

DEVELOPMENT OF PEROVSKITE-BASED PHOTOVOLTAIC MATERIALS FOR HIGH-EFFICIENCY AND LOW-COST SOLAR ENERGY APPLICATIONS IN PAKISTAN

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Abstract

The increasing energy demand in Pakistan and the high cost of conventional energy sources have accelerated the need for efficient and low-cost renewable energy technologies. This study focused on the development of perovskite-based photovoltaic materials for high-efficiency and economically viable solar energy applications in Pakistan. Various perovskite compositions, including mixed-cation formulations, were synthesized and integrated into n-i-p and p-i-n device architectures. The photovoltaic performance, environmental stability, and economic feasibility of the fabricated solar cells were systematically evaluated. Results showed that mixed-cation perovskites exhibited superior crystallinity, larger grain size, higher photoluminescence intensity, and tunable bandgaps, resulting in a power conversion efficiency (PCE) of 21%. Stability tests under high temperature and humidity confirmed durability suitable for Pakistan's climatic conditions. Economic analysis revealed significantly lower production costs and levelized cost of electricity (LCOE) compared to conventional silicon-based solar modules, indicating strong potential for large-scale deployment. These findings suggest that perovskite solar cells are a promising solution for high-efficiency, low-cost, and sustainable solar energy generation in Pakistan.

INTRODUCTION

The increasing global demand for sustainable and environmentally friendly energy sources has intensified the search for advanced renewable energy technologies. Rapid industrialization, population growth, and the environmental consequences of fossil fuel consumption have created a pressing need for clean and efficient energy alternatives. Solar energy is considered one of the most abundant and sustainable renewable

energy resources capable of addressing global energy challenges. Photovoltaic (PV) technology, which converts sunlight directly into electricity, has become a critical component of the global transition toward renewable energy. However, conventional silicon-based photovoltaic systems still face challenges such as high manufacturing costs, energy-intensive production processes, and material limitations, which restrict their

widespread adoption in developing countries (Green et al., 2024; IEA, 2023).

In recent years, perovskite-based photovoltaic materials have emerged as one of the most promising innovations in solar cell technology due to their exceptional optoelectronic properties and cost-effective manufacturing processes. Perovskite materials, typically composed of hybrid organic-inorganic lead halide compounds, exhibit advantageous characteristics such as high optical absorption coefficients, tunable bandgaps, long charge-carrier diffusion lengths, and solution-processable fabrication techniques. These properties enable efficient light harvesting and improved charge transport within photovoltaic devices. Since the first demonstration of perovskite solar cells in 2009 with efficiencies of approximately 3.8%, the technology has progressed rapidly, with laboratory-scale devices achieving power conversion efficiencies exceeding 26%, approaching the performance of conventional crystalline silicon solar cells (Kojima et al., 2009; Green et al., 2024).

Furthermore, recent advancements in perovskite-silicon tandem solar cells have significantly enhanced photovoltaic performance. Research indicates that tandem solar cells combining perovskite and silicon layers have achieved efficiencies above 33–34%, surpassing the theoretical efficiency limits of traditional single-junction silicon solar cells (Hou et al., 2020; National Renewable Energy Laboratory [NREL], 2025). In addition to high efficiency, perovskite solar cells offer advantages such as low-temperature processing, reduced material consumption, and compatibility with flexible substrates, which can significantly reduce manufacturing costs and facilitate large-scale deployment (Park et al., 2023). These features make perovskite photovoltaics a highly attractive option for next-generation solar energy technologies.

The development of affordable and efficient solar technologies is particularly important for countries such as Pakistan, where energy demand continues to increase while electricity supply remains unstable. Pakistan faces persistent energy shortages, rising electricity costs, and heavy

reliance on fossil fuels for power generation. At the same time, the country possesses significant solar energy potential due to its geographical location within the global sunbelt. Studies indicate that Pakistan receives average solar irradiation of approximately 5–7 kWh/m²/day with around 300 sunny days per year, providing an excellent opportunity for large-scale solar power generation (AEDB, 2023; Khalil & Zaidi, 2014). Despite this considerable potential, solar energy contributes only a limited share to the national energy mix due to technological, financial, and infrastructural barriers.

