

COMPREHENSIVE REVIEW OF PEROVSKITE MATERIALS: DEVELOPMENTS IN CRYSTAL ENGINEERING, DEVICE INTEGRATION, AND BROAD-SPECTRUM APPLICATIONS IN ENERGY AND ELECTRONICS

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Abstract

Perovskites—materials adopting or derived from the ABX_3 structural archetype—have progressed from classical oxide ferroelectrics and superconductors to today’s halide-based optoelectronics, catalysis, and Ionics. This chapter surveys crystal chemistry and structure–property relationships across oxide and halide families; defect physics and ion transport; synthesis and microstructure control from bulk to nanocrystals and 2D phases; and device-level advances in photovoltaics, light emission, sensing, catalysis, solid-state Ionics, and beyond-CMOS electronics. We also review stability pathways, lead-free strategies, environmental and sustainability considerations, characterization toolkits, and computational discovery. Emphasis is placed on how fundamental mechanisms—tolerance factor, octahedral tilts, soft lattices, defect tolerance, excitonic effects, and dynamic disorder—enable rapid translation from lab to technology.

Keywords: perovskite, ABX_3 , halide perovskite, oxide perovskite, photovoltaics, ferroelectric, catalysis, ion migration, 2D perovskite, stability.

1. Introduction

1.1 Background & Significance

With the arrival of the 5G era and the “Internet of Things” era, the demand for human perception of the objective world has rapidly increased, driving the rapid development of sensor technology. As smart material technology advances, different solid surface morphologies are crucial. The field of crystallography conducted extensive research on the structure of crystals just prior to the development of the atomic theory of solids around the end of the nineteenth century. In 1839, Gustav Rose made the first discovery of the calcium titanium oxide ($CaTiO_3$) perovskite structure in the Ural Mountains of Russia. It is widely recognized as a perovskite material and was named after the Russian mineralogist L.A. Perovski (1792–1856) [1]. The research on tools is in full swing, and related achievements have been published one after another. Among them, perovskite material has received a lot of attention as a photoelectric semiconductor material. Its excellent material properties [2,3,4,5], low manufacturing cost, and simple preparation process [6,7,8] have made it shine in the field of solar cells. The power conversion efficiency (PCE) of solar cells utilizing perovskite materials as the central component has significantly advanced, rising from 3.81% [9], as first reported in 2009, to 34.06% [10] in 2024 with the use of a $RbPbBr$ absorber. This remarkable progress has contributed a pivotal

chapter to the development of solar cell research. At the same time, perovskite materials have also received attention in research fields such as light-emitting diodes [11,12], lasers [13], and field-effect transistors [14]. The excellent optoelectronic properties of perovskite are destined to play an important role in the field of optoelectronic detection.

1.2 Scope of the review

This review mainly includes an introduction to perovskite-based energy & electronics, perovskite materials and structures, the working principle of perovskite photodetectors, device manufacturing techniques, performance optimization methods, and equipment architecture and configuration, as well as equipment integration and application. The difficulties and future of perovskite electronics and energy are finally covered. The mineral CaTiO_3 and its structural categorization are both referred to as "perovskites." Although this dual usage of the term is rarely addressed openly, it commonly leads to confusion in the field of materials science. Muller and Roy's textbook went into great detail regarding the nomenclature problem and offered a formalization as a remedy [15].

1.3 Overview of Perovskite in Energy & Electronics

Perovskites constitute a broad class of materials whose idealized structure is the cubic ABX_3 lattice [16], where A is a large cation (e.g., Cs^+ , $\text{MA}^+ = \text{CH}_3\text{NH}_3^+$, $\text{FA}^+ = \text{HC}(\text{NH}_2)_2^+$, or rare-earth/alkaline-earth ions), B is a smaller metal cation (Pb^{2+} , Sn^{2+} , Ti^{4+} , Nb^{5+} , Mn^{3+} , etc.), and X is an anion (O^{2-} in oxides; $\text{Cl}^-/\text{Br}^-/\text{I}^-$ in halides). The corner-sharing BX_6 octahedral network defines most electronic, ionic, and structural behaviors. Historically, oxide perovskites (e.g., BaTiO_3 , SrTiO_3 , $\text{La}_{1-x}\text{Sr}_x\text{MnO}_3$, $\text{YBa}_2\text{Cu}_3\text{O}_{7-\delta}$ -related families) drove ferroelectrics, dielectrics, piezoelectrics, mixed conductors, and superconductivity. Around 2012–2013, organic–inorganic halide perovskites unlocked defect-tolerant semiconductors with exceptional optical absorption, long diffusion lengths, and solution processability—propelling rapid gains in solar cells, LEDs, and detectors [17].

2. Perovskites Materials & structure

2.1- Crystal Chemistry and Structure

Structural flexibility: Large chemical phase space; tolerance of vacancies and substitutions; 3D, 2D (Ruddlesden–Popper), 1D, and 0D derivatives.

