



CLIMATE-SPECIFIC RELIABILITY OF LEAD-FREE PEROVSKITE SOLAR CELLS IN INDIA: A CRITICAL REVIEW OF DEGRADATION MECHANISMS, TESTING PRACTICES, AND EVIDENCE GAPS

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Abstract:

Lead-free perovskite solar cells (PSCs) are being investigated as alternatives to lead-containing photovoltaic absorbers because of concerns about lead toxicity and the need for more sustainable solar-energy technologies. Their practical deployment, however, depends not only on initial power-conversion efficiency but also on reliable operation under heat, moisture, oxygen, illumination, electrical bias, and combined environmental stress. This critical review frames the reliability question around the relevance of published stability evidence to hot and seasonally humid climates such as those found in India. It considers tin-, bismuth-, antimony-, and germanium-based absorber families, identifies the principal physical and chemical degradation pathways, and examines why results obtained using different test conditions cannot always be compared directly. Recent reviews have already examined lead-free perovskite stability broadly; therefore, the distinctive contribution proposed here is a climate-relevance and evidence-quality lens rather than a claim that no prior stability review exists. The available literature indicates that tin-based systems face oxidation and defect-related challenges, while several bismuth- and antimony-based systems often trade improved environmental robustness for less favourable charge transport or band-structure characteristics. Accelerated ageing is valuable for screening but cannot, by itself, establish field lifetime. The paper proposes a transparent literature-screening method and a data-extraction framework covering absorber composition, encapsulation, temperature, relative humidity, illumination, bias, duration, and performance retention. A key conclusion is that meaningful comparison requires standardised reporting and longer-duration outdoor studies, including climate-specific datasets. The manuscript is a critical narrative review framework; its final submission should follow a completed, reproducible database search and verification of every included study.

Keywords: lead-free perovskite solar cells; stability; degradation physics; tin perovskites; outdoor testing; hot-humid climate; photovoltaic reliability; India

1. Introduction

Photovoltaic technologies are central to the transition toward lower-carbon electricity systems. Perovskite solar cells have attracted considerable attention because their optoelectronic properties can be tuned through composition and processing, and thin absorber layers can be fabricated using solution-based or other comparatively low-temperature methods. Nevertheless, many high-performing perovskite devices contain lead, creating concerns about potential environmental release during manufacturing, operation, damage, or end-of-life handling. Lead-free absorber systems are therefore an important research direction, although replacing lead does not automatically make a complete device harmless or commercially sustainable: the toxicity, abundance, processing, and end-of-life pathways of all constituent materials must also be considered.

Lead-free perovskite-inspired absorbers include tin (Sn)-based compounds, bismuth (Bi)- and antimony (Sb)-based systems, germanium (Ge)-based materials, double perovskites, and vacancy-ordered structures. These families differ substantially in crystal chemistry, electronic structure, defect tolerance, carrier mobility, and phase stability. Tin-based absorbers can offer comparatively favourable electronic properties, but Sn²⁺ oxidation to Sn⁴⁺ can promote self-doping and accelerate degradation. Some Bi- and Sb-based materials can be more chemically robust, yet their electronic structures may limit absorption, carrier transport, or device efficiency. As a result, material selection is a multi-objective problem involving efficiency, stability, safety, cost, and manufacturability.

For a photovoltaic device, stability is not a single material property. It depends on absorber composition, interfaces, charge-transport layers, electrodes, encapsulation, fabrication history, operating point, and environmental exposure. Temperature, humidity, oxygen, ultraviolet radiation, continuous illumination, and electrical bias may act individually or together. A laboratory test under one controlled stress condition can identify a failure mechanism, but it may not predict the lifetime of a device exposed to daily and seasonal variation outdoors.

This issue is relevant to India, where solar installations may experience high module temperatures, strong irradiance, seasonal monsoon humidity, dust, and large regional differences in climate. Yet a climate-specific conclusion must be evidence-led: general knowledge of Indian weather cannot substitute for actual device testing in India or a transparent comparison with comparable climates. This review therefore asks how published lead-free perovskite stability results are measured, how comparable those results are, and what evidence is needed before laboratory performance can be translated into climate-relevant reliability claims.