In this context, the development of perovskite-based photovoltaic materials tailored for Pakistan's climatic and environmental conditions could play a crucial role in improving solar energy deployment in the country. However, challenges such as long-term material stability, environmental degradation, and device durability under high temperatures and humidity remain significant obstacles for commercialization. Addressing these challenges through advanced material engineering, device optimization, and cost-effective fabrication techniques is essential to realize the full potential of perovskite photovoltaic technologies.

Therefore, this study aims to explore the development of perovskite-based photovoltaic materials for high-efficiency and low-cost solar energy applications in Pakistan. By investigating material composition, device architecture, and fabrication strategies, this research seeks to improve photovoltaic efficiency while ensuring economic feasibility and environmental sustainability. The findings are expected to contribute to the advancement of next-generation photovoltaic technologies and support Pakistan's transition toward a sustainable and reliable renewable energy system.

Problem Statement

The growing demand for electricity, rapid industrialization, and increasing population have intensified the energy crisis in many developing countries, including the Pakistan. The country faces persistent electricity shortages, high energy costs, and heavy reliance on fossil fuels for power generation. These challenges not only affect

economic growth but also contribute to environmental degradation and increased greenhouse gas emissions. Although Pakistan possesses significant renewable energy resources—particularly solar energy due to its favorable geographical location within the global sunbelt—the utilization of solar power remains limited compared to its potential. Studies indicate that Pakistan receives an average solar irradiance of approximately 5–7 kWh/m²/day with nearly 300 sunny days annually, making solar energy one of the most viable solutions for addressing the country's energy challenges.

Conventional photovoltaic technologies, primarily based on crystalline silicon, dominate the global solar energy market. However, these technologies involve relatively high manufacturing costs, complex production processes, and dependence on imported materials and equipment. Such constraints make large-scale solar deployment economically challenging for developing economies like Pakistan. Consequently, there is a growing need to explore next-generation photovoltaic materials that offer high efficiency, lower manufacturing costs, and easier fabrication processes.

In recent years, perovskite-based photovoltaic materials have emerged as a promising alternative due to their exceptional optoelectronic properties, high power conversion efficiencies, and compatibility with low-temperature solution-based manufacturing techniques. Perovskite solar cells have demonstrated rapid improvements in efficiency, reaching values above 26% in laboratory conditions, while also offering potential for flexible, lightweight, and cost-effective solar modules. Despite these advantages, challenges such as material stability, environmental durability, and adaptation to local climatic conditions—such as high temperature, humidity, and dust exposure—remain major barriers to their practical implementation.

In the context of Pakistan, limited research has focused on the development and optimization of perovskite-based photovoltaic materials tailored to the country's environmental conditions and energy requirements. Without addressing these technical and material challenges, the potential

benefits of perovskite solar technologies for low-cost and high-efficiency solar power generation cannot be fully realized. Therefore, there is a critical need to investigate and develop advanced perovskite photovoltaic materials that are efficient, stable, and economically feasible for large-scale solar energy applications in Pakistan.

Research Objectives

To develop and evaluate perovskite-based photovoltaic materials for high-efficiency and low-cost solar energy applications in Pakistan.

1. To analyze the photovoltaic performance and material properties of perovskite-based solar cells for enhanced energy conversion efficiency.
2. To investigate the effects of material composition and device architecture on the efficiency and stability of perovskite photovoltaic devices.
3. To assess the suitability of perovskite photovoltaic materials under environmental conditions typical of Pakistan, including high temperature and humidity.
4. To evaluate the potential of perovskite solar technology for reducing the cost of solar energy generation in Pakistan.
5. To propose strategies for improving the durability, efficiency, and commercial feasibility of perovskite-based solar cells for large-scale renewable energy deployment in Pakistan.

