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Perovskite Solar Cells: Recent Advances, Challenges and Future Outlook

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Abstract:

Perovskite solar cells (PSCs) have emerged as one of the most promising next-generation photovoltaic technologies owing to their remarkable power conversion efficiency (PCE), cost-effective fabrication, and excellent optoelectronic properties. Since their introduction in 2009, PSCs have experienced unprecedented progress, with certified efficiencies increasing from less than 4% to over 27% for single-junction devices, while perovskite–silicon tandem solar cells have surpassed 34% efficiency. Recent developments in material engineering, interface passivation, charge transport layers, tandem architectures, and scalable fabrication techniques have significantly enhanced both device efficiency and operational stability. Despite these remarkable achievements, challenges related to long-term environmental stability, lead toxicity, ion migration, large-scale manufacturing, and commercialization continue to limit widespread adoption. This review summarizes the recent advances in perovskite solar cell technology, emphasizing innovations in material composition, interface engineering, tandem photovoltaics, flexible devices, and manufacturing approaches. The major challenges affecting the commercialization of PSCs are critically discussed, including degradation mechanisms under moisture, oxygen, ultraviolet radiation, and thermal stress. Emerging strategies such as lead-free perovskites, machine learning-assisted material discovery, scalable roll-to-roll processing, and advanced encapsulation technologies are highlighted as promising directions for future development. Overall, perovskite solar cells possess tremendous potential to transform the renewable energy sector by providing highly efficient, lightweight, and economically viable photovoltaic devices. Continued interdisciplinary research is expected to accelerate the commercialization of PSCs and contribute significantly toward achieving global sustainable energy goals.

Keywords: Perovskite Solar Cells; Photovoltaics; Renewable Energy; Tandem Solar Cells; Interface Engineering

Introduction:

The growing global demand for clean and sustainable energy has intensified research into advanced photovoltaic technologies capable of replacing fossil fuel-based electricity generation. Conventional crystalline silicon solar cells currently dominate the photovoltaic market because of their high stability and mature manufacturing processes. However, their fabrication requires energy-intensive processing, rigid substrates, and relatively high production costs. Consequently, researchers have focused on alternative photovoltaic materials that combine high efficiency with low-cost manufacturing and mechanical flexibility. Among emerging photovoltaic technologies, perovskite solar cells (PSCs) have attracted extraordinary attention due to their rapid improvements in performance over the past decade. The term "perovskite" refers to materials possessing the ABX_3 crystal structure, where A represents an organic or inorganic cation, B is typically lead (Pb) or tin (Sn), and X denotes halide ions such as iodine, bromine, or chlorine. These materials exhibit excellent optical absorption, tunable band gaps, long carrier diffusion lengths, high absorption coefficients, and low exaction binding energies, making them ideal light-harvesting materials for photovoltaic applications (Singh *et al.*, 2020). The first perovskite solar cell, reported in 2009, achieved a modest power conversion efficiency of approximately 3.8%. Since then, continuous advances in crystal engineering, defect passivation, interface optimization, and tandem device architectures have enabled laboratory efficiencies exceeding 27% for single-junction devices, while perovskite–silicon tandem cells have surpassed 34% efficiency, approaching the theoretical limits of photovoltaic conversion. Beyond high efficiency, PSCs offer several practical advantages. They can be fabricated using solution-based deposition methods at relatively low temperatures, enabling inexpensive manufacturing on flexible substrates. Their lightweight nature, semi-transparency, and compatibility with building-integrated photovoltaics (BIPV), wearable electronics, and portable power systems further expand their application potential. Despite these promising characteristics, several critical barriers continue to hinder commercial deployment. Moisture sensitivity, thermal degradation, ultraviolet instability, ion migration, lead toxicity, and large-scale manufacturing challenges remain significant concerns (Kojima *et al.*, 2009). Therefore, current research focuses not only on maximizing device efficiency but also on improving operational stability, environmental sustainability, and industrial scalability. Perovskite solar cell technology is advancing quickly in processing large-area modules (roll-to-roll and sheet-to-sheet printing), achieving a longer lifespan, and producing tandem cells with noticeably greater photovoltaic conversion efficiency. Ashouri *et al.* recently claimed a world record efficiency of >29% for monolithic perovskite/silicon tandem solar cells with an active area of 1.064 cm^2. The key benefit of this technology in the Indian context is that it can be effectively integrated into buildings and utilized as a standalone system to supply electricity. Perovskites are an emerging technology, thus there is a chance for India to be involved in their development and benefit from it as it grows to the point where it can be marketed.