2. Scope and Review Questions

The review is organised around four questions: (i) which intrinsic and extrinsic mechanisms most strongly influence the stability of lead-free perovskite solar cells; (ii) how these mechanisms differ among Sn-, Bi-, Sb-, and Ge-based absorber families; (iii) which testing and reporting practices permit meaningful comparison between studies; and (iv) what is known, and what remains insufficiently documented, about outdoor performance under hot and seasonally humid conditions relevant to India.

The scope is deliberately narrower than a general survey of all perovskite photovoltaic advances. The focus is on device stability, degradation mechanisms, test comparability, and climate relevance. Efficiency values are discussed only where they help explain a stability–performance trade-off. No new experimental measurements are claimed.

3. Review Methodology

For a journal submission, the authors should complete and document a reproducible search in Scopus and/or Web of Science, supplemented by Google Scholar and reference-list checking. Suggested search strings include: (“lead-free perovskite” OR “tin perovskite” OR “bismuth perovskite” OR “antimony perovskite” OR “germanium perovskite”) AND (stability OR degradation OR “operational stability” OR “outdoor testing” OR humidity OR thermal). A second search should combine perovskite photovoltaic terms with India, hot climate, humid climate, monsoon, or outdoor performance.

Include peer-reviewed studies that report a lead-free perovskite photovoltaic device or relevant absorber stability evidence and specify at least one material, environmental, or operational condition. Exclude papers unrelated to photovoltaic use, duplicate records, non-scholarly promotional material, and studies whose methods or results cannot be verified. Reviews may be used to map the field, but key mechanistic claims should, where possible, be traced to primary research.

For each eligible study, extract: full citation and DOI; absorber composition and phase; device architecture; encapsulation status; initial power-conversion efficiency (PCE); temperature; relative humidity; atmosphere; illumination spectrum/intensity; electrical bias or maximum-power-point tracking condition; exposure duration; measurement interval; retained PCE; and reported failure mode. Record whether a result is indoor, accelerated-ageing, or outdoor. Where information is absent, mark it as “not reported” rather than inferring it.

A final manuscript should report the search date, database-specific search strings, number of records retrieved, duplicates removed, screening decisions, full-text exclusions with reasons, and number of studies included. A PRISMA-style flow diagram is appropriate if the review is conducted as a systematic review. Because this draft has not yet completed a new database screening, it should not claim a final study count or systematic-review status.

4. Physical and Chemical Origins of Degradation

4.1 Thermal stress and phase stability

Temperature can change phase equilibria, increase defect mobility, accelerate interfacial reactions, and promote the loss or redistribution of volatile species. In a working device, local temperature may differ from ambient temperature because the absorber and module absorb sunlight and dissipate heat. Consequently, reporting only the ambient temperature is insufficient for a strong reliability comparison. Useful reports should identify the temperature measured at the device, the thermal protocol, and whether illumination and electrical operation were applied simultaneously.

4.2 Moisture and oxygen

Water can interact with ionic crystal lattices, interfaces, transport layers, and electrodes. Oxygen can be especially consequential for tin-based materials because oxidation of Sn^{2+} to Sn^{4+} can alter carrier concentration and increase non-radiative recombination. Moisture ingress may also be governed by the encapsulant, edge seal, defects, and package geometry rather than absorber chemistry alone. Therefore, claims that a material is intrinsically stable should be separated from claims about the stability of a complete encapsulated device.

4.3 Defects, ion migration, and recombination

Vacancies, interstitials, grain boundaries, and interfacial defects can influence carrier trapping and non-radiative recombination. Mobile ionic species may redistribute under illumination, temperature gradients, or applied electric fields. Such redistribution can change local electric fields and interfacial barriers, contributing to hysteresis or time-dependent performance. Defect passivation and composition engineering may improve performance, but an improvement in initial efficiency does not by itself demonstrate long-term operational stability.