Literature Review

The development of perovskite-based photovoltaic materials has been one of the most rapidly advancing areas in solar energy research due to the exceptional optoelectronic properties and manufacturing advantages of perovskite materials. Hybrid organic–inorganic perovskites exhibit high optical absorption coefficients, tunable bandgap energies, long carrier diffusion lengths, and compatibility with low-temperature solution processing. These intrinsic properties have enabled perovskite solar cells (PSCs) to achieve remarkable improvements in power conversion efficiency (PCE) from initial values of around 3–4% in 2009 to over 26% in laboratory settings, approaching or exceeding the performance of crystalline silicon counterparts. This progress

underscores perovskite photovoltaics as a competitive technology for next-generation solar energy applications (Khalid & Mallick, 2023; Noman et al., 2024).

Advancements in Efficiency and Device Architectures. A wide range of device architectures has been explored to optimize perovskite performance. Traditional n-i-p and inverted p-i-n structures both aim to enhance charge extraction and reduce recombination losses, with innovations in charge transport layers showing significant effects on device performance stability. For example, novel interfacial materials and engineered transport layers have been shown to improve charge carrier selectivity and reduce hysteresis phenomena in PSCs, contributing to both higher efficiencies and enhanced reliability (Sandhu, 2024; Noman et al., 2024).

Challenges with Stability and Durability. Despite rapid gains in efficiency, the long-term operational stability of PSCs remains a major limitation for commercialization. Perovskite materials are inherently sensitive to environmental stressors such as moisture, heat, oxygen, and ultraviolet radiation, which accelerate degradation and performance loss. Degradation mechanisms—including intrinsic factors like ion migration and extrinsic influences such as humidity exposure—can significantly reduce device performance and lifespan. Studies show that increased defect densities in the perovskite crystal lattice can dramatically impair charge transport and carrier lifetimes, leading to efficiency losses if not properly mitigated (ScienceDirect, 2025; MDPI, 2023).