Fundamentals of Perovskite Solar Cells:

Perovskite solar cells operate by converting incident sunlight into electrical energy through photo-induced charge generation and transport. Their exceptional performance originates from the unique crystal structure and favorable electronic properties of perovskite materials.

Crystal Structure: The general chemical formula of perovskites is ABX_3, where:

A-site cation: Methylammonium (MA^+), Formamidinium (FA^+), Cesium (Cs^+)

B-site cation: Lead (Pb^{2+}) or Tin (Sn^{2+})

X-site anion: Iodide (I^-), Bromide (Br^-), or Chloride (Cl^-)

The crystal structure can be tuned by modifying these ions, enabling optimization of band gap, stability, carrier mobility, and light absorption characteristics. Mixed-cation and mixed-halide compositions have become particularly important for improving efficiency and long-term stability. The operation of PSCs involves several sequential processes:

- Absorption of sunlight by the perovskite absorber.
- Generation of electron–hole pairs.
- Separation of charge carriers.
- Electron transport through the electron transport layer (ETL).
- Hole transport through the hole transport layer (HTL).
- Collection of charges at the electrodes to generate electricity.

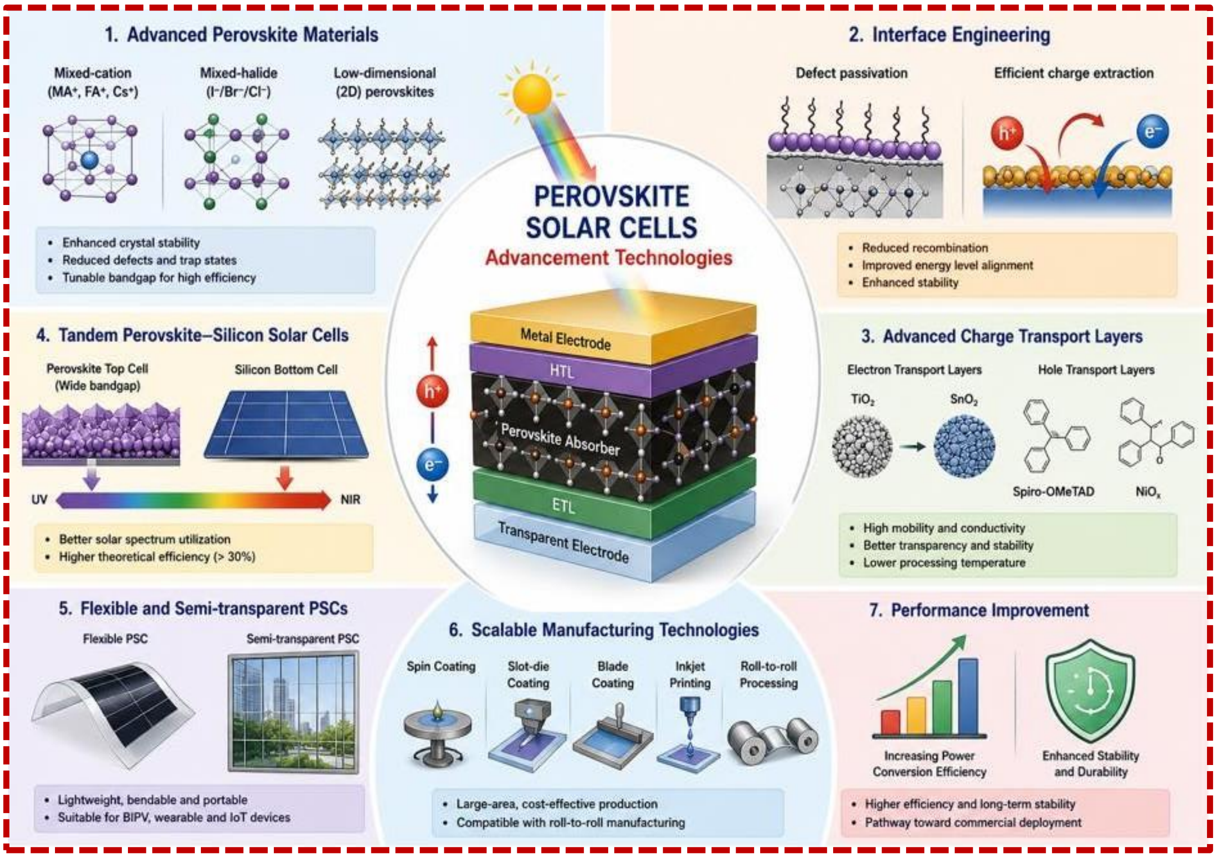
Efficient charge extraction and minimal recombination losses are essential for achieving high photovoltaic performance. Recent interface engineering strategies have substantially reduced defect-induced recombination, thereby increasing both efficiency and stability.