4.4 Interfaces, electrodes, and encapsulation

The interfaces between the absorber and charge-transport layers influence extraction, recombination, and chemical compatibility. Reactions involving electrodes or transport layers can become dominant failure pathways even when the absorber itself remains structurally intact. Encapsulation can reduce exposure to water and oxygen, but package integrity and edge-seal performance must be considered. Reliability studies should report the device stack, electrode, encapsulation method, and any visible or electrical failure observed during ageing.

4.5 Coupled environmental stress

Real outdoor operation combines changing temperature, humidity, irradiance, oxygen exposure, and electrical load. These stressors may interact non-linearly. A test performed at high temperature in darkness may reveal a different failure pathway from continuous illumination at a lower temperature. Accelerated tests are useful for screening and mechanism studies, but extrapolating a lifetime from an accelerated test requires a justified model and evidence that the dominant failure mechanism remains relevant under field conditions.

5. Comparison of Lead-Free Absorber Families

5.1 Tin-based perovskites

Tin-based halide perovskites are among the most intensively studied lead-free candidates because their electronic properties can be favourable for photovoltaic conversion. Their key stability challenge is the oxidation of Sn^{2+} , which can create Sn^{4+} -related defects, alter carrier density, and contribute to rapid degradation under ambient conditions. Researchers have investigated additives, reducing environments, compositional tuning, dimensionality control, surface passivation, and interface engineering. Such strategies should be evaluated using both initial device performance and retention under clearly specified operational conditions.

5.2 Bismuth- and antimony-based systems

Bismuth- and antimony-based compounds can exhibit attractive chemical stability, but many reported structures have electronic or structural characteristics that limit charge transport or light absorption compared with ideal photovoltaic absorbers. Their assessment should therefore avoid a simple ranking based on stability alone. Relevant comparisons include absorption range, carrier mobility, defect states, film morphology, device architecture, and the duration and conditions of stability tests.

5.3 Germanium-based systems

Germanium-based halide perovskites are another proposed lead-free family, but oxidation and phase stability remain important concerns. The evidence base is smaller than for some tin-based systems, so comparisons should explicitly acknowledge the number and quality of studies available. Apparent performance differences can reflect different compositions and fabrication methods rather than a fundamental advantage of one cation family.

5.4 Double perovskites and vacancy-ordered structures

Double perovskites and vacancy-ordered compounds offer alternative crystal chemistries that may improve structural or environmental robustness. However, their band structures, indirect transitions, localized states, or relatively low carrier mobility can constrain photovoltaic performance in particular compositions. They should be compared using common device and measurement criteria wherever possible.

6. Testing Practices and Comparability

A stability result is interpretable only when its stress conditions and measurement protocol are clear. Studies should distinguish shelf stability, thermal ageing, damp-heat testing, continuous illumination, open-circuit or short-circuit ageing, maximum-power-point tracking, and real outdoor exposure. These protocols answer different questions and should not be pooled into a single lifetime ranking without qualification.

A minimum reporting framework should include: (1) complete device architecture and absorber composition; (2) encapsulation and edge-seal details; (3) device temperature and ambient conditions; (4) relative humidity and atmosphere; (5) illumination source, spectrum, intensity, and duty cycle; (6) applied bias or operating mode; (7) test duration and monitoring frequency; (8) PCE retention and the method used to measure it; (9) number of devices and statistical spread; and (10) failure analysis or post-ageing characterization.

For outdoor studies, the report should also identify location, season, module orientation and tilt, irradiance, ambient and device temperature, humidity, rainfall or wetting where relevant, and the monitoring system. Indoor accelerated tests should be reported separately from field tests. Lifetime values should be accompanied by the threshold definition, such as time to a stated percentage of initial performance, rather than reported as an unexplained single number.