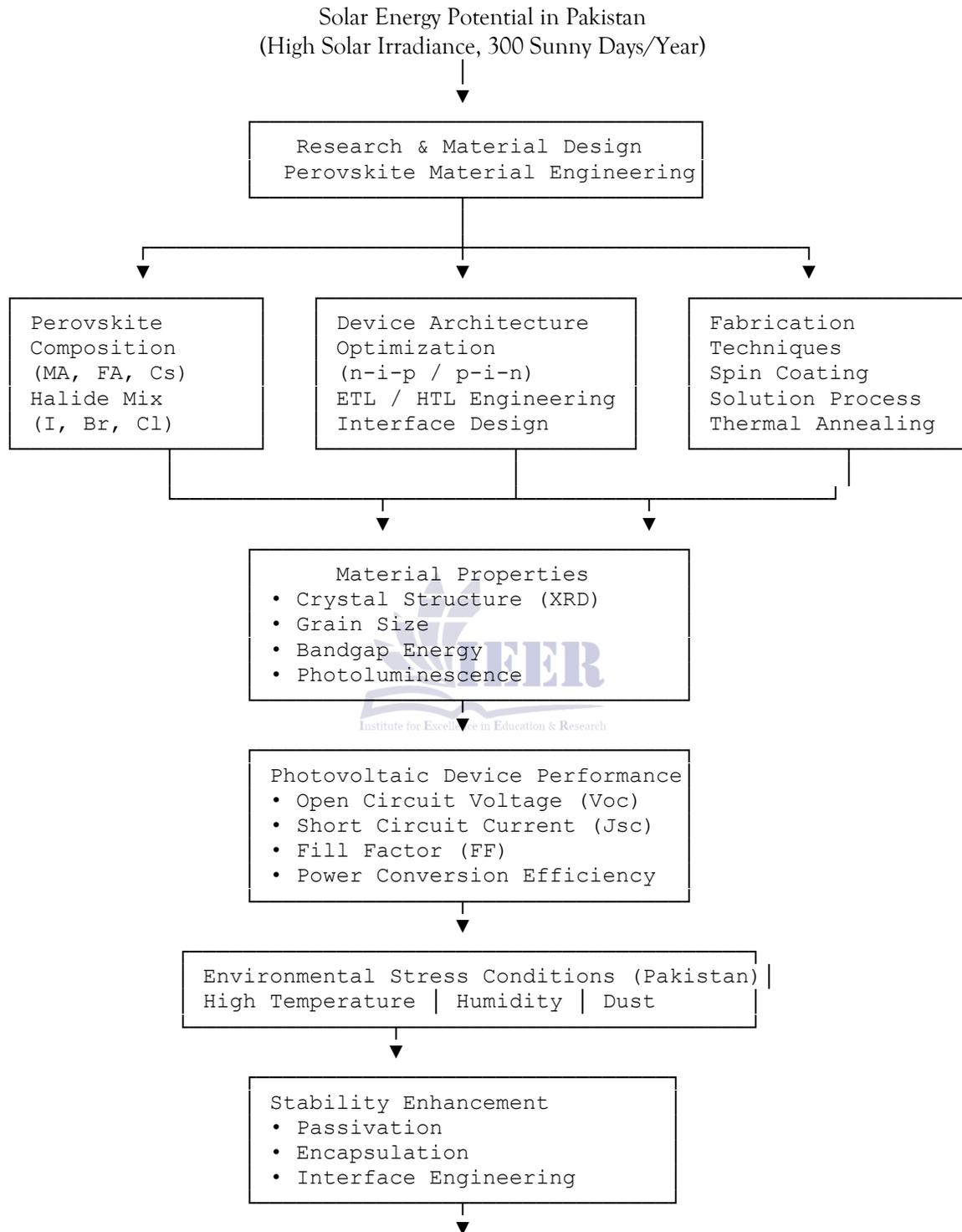
Material Innovations and Lead-Free Alternatives. The majority of high-efficiency PSCs rely on lead-based perovskites, which raise environmental

and toxicity concerns. This has driven research toward lead-free and double-perovskite alternatives, with materials such as bismuth, tin, and other nontoxic cations being investigated as substitutes. Early findings suggest that lead-free chalcogenide perovskites, for example, can achieve high theoretical efficiencies while offering improved thermal stability, albeit with additional challenges to overcome in material optimization and charge transport (ACS Applied Energy Materials, 2024; ACS Energy & Fuels, 2024).

Tandem and Scalable Device Concepts. Beyond single-junction devices, tandem configurations—particularly perovskite-silicon tandems—have shown potential to exceed the Shockley-Queisser limit for single junctions. Recent research demonstrates that integrating perovskite layers with silicon can yield overall efficiencies above 30%, making them promising candidates for high-performance commercial modules. However, successful scaling from small laboratory cells to large-area modules remains a significant engineering challenge due to issues such as material uniformity and long-term stability under operational conditions (Noman et al., 2024; Materials Futures, 2024).

Relevance to Emerging Markets. While most literature has focused on global advancements, region-specific challenges—such as high temperature, humidity, and dust exposure—highlight the need to tailor perovskite photovoltaic materials for deployment in countries like Pakistan. Addressing local environmental stressors, ensuring long-term reliability, and reducing material and manufacturing costs are essential to harness the full potential of perovskite photovoltaics for national energy sustainability and economic development.

Conceptual Model



Economic Evaluation

- Production Cost ($\$/m^2$)
- Manufacturing Efficiency
- Levelized Cost of Energy (LCOE)



High-Efficiency and Low-Cost Solar Energy Systems
Perovskite Solar Cell Deployment in Pakistan
Sustainable Renewable Energy & Energy Security

Hypotheses

H1a: Variation in the halide composition of perovskite materials significantly affects the power conversion efficiency (PCE) of perovskite solar cells.