Recent Advances in Perovskite Solar Cells:

Perovskite solar cells (PSCs) have experienced remarkable progress over the past decade, making them one of the fastest-growing photovoltaic technologies. Continuous innovations in perovskite composition, interface engineering, charge transport materials, tandem device architectures, and scalable fabrication techniques have resulted in unprecedented improvements in power conversion efficiency (PCE) and operational stability. According to recent reports, certified efficiencies of single-junction PSCs have exceeded 27%, while perovskite–silicon tandem solar cells have achieved efficiencies greater than 34%, demonstrating the enormous potential of this technology for next-generation renewable energy systems (Kabir *et al*., 2018).

Advances in Perovskite Material Engineering:

Material engineering has been a major driving force behind the rapid improvement of PSC performance. Early devices primarily employed methylammonium lead iodide ($MAPbI_3$), which exhibited high efficiency but suffered from poor thermal and moisture stability. Consequently, researchers have developed mixed-cation and mixed-halide perovskites by incorporating formamidinium (FA^+), cesium (Cs^+), and rubidium (Rb^+), resulting in enhanced crystal quality, reduced defect density, and improved environmental stability. The incorporation of multiple cations stabilizes the perovskite crystal lattice by reducing structural distortion and suppressing phase transitions. Similarly, mixed-halide compositions enable band-gap tuning, allowing optimization for both single-junction and tandem solar cell applications (Reddy *et al*., 2020). Wide-bandgap perovskites have become particularly important for tandem architectures because they efficiently absorb high-energy photons while allowing lower-energy photons to pass to the silicon bottom cell. Another important development is defect passivation. Grain boundaries and crystal defects act as recombination centers that reduce photovoltaic performance. Recent studies have demonstrated that incorporating organic ammonium salts, Lewis bases, alkali-metal ions, and two-dimensional (2D) perovskite layers effectively passivates these defects, thereby increasing carrier lifetime, open-circuit voltage, and overall device efficiency.



Interface Engineering:

Interface engineering has emerged as one of the most effective strategies for enhancing PSC efficiency and long-term stability. Since charge extraction occurs at the interfaces between the perovskite absorber and transport layers, minimizing interfacial defects is essential for reducing charge recombination losses (Nakamura *et al*., 2019). Surface passivation techniques using self-assembled monolayers (SAMs), fullerene derivatives, organic molecules, and polymer coatings have significantly improved charge transfer while suppressing non-radiative recombination. These modifications also enhance energy-level alignment between adjacent layers, resulting in higher fill factors and increased power conversion efficiencies. In addition, advanced interfacial engineering improves moisture resistance and thermal durability by preventing ion migration and chemical reactions between device layers. Such improvements have substantially increased operational stability under continuous illumination and elevated temperatures, bringing PSCs closer to commercial reliability.

