

Analysis of Lead-Free Perovskite Solar Cell Materials for High-Efficiency Photovoltaic Under Climatic Change

Dr. Dharmendra Kumar

Associate Professor, Department of Physics, K.K. (P.G.) College, Etawah, INDIA

Corresponding Author: dkjcb2010@gmail.com



www.jrasb.com || Vol. 3 No. 6 (2024): December Issue

Received: 06-12-2024

Revised: 17-12-2024

Accepted: 23-12-2024

ABSTRACT

The rapid advancement of perovskite solar cells (PSCs) has positioned them as promising candidates for next-generation photovoltaic technologies due to their high power conversion efficiency (PCE), low fabrication cost, and tunable optoelectronic properties. However, conventional perovskite absorbers contain lead (Pb), raising environmental and health concerns that limit large-scale deployment, particularly in countries such as India where high solar irradiance and expanding renewable energy infrastructure create strong demand for sustainable photovoltaic solutions. Lead-free perovskite materials based on tin (Sn), bismuth (Bi), antimony (Sb), titanium (Ti), and double perovskite structures have emerged as viable alternatives. This research paper presents a comprehensive analysis of lead-free perovskite materials, focusing on their structural characteristics, photovoltaic performance, stability challenges, and suitability under Indian climatic conditions characterized by high temperature (40–50°C), high humidity during monsoons, and significant dust accumulation. The study evaluates material engineering strategies, interface optimization, additive incorporation, and encapsulation techniques developed up to 2024. Results indicate that tin-based perovskites currently demonstrate the highest efficiencies among lead-free systems, whereas double perovskites offer superior environmental stability. The paper concludes with recommendations for climate-adapted device engineering, field testing in Indian conditions, and future research directions for scalable and sustainable photovoltaic deployment.

Keywords- Perovskite Materials, Solar Cell, Climatic Parameters.

I. INTRODUCTION

India has rapidly expanded its solar energy capacity under national renewable energy initiatives, positioning photovoltaic technology as a cornerstone of sustainable development [1]. The country's high solar irradiance makes it ideally suited for solar power generation. However, the durability and environmental safety of photovoltaic materials are critical for long-term deployment.

Perovskite solar cells have attracted global scientific attention due to their remarkable rise in efficiency, surpassing 25% in laboratory-scale devices. Their success stems from strong light absorption, long carrier diffusion lengths, tunable bandgaps, and solution-processable fabrication techniques [2].

Despite these advantages, traditional perovskite absorbers contain lead (Pb), which poses environmental toxicity concerns. Potential leakage during module degradation or disposal may create ecological hazards, particularly in tropical regions with heavy rainfall [3].

To address these concerns, researchers have developed lead-free perovskite materials that replace Pb with less toxic elements such as Sn, Bi, Sb, and Ti. These alternatives aim to maintain favorable optoelectronic properties while reducing environmental risk [4].

Indian climatic conditions present unique challenges for PSC stability. High summer temperatures accelerate thermal degradation and ion migration, while monsoonal humidity enhances moisture-induced decomposition. Additionally, dust deposition reduces optical transmission and increases thermal stress [5].

Tin-based perovskites are considered the closest structural analogues to lead-based materials, offering suitable bandgaps (~1.2–1.4 eV). However, oxidation of Sn^{2+} to Sn^{4+} significantly reduces device stability [6].

Double perovskites such as $\text{Cs}_2\text{AgBiBr}_6$ exhibit improved chemical stability but often suffer from wider bandgaps, limiting current density and overall efficiency [7].

Device architecture also plays a critical role in performance under environmental stress. Transport layer compatibility, interface engineering, and encapsulation strategies strongly influence operational lifetime.

Stability enhancement through additive engineering, dimensional control (2D/3D hybrid structures), and surface passivation has significantly improved device durability up to 2024 [8].

Given India's climate diversity and renewable energy goals, it is essential to evaluate lead-free perovskite materials not only in terms of efficiency but also in terms of thermal resilience, moisture tolerance, and scalability.

The present study systematically reviews lead-free perovskite materials and assesses their suitability for photovoltaic applications under Indian climatic conditions.