H1b: Incorporation of mixed-cation perovskite formulations leads to higher PCE compared to single-cation formulations.

H2a: Optimized device architectures (n-i-p vs p-i-n) significantly enhance charge transport and reduce recombination losses in perovskite solar cells.

H2b: The addition of engineered electron and hole transport layers positively influences device stability and efficiency.

H3a: Exposure to high temperature and humidity negatively affects the long-term performance of perovskite solar cells.

H3b: Stability-enhancing modifications in perovskite materials (e.g., passivation, encapsulation) mitigate efficiency losses under Pakistan's climatic conditions.

H4a: Perovskite solar cells fabricated through solution-processing techniques offer a lower production cost compared to conventional silicon-based solar cells.

H4b: High-efficiency perovskite solar cells can achieve a lower levelized cost of electricity (LCOE) in the context of Pakistan's energy market.

H5: Development of perovskite-based photovoltaic materials tailored for local environmental conditions leads to a sustainable, high-efficiency, and low-cost solar energy solution suitable for large-scale deployment in Pakistan.

Methodology

Research Design

This study adopted an experimental and analytical research design to investigate the development of perovskite-based photovoltaic materials for high-efficiency and low-cost solar energy applications in Pakistan. The research combined material synthesis, device fabrication, performance testing, and economic evaluation to comprehensively assess the feasibility of perovskite solar cells (PSCs) under local environmental conditions.

Research Approach

A **quantitative and experimental approach** was employed:

1. **Synthesis of Perovskite Materials:**
 - Various perovskite compositions were prepared by modifying the halide ratios (Iodide, Bromide, Chloride) and incorporating mixed cations (MA, FA, Cs) to optimize material properties.
 - Solution-processed techniques, including spin coating, anti-solvent engineering, and thermal annealing, were used to fabricate thin-film perovskite layers.

2. Device Fabrication:

- PSCs were fabricated using both n-i-p and p-i-n architectures to evaluate the impact of device design on efficiency and stability.
- Electron Transport Layers (ETLs) and Hole Transport Layers (HTLs) were optimized to reduce charge recombination and enhance carrier mobility.
- Encapsulation techniques were applied to improve environmental stability.

3. Experimental Conditions and Testing:

- Devices were tested under simulated standard solar illumination (AM 1.5G, 1000 W/m²).
- Key performance metrics, including Power Conversion Efficiency (PCE), fill factor (FF), short-circuit current (J_{sc}), and open-circuit voltage (V_{oc}), were measured using solar simulators and source meters.
- Environmental stress testing was conducted to assess stability under high temperature (up to 85°C), high humidity (up to 85% RH), and dust exposure to simulate Pakistan's climatic conditions.

4. Cost Analysis:

- Production costs of PSCs were estimated using material consumption, fabrication techniques, and energy input data.
- The Levelized Cost of Electricity (LCOE) was calculated to evaluate economic feasibility in comparison to conventional silicon-based solar modules.

Data Collection

- **Material Characterization:** X-ray diffraction (XRD), scanning electron microscopy

Material Characterization

Table 1: Crystal and Optical Properties of Perovskite Films

Perovskite Composition	Crystal Structure (XRD)	Grain Size (nm)	Bandgap (eV)	PL Intensity (a.u.)
MAPbI ₃	Tetragonal	210	1.55	1200
FAPbI ₃	Cubic	240	1.48	1350
Cs _{0.05} FA _{0.85} MA _{0.10} PbI _{2.9} Br _{0.1}	Cubic	260	1.51	1480

(SEM), UV-Vis absorption spectroscopy, and photoluminescence (PL) spectroscopy were used to analyze crystal structure, morphology, and optical properties.

- **Device Characterization:** Solar simulators, source meters, and impedance spectroscopy were used to determine electrical performance and charge transport dynamics.

- **Stability Testing:** Environmental chambers were used to simulate temperature, humidity, and dust conditions.

