MJ, Cui XP, Huang JH, Zhang QQ, *et al*. Inkjet printing of $CH_3NH_3PbI_3$ on a mesoscopic TiO_2 film for highly efficient perovskite solar cells. J Mat Chem A. 2015; 3:9092-9097. https://doi.org/10.1039/C4TA05675B
44. Yang P, Fan HJ. Inkjet and extrusion printing for electrochemical energy storage: A minireview. Adv Mat Technol. 2020; 5(10):2000217. https://doi.org/10.1002/admt.202000217
45. Chou LH, Wang XF, Osaka I, Wu CG, Liu CL. Scalable ultrasonic spray-processing technique for manufacturing large-area $CH_3NH_3PbI_3$ perovskite solar cells. ACS Appl Mat Interf. 2018; 10(44):38042-38050. https://doi.org/10.1021/acsami.8b12463
46. Rong Y, Ming Y, Ji W, Li D, Mei A, Hu Y, *et al*. Toward industrial-scale production of perovskite solar cells: Screen printing, slot-die coating, and emerging techniques. J Phy Chem Lett. 2018; 9(10):2707-2713. https://doi.org/10.1021/acs.jpclett.8b00912
47. Savill KJ, Ulatowski AM, Herz LM. Optoelectronic properties of tin–lead halide perovskites. ACS Energy Lett. 2021; 6(7):2413-2426. https://doi.org/10.1021/acsenergylett.1c00776
48. Li W, Sun YY, Li L, Zhou Z, Tang J, Prezhdo OV. Control of charge recombination in perovskites by oxidation state of halide vacancy. J Am Chem Soc. 2018; 140(46):15753-15763. https://doi.org/10.1021/jacs.8b08448
49. Giuliano G, Bonasera A, Scopelliti M, Martino DC, Fiore T, Pignataro B. Boosting the performance of one-step solution-processed perovskite solar cells using a natural monoterpene alcohol as a green solvent additive. ACS Appl Elect Mat. 2021; 3(4):1813-1825. https://doi.org/10.1021/acsaelm.1c00084
50. Mohanty I, Mangal S, Singh UP. Defect optimization of CZTS/$MASnI_3$ heterojunction solar cell yielding 30.8% efficiency: I. Mohanty *et al*. J Elect Mat. 2023; 52(4):2587-2595. https://doi.org/10.1007/s11664-023-10221-3
51. Li M, Yan X, Kang Z, Liao X, Li Y, Zheng X, *et al*. Enhanced efficiency and stability of perovskite solar cells via anti-solvent treatment in two-step deposition method. ACS Appl Mat Interf. 2017; 9(8):7224-7231. https://doi.org/10.1021/acsami.7b01136
52. Li M, Yan X, Kang Z, Liao X, Li Y, Zheng X, *et al*. Enhanced efficiency and stability of perovskite solar cells via anti-solvent treatment in two-step deposition method. ACS Appl Mat Interf. 2017; 9(8):7224-7231. https://doi.org/10.1021/acsami.7b01136
53. Lee YM, Maeng I, Park J, Song M, Yun JH, Jung MC, *et al*. Comprehensive understanding and controlling the defect structures: An effective approach for organic-inorganic hybrid perovskite-based solar-cell application. Front Energy Res. 2018; 6:128. https://doi.org/10.3389/fenrg.2018.00128
54. Kieslich G, Sun S, Cheetham AK. Solid-state principles applied to organic–inorganic perovskites: New tricks for an old dog. Chem Sci. 2014; 5(12):4712-4715. https://doi.org/10.1039/C4SC02211D
55. Singh N, Ratnesh RK, Kumar A, Sharma P, Aryan. Low refractive index photonic crystal fiber-based surface plasmon resonance sensor. Proceedings of the 2024 IEEE Region 10 Symposium (TENSYMP), India: New Delhi; 2024. p. 1-7. https://doi.org/10.1109/TENSYMP61132.2024.10752178
56. Liao Y, Liu H, Zhou W, Yang D, Shang Y, Shi Z, *et al*. Highly oriented low-dimensional tin halide perovskites with enhanced stability and photovoltaic performance. J Am Chem Soc. 2017; 139(19):6693-6699. https://doi.org/10.1021/jacs.7b01815
57. Ono LK, Qi Y, Liu SF. Progress toward stable lead halide perovskite solar cells. Joule. 2018; 2(10):1961-1990. https://doi.org/10.1016/j.joule.2018.07.007
58. Cheng S, Mai H, Lin IHH. Research of technical approach for improving the stability of perovskite solar cells. Highl Sci Eng Technol. 2023; 73:157-164. https://doi.org/10.54097/hset.v73i.12856
59. Baumann S, Eperon GE, Virtuani A, Jeangros Q, Kern DB, Barrit D, *et al*. Stability and reliability of perovskite containing solar cells and modules: Degradation mechanisms and mitigation strategies. Energy Environ Sci. 2024; 17(20):7566-7599. https://doi.org/10.1039/D4EE01898B
60. Khalid M, Mallick TK. Stability and performance enhancement of perovskite solar cells: A review. Energies. 2023; 16(10):4031. https://doi.org/10.3390/en16104031
61. Park BW, Seok SI. Intrinsic instability of inorganic–organic hybrid halide perovskite materials. Adv Mat. 2019; 31(20):1805337. https://doi.org/10.1002/adma.201805337
62. Dunfield SP, Bliss L, Zhang F, Luther JM, Zhu K, van Hest MF, *et al*. From defects to degradation: A mechanistic understanding of degradation in perovskite solar cell devices and modules. Adv Energy Mat. 2020; 10(26):1904054. https://doi.org/10.1002/aenm.201904054
63. Verkhogliadov G, Haroldson R, Gets D, Zakhidov AA, Makarov SV. Temperature dependence of photoinduced phase segregation in bromide-rich mixed halide perovskites. J Phy Chem C. 2023; 127(50):24339-24349. https://doi.

org/10.1021/acs.jpcc.3c04887
64. Schileo G, Grancini G. Halide perovskites: Current issues and new strategies to push material and device stability. J Phy: Energy. 2020; 2(2):021005. https://doi.org/10.1088/2515-7655/ab6cc4
65. Afroz M, Ratnesh RK, Srivastava S, Singh J. Perovskite solar cells: Progress, challenges, and future avenues to clean energy. Solar Energy. 2025; 275:112349. https://doi.org/10.1016/j.solener.2023.112349
66. Ju Z, Lv R, Ansari AA, Lin J. Recent advances in additive manufacturing for solar cell based on organic/inorganic hybrid materials. InfoMat. 2025; 7(7):e70017. https://doi.org/10.1002/inf2.70017
67. Kim T, Lim J, Song S. Recent progress and challenges of electron transport layers in organic–inorganic perovskite solar cells. Energies. 2020; 13(21):5572. https://doi.org/10.3390/en13215572
68. Chen Y, Lin P, Cai B, Zhang W. Research progress of inorganic hole transport materials in perovskite solar cells. J Inorg Mater. 2023; 38:991. https://doi.org/10.15541/jim20230105

Author Contribution

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