II. METHODOLOGY

This research adopts a systematic and analytical literature review methodology based on peer-reviewed journal publications, conference proceedings, technical reports, and internationally recognized photovoltaic performance databases published up to 2024 [1]. The primary objective of this methodology is to critically evaluate the progress, performance trends, stability challenges, and climate adaptability of lead-free perovskite solar cell materials with particular emphasis on their deployment potential under Indian environmental conditions.

The literature survey was conducted using scientific databases such as Scopus, Web of Science, ScienceDirect, ACS Publications, RSC Publishing, Wiley Online Library, and SpringerLink. Keywords used during the search process included “lead-free perovskite solar cells,” “tin-based perovskites,” “double perovskite photovoltaics,” “perovskite stability under humidity,” “encapsulation strategies,” and “thermal degradation in PSCs.” Only studies published in English and reporting experimental photovoltaic data were considered.

Relevant studies were selected based on well-defined inclusion criteria. These criteria included:

1. Use of lead-free perovskite absorber materials (complete replacement of Pb).
2. Reported photovoltaic performance parameters (Voc, Jsc, FF, PCE).
3. Stability testing under thermal, humidity, or illumination stress.

4. Clear discussion of degradation pathways and mitigation strategies.

5. Reproducible device fabrication methods and transparent reporting standards.

Studies that lacked quantitative photovoltaic data, focused solely on theoretical simulations without experimental validation, or involved partial Pb substitution were excluded to maintain analytical consistency.

Material categories evaluated in this study include tin-based perovskites (e.g., FASnI_3 and MASnI_3 systems), double perovskites such as $\text{Cs}_2\text{AgBiBr}_6$, vacancy-ordered structures like Cs_2SnI_6 , and titanium-based halide perovskites [2]. These categories were selected because they represent the most extensively researched lead-free alternatives reported in literature up to 2024.

A comparative analysis of key photovoltaic parameters was performed to evaluate device performance across different material systems. The parameters analyzed include:

- **Open-circuit voltage (Voc):** indicator of recombination losses and material bandgap alignment.
- **Short-circuit current density (Jsc):** reflects light absorption efficiency and charge collection.
- **Fill factor (FF):** measures internal resistive losses and carrier transport quality.
- **Power conversion efficiency (PCE):** overall device performance metric.

Where available, certified efficiency records were prioritized over laboratory-only reports to ensure reliability.

Stability assessment formed a central component of the methodology. Data from accelerated aging tests were systematically reviewed, including:

- **Thermal cycling tests** (25–85°C temperature variation).
- **Humidity exposure studies** (relative humidity 60–90%).
- **Continuous illumination stress tests** under simulated AM 1.5G sunlight.
- **Combined stress testing** (heat + humidity + light), where reported [3].

Operational lifetime indicators such as T80 (time to 80% of initial efficiency) were compared across materials to assess durability trends.

Research addressing encapsulation technologies and environmental barrier strategies was integrated into the analysis to evaluate real-world feasibility. Studies on polymeric encapsulants, glass-glass lamination, edge sealing, and internal moisture barriers were reviewed to determine their effectiveness in extending device lifespan under harsh climatic conditions.

Thematic analysis was conducted to synthesize trends in material engineering strategies. Particular emphasis was placed on:

- Additive incorporation (e.g., SnF_2 antioxidants).

- Bandgap tuning via compositional engineering.
- Interface optimization and surface passivation.
- Dimensional engineering (2D/3D hybrid structures).
- Charge transport layer compatibility.

Indian climatic parameters were explicitly incorporated into the evaluation framework. These include temperature ranges between 20–50°C, relative humidity levels from 40–90% (particularly during monsoon seasons), and significant dust deposition in arid and semi-urban regions. These environmental factors were used as reference conditions when interpreting reported stability data.

Comparative interpretation rather than statistical meta-analysis was employed due to variations in fabrication methods, testing protocols, and reporting standards across studies. This approach allows identification of technological feasibility, strengths and weaknesses of material systems, and existing research gaps without overgeneralizing heterogeneous datasets.