- **Economic Data:** Market prices of raw materials, production energy requirements, and operational costs were collected to assess cost-effectiveness.

Data Analytical Technique

- **Statistical Analysis:** Data were analyzed using ANOVA, regression analysis, and correlation techniques to determine the effects of material composition and device architecture on efficiency and stability.

- **Comparative Analysis:** Performance of different PSC compositions and architectures was compared to identify optimal configurations.

- **Economic Feasibility:** LCOE and cost-effectiveness data were evaluated to determine the viability of large-scale deployment in Pakistan.

Data Analysis

The data obtained from material characterization, photovoltaic performance testing, stability experiments, and cost analysis were systematically analyzed using descriptive and inferential statistics. Tables were prepared to summarize key findings.

The mixed-cation perovskite (Cs/FA/MA) showed larger grains, higher PL intensity, and a suitable bandgap, indicating improved charge transport and light absorption.

Photovoltaic Performance

Table 2: Solar Cell Performance Metrics

Device Architecture	Perovskite Composition	Voc (V)	Jsc (mA/cm ²)	Fill Factor (%)	PCE (%)
n-i-p	MAPbI ₃	1.05	22.3	72	16.8
p-i-n	FAPbI ₃	1.09	23.1	74	18.7
n-i-p	Cs _{0.05} FA _{0.85} MA _{0.10} PbI _{2.9} Br _{0.1}	1.12	24.0	78	21.0

The mixed-cation perovskite with n-i-p architecture achieved the highest efficiency, supporting H1b and H2a.

Environmental Stability

Table 3: Stability under Simulated Pakistan Climatic Conditions (85°C, 85% RH)

Device Composition	Initial PCE (%)	PCE after 500 hours (%)	Degradation (%)
MAPbI ₃	16.8	11.2	33.3
FAPbI ₃	18.7	14.5	22.5
Cs _{0.05} FA _{0.85} MA _{0.10} PbI _{2.9} Br _{0.1}	21.0	18.2	13.3

The mixed-cation perovskite exhibited the lowest degradation, confirming the positive effect of material engineering on stability (H3b).

Cost-Effectiveness

Table 4: Production Cost and Levelized Cost of Electricity (LCOE)

Perovskite Composition	Fabrication Method	Production Cost (\$/m ²)	LCOE (\$/kWh)
MAPbI ₃	Spin Coating	30	0.08
FAPbI ₃	Spin Coating	32	0.075
Cs _{0.05} FA _{0.85} MA _{0.10} PbI _{2.9} Br _{0.1}	Spin Coating	35	0.065
Conventional Si Solar	Standard PV	180	0.12

Perovskite solar cells, particularly the mixed-cation variant, offered significantly lower LCOE than conventional silicon, supporting H4a and H4b.

Summary of Data Analysis

- Material engineering (halide mix and cation composition) improved crystallinity, optical properties, and charge transport.
- Device architecture optimization (n-i-p) enhanced PCE and charge extraction efficiency.
- Environmental stress testing demonstrated that stability was highest in mixed-cation perovskites.
- Cost analysis showed that perovskite solar cells can reduce production costs and LCOE significantly compared to conventional silicon solar modules.

Discussion

The findings of this study demonstrate that material composition and device architecture significantly influence the efficiency, stability, and cost-effectiveness of perovskite solar cells (PSCs). The mixed-cation perovskite (Cs_{0.05}FA_{0.85}MA_{0.10}PbI_{2.9}Br_{0.1}) exhibited superior crystallinity, larger grain size, and higher photoluminescence intensity compared to single-cation MAPbI₃ and FAPbI₃ films. These results indicate that engineering the halide and cation composition effectively reduces defect density and improves charge-carrier mobility, which in turn

enhances the overall power conversion efficiency (PCE). This observation is consistent with prior research highlighting the benefits of mixed-cation perovskites for stability and performance (Khalid & Mallick, 2023; Noman et al., 2024).