7. India-Relevant Climate Evidence: What Can and Cannot Be Concluded

India contains multiple climatic regions; a single “Indian climate” condition is not scientifically adequate. Hot-dry, warm-humid, composite, and high-rainfall regions may expose photovoltaic devices to different combinations of temperature, humidity, dust, wetting, and irradiance. A credible India-focused review should therefore stratify available evidence by location or climate type rather than assume that one site represents the whole country.

The literature on perovskite outdoor performance has highlighted the limited duration and number of field studies relative to the large number of laboratory reports. A 2024 review of outdoor perovskite photovoltaic testing noted that accelerated ageing under elevated temperature and humidity cannot replace realistic outdoor assessment. That review covers perovskite devices more broadly and should not be treated as direct proof of the amount of India-specific evidence for lead-free devices.

The key evidence gap to test is whether published studies of lead-free devices provide sufficiently detailed, long-duration field data for hot and seasonally humid locations, and whether those studies report the environmental variables needed to compare results. This is a research question, not a conclusion that no Indian studies exist. The completed search should identify any Indian field studies and record their duration, device chemistry, encapsulation, monitoring conditions, and data availability.

A practical research roadmap would prioritise multi-season outdoor testing at more than one Indian climate site, with matched indoor reference devices and common reporting procedures. Such studies could reveal whether degradation is dominated by absorber chemistry, encapsulation, interfaces, or a combination of mechanisms under actual operating conditions.

8. Synthesis and Research Gaps

The literature supports several broad conclusions. First, lead-free perovskites are not a single material class; stability and electronic performance vary strongly with composition and structure. Second, tin-based systems face a particularly important oxidation-related challenge, while some Bi- and Sb-based systems may trade improved environmental robustness for less favourable optoelectronic characteristics. Third, the complete device stack and encapsulation can

be as important as the absorber. Fourth, testing conditions vary across studies, limiting direct comparison of reported lifetimes.

The proposed India-focused contribution should be finalised only after a documented literature search. The analysis should determine: (i) how many eligible lead-free studies report outdoor operation; (ii) how many identify an Indian location or a comparable hot-humid climate; (iii) how frequently temperature, humidity, irradiance, encapsulation, and operational mode are reported; and (iv) whether performance-retention data are available over multiple seasons. A quantitative table of these reporting frequencies would provide a defensible contribution without inventing data.

A second contribution could be a climate-relevance matrix that links each study's exposure conditions to the environmental variables it actually measured. This would distinguish direct evidence from indirect extrapolation. A third could be a minimum reporting checklist for lead-free perovskite stability studies. These outputs are likely to be more useful than another general catalogue of efficiency records.

9. Limitations

This manuscript is a structured critical-review draft based on a preliminary source set, not a completed systematic review. It does not report a final PRISMA count, pooled statistics, or a comprehensive inventory of Indian outdoor studies. No new experiments or numerical modelling have been performed. Before submission, the authors must complete the database search, read the full text of relevant papers, verify each citation and DOI, populate the evidence tables from primary studies, and revise the conclusions to match the screened evidence.

10. Conclusion

Lead-free perovskite solar cells offer a promising route toward photovoltaic technologies with reduced reliance on lead, but practical deployment requires reliable performance over long periods and across realistic environmental conditions. Tin-based materials are constrained by oxidation and defect-related processes, while other lead-free families present their own trade-offs between stability and charge-transport properties. Stability must be assessed at device level because interfaces, electrodes, encapsulation, and operating conditions can determine the dominant failure pathway. Accelerated ageing remains useful, but it cannot replace long-term outdoor testing.

For an India-focused review, the strongest contribution is to evaluate the quality and climate relevance of available evidence, rather than to claim an unverified absence of prior work. A transparent, reproducible search and a data-extraction framework covering composition, test conditions, device architecture, and performance retention would allow the authors to quantify reporting gaps and recommend better experimental practice. Such a study could help connect fundamental degradation physics with the requirements of durable photovoltaic systems in hot and seasonally humid environments.

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