Overall, this methodology provides a structured and climate-specific evaluation framework, ensuring that conclusions drawn regarding lead-free perovskite suitability are scientifically grounded and relevant to large-scale photovoltaic deployment in India.

III. RESULTS

The review indicates that tin-based perovskites demonstrate the highest efficiencies among lead-free materials, with reported PCE values exceeding 14% in optimized laboratory devices.

However, rapid oxidation of Sn²⁺ remains a primary stability limitation, particularly under high humidity conditions.

Double perovskite systems such as Cs₂AgBiBr₆ show lower efficiencies (typically below 10%) but exhibit significantly enhanced chemical and thermal stability.

Additive engineering using SnF₂ and antioxidant agents has reduced defect density and improved film morphology in tin-based systems.

2D/3D hybrid structures enhance moisture resistance by forming protective organic layers over the perovskite surface.

Encapsulation significantly improves operational lifetime under simulated Indian climatic stress.

Table 1: Lead-Free Perovskite Material Performance

Material Type	Bandgap (eV)	Typical PCE (%)	Stability Trend
FASnI ₃ -based	1.3	12–15	Moderate (oxidation sensitive)
Cs ₂ AgBiBr ₆	1.9	6–10	High chemical stability
Cs ₂ SnI ₆	1.5	5–8	Improved moisture resistance
Ti-based systems	1.8–2.0	<5	High stability, low efficiency

Table 2: Degradation Factors under Indian Conditions

Environmental Factor	Effect on Device	Impact Level
High Temperature	Ion migration, phase instability	High
High Humidity	Hydrolysis, oxidation	Very High
Dust Deposition	Reduced light absorption	Moderate
UV Exposure	Photochemical degradation	Moderate

Table 3: Stability Enhancement Strategies

Strategy	Mechanism	Effectiveness
SnF ₂ Additives	Oxidation suppression	High
2D/3D Structures	Surface protection	Moderate-High
Interface Passivation	Reduced recombination	High
Encapsulation	Moisture barrier	Very High

IV. DISCUSSION AND CONCLUSION

Lead-free perovskite research has made substantial progress toward environmentally safe photovoltaic materials. Tin-based perovskites currently offer the most promising efficiency levels, yet their environmental sensitivity demands improved oxidation control and encapsulation.

Double perovskites present a stability advantage that aligns well with India’s humid climate, though bandgap engineering remains necessary to achieve competitive efficiencies.

Indian climatic conditions amplify degradation pathways due to heat and humidity. Therefore, future development must prioritize thermal tolerance and moisture-resistant device architectures.



Encapsulation and module engineering will be critical for real-world deployment. Climate-adapted testing protocols should be implemented to evaluate device performance under realistic diurnal and seasonal cycles.

Future research should focus on scalable manufacturing processes compatible with Indian photovoltaic industries, lifecycle safety evaluation, and long-term outdoor stability data collection.

In conclusion, while lead-free perovskite solar cells have not yet matched the efficiency of lead-based counterparts, they represent a viable and environmentally responsible pathway for India's renewable energy expansion. Continued interdisciplinary research integrating materials science, device physics, and environmental engineering is essential for successful commercialization.

REFERENCES

- [1] National Renewable Energy Reports. (2023). Government of India.
- [2] NREL. (2024). *Best research-cell efficiencies*.
- [3] Kamat, P. V. (2017). Lead-free perovskite solar cells. *ACS Energy Letters*.
- [4] *Advanced Science*. (2023). Durability of tin-based perovskite solar cells.
- [5] *Solar Energy Materials & Solar Cells*. (2024). Outdoor performance of perovskite solar cells.
- [6] Wang, X., et al. (2024). Tin-based perovskite stability strategies.
- [7] *RSC Advances*. (2024). Bandgap engineering in double perovskites.
- [8] *Micromachines*. (2024). Stability enhancement in lead-free PSCs.
- [9] *Journal of Materials Chemistry A*. (2022). Interface engineering in PSCs.
- [10] *Materials Today Energy*. (2023). Encapsulation of perovskite solar modules.
- [11] *Progress in Photovoltaics*. (2022). Perovskite stability testing standards.
- [12] *Energy & Environmental Science*. (2021). Perovskite solar cell degradation mechanisms.