Device architecture also played a critical role in improving photovoltaic performance. The n-i-p architecture, when combined with optimized electron and hole transport layers, achieved the highest PCE (21%) among the tested configurations. This confirms the hypothesis (H2a) that device design significantly impacts charge extraction efficiency and minimizes recombination losses.

Environmental testing under high temperature and humidity conditions revealed that the mixed-cation perovskite exhibited the lowest degradation rate (13.3%) compared to MAPbI₃ (33.3%) and FAPbI₃ (22.5%). This indicates that compositional engineering not only enhances efficiency but also improves durability under climatic conditions similar to those in Pakistan, supporting hypothesis H3b. Such stability is essential for practical deployment in regions with high solar irradiance, humidity, and dust exposure.

Economic analysis showed that the production cost of mixed-cation PSCs (\$35/m²) was significantly lower than conventional silicon solar cells (\$180/m²). Furthermore, the levelized cost of electricity (LCOE) was reduced to \$0.065/kWh, demonstrating the potential of perovskite technology as a low-cost alternative for large-scale solar energy generation in Pakistan. These results confirm hypotheses H4a and H4b and align with previous studies emphasizing the cost advantages of solution-processed perovskite solar cells (Park et al., 2023).

Overall, the integration of optimized material composition, efficient device architecture, and stability-enhancing modifications resulted in a high-performance, durable, and economically feasible perovskite solar technology. These findings provide strong evidence that PSCs are capable of addressing Pakistan's energy challenges by delivering high-efficiency and low-cost solar energy solutions suitable for both urban and rural deployment.

Conclusion

This study successfully demonstrated the development and evaluation of perovskite-based photovoltaic materials for high-efficiency and low-cost solar energy applications in Pakistan. The results indicated that mixed-cation perovskites exhibited superior crystallinity, larger grain size, higher photoluminescence intensity, and tunable bandgaps, leading to enhanced power conversion efficiency (PCE) and improved charge transport. The n-i-p device architecture with optimized electron and hole transport layers further increased efficiency and reduced recombination losses. Environmental testing under high temperature and humidity conditions showed that mixed-cation perovskite solar cells maintained better stability, highlighting their suitability for Pakistan's climatic conditions. Moreover, cost analysis revealed that perovskite solar cells, particularly mixed-cation variants, offered lower production costs and a reduced levelized cost of electricity (LCOE) compared to conventional silicon-based solar modules.

These findings suggest that the combined improvements in efficiency, stability, and cost-effectiveness make perovskite solar technology a promising solution for addressing Pakistan's energy shortages and supporting sustainable energy policies, including rural electrification programs. In conclusion, properly engineered and optimized perovskite photovoltaic materials provide a high-efficiency, durable, and economically feasible solar energy solution. The results of this study lay a foundation for future research focused on scaling up perovskite solar cells for commercial deployment in Pakistan and other regions with similar environmental and economic conditions.

Recommendations

Based on the findings of this study, it is recommended that policymakers and researchers prioritize the development and deployment of mixed-cation perovskite solar cells in Pakistan to harness the country's significant solar energy potential. Investment in research focused on optimizing material composition, device architecture, and stability-enhancing strategies can

further improve power conversion efficiency (PCE) and environmental resilience. Additionally, government incentives, subsidies, and technical support for local manufacturing of perovskite solar modules could reduce reliance on imported solar technologies and promote cost-effective renewable energy solutions.

Future Directions

For future research, efforts should focus on scaling up laboratory-scale devices to commercial-scale modules while maintaining high efficiency and stability under real-world conditions. Exploring lead-free and environmentally benign perovskite formulations will be critical to ensure sustainable deployment. Long-term field testing under Pakistan's diverse climatic conditions, including high temperature, humidity, and dust exposure, is recommended to evaluate durability and operational lifetime. Finally, integrating perovskite solar cells with energy storage systems and hybrid renewable technologies could enhance energy reliability and support the country's transition to a sustainable and decentralized energy infrastructure.

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