Development of Advanced Charge Transport Layers:

Charge transport layers (CTLs) play a crucial role in facilitating efficient extraction of photogenerated electrons and holes while minimizing recombination losses. Significant progress has been made in developing both electron transport layers (ETLs) and hole transport layers (HTLs). Traditional ETLs such as titanium dioxide (TiO_2) have been partially replaced by tin oxide (SnO_2) because of its superior electron mobility, lower processing temperature, excellent optical transparency, and reduced ultraviolet-induced degradation (Das *et al.*, 2018). Surface modification of SnO_2 nanoparticles further improves electron extraction efficiency and suppresses interface defects. Similarly, conventional organic HTLs such as Spiro-OMeTAD have been modified through dopant engineering and molecular design to improve conductivity and reduce moisture sensitivity. Alternative inorganic HTLs including nickel oxide (NiO_x), copper thiocyanate (CuSCN), and copper oxide (Cu_2O) have also attracted considerable attention due to their superior thermal stability, lower cost, and enhanced chemical durability.

Tandem Perovskite–Silicon Solar Cells:

One of the most significant breakthroughs in recent photovoltaic research is the development of tandem perovskite–silicon solar cells. Unlike conventional silicon solar cells, tandem devices combine a wide-bandgap perovskite top cell with a crystalline silicon bottom cell, allowing more efficient utilization of the solar spectrum. The perovskite absorber efficiently converts short-wavelength photons into electricity, while longer-wavelength photons pass through to the silicon layer. This complementary absorption significantly reduces thermalization losses and increases theoretical efficiency beyond the Shockley–Queisser limit for single-junction devices. Recent advances in tandem device fabrication have resulted in certified efficiencies exceeding 34%, making tandem PSCs among the most efficient photovoltaic technologies reported to date. Furthermore, improvements in interface passivation, textured silicon substrates, optical management, and low-temperature processing have enhanced both efficiency and operational durability, indicating strong prospects for industrial-scale commercialization.

Flexible and Semi-Transparent Perovskite Solar Cells:

The exceptional mechanical flexibility of perovskite materials has enabled the development of lightweight and bendable photovoltaic devices. Flexible PSCs can be fabricated on polymer substrates using low-temperature solution processing, making them suitable for wearable electronics, portable power systems, Internet of Things (IoT) devices, and aerospace applications. Semi-transparent PSCs have also gained increasing attention because they can simultaneously generate electricity while transmitting visible light. These characteristics make them highly attractive for building-integrated photovoltaics (BIPV), greenhouse agriculture, automobile sunroofs, and smart windows. Continued improvements in transparent electrodes and perovskite band-gap engineering have further enhanced their optical and electrical performance.

Scalable Manufacturing Technologies:

Although laboratory-scale PSCs have demonstrated exceptional efficiencies, commercial deployment requires scalable and cost-effective manufacturing techniques. Researchers are therefore focusing on transitioning from spin coating toward industrially compatible fabrication methods such as slot-die coating, blade coating, inkjet printing, spray coating, and roll-to-roll processing. These scalable deposition techniques enable continuous production of large-area perovskite modules while reducing manufacturing costs and material wastage. Simultaneously, advances in solvent engineering, crystallization control, and ambient-air processing have improved film uniformity and reproducibility. Such developments are expected to facilitate large-scale commercialization of PSC technology in the near future.

Future Perspectives:

The future of perovskite solar cells lies in overcoming challenges associated with long-term stability, environmental sustainability, and large-scale commercialization. Research is increasingly focused on developing lead-free perovskite materials, advanced encapsulation strategies, and defect passivation techniques to enhance device durability and reduce environmental concerns. Integration of artificial intelligence and machine learning for materials discovery and device optimization is expected to accelerate innovation. Furthermore, scalable manufacturing methods such as roll-to-roll printing and tandem perovskite–silicon architectures will facilitate industrial production. Continued interdisciplinary collaboration between materials scientists, engineers, and industry partners will be crucial for realizing the commercial potential of perovskite solar cells.

Conclusion:

Perovskite solar cells have emerged as a transformative photovoltaic technology owing to their high-power conversion efficiency, low-cost fabrication, and versatile device architectures. Significant advances in material engineering, interface optimization, tandem solar cell design, and scalable manufacturing have accelerated their progress toward commercialization. Nevertheless, challenges related to long-term stability, lead toxicity, and large-scale production remain. Continued interdisciplinary research focusing on environmentally friendly materials, improved durability, and industrial-scale fabrication is expected to enable widespread adoption of perovskite solar cells for sustainable and efficient renewable energy generation.

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