- **Soft lattice, strong coupling:** Polarons, anharmonic phonons, dynamic disorder, and facile ion migration yield unusual combinations of electronic and ionic transport.

- **Defect tolerance:** Shallow defect formation in many halides permits high performance despite low-temperature processing.

- **Low-cost manufacturing:** From bulk ceramics to single crystals and thin films via solution or vapor routes [18]. The perovskite structure schematic diagram is shown in Figure 1, and the cation (red ball) may be an inorganic alkali metal (e.g.,) or an organic cation (e.g., (MA), (FA)). Typically, a halogen ion (or a combination of them) is the anion (green ball) and the cation (blue ball). Within the corner-shared octahedral framework, the A cation is situated in the cubo-octahedral cavity, creating a three-dimensional (3D) structure. Perovskite materials are perfect for optoelectronic applications because of their high optical absorption coefficient, wide absorption spectrum, and extended carrier lifetime. Their three-dimensional structure comprising corner-sharing octahedra (BX_6), with the A cation residing in the cubo-octahedral cavities, allows for the substitution of various ions at the, and sites, enabling fine-tuning of their optical and electronic properties. Efficiency improvements are shown in Figure 2.

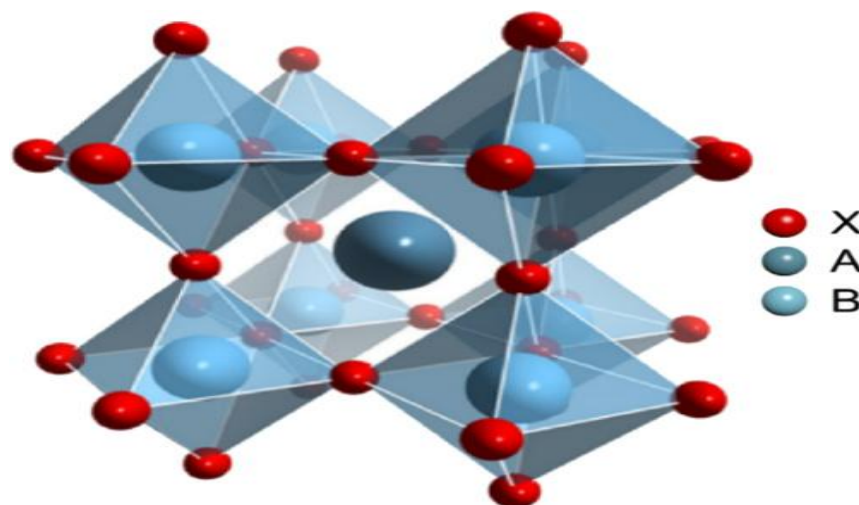


Fig. 1. Schematic diagram of the perovskite structure [19]. Copyright 2024 RSC.

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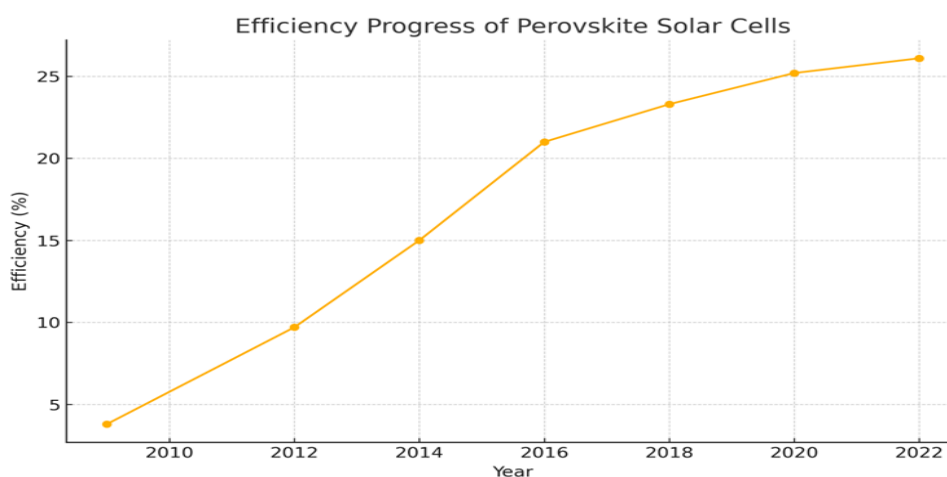


Fig. 2. Efficiency trend of perovskite solar cells.

2.2 Tolerance factor and octahedral connectivity

The Goldschmidt tolerance factor

$$t = \frac{r_A + r_X}{\sqrt{2} (r_B + r_X)}$$

predicts structural stability: $t \approx 0.8-1.0$ favors perovskite connectivity. Deviations drive octahedral tilts (Glazer notation $a^+ / a^- / c0$), symmetry lowering (cubic \rightarrow tetragonal/orthorhombic/rhombohedral), and property changes—bandgap shifts in halides; polarization in oxides[20].

2.3 Dimensionality engineering

Layered perovskites (Ruddlesden–Popper, $(A')_2A_{n-1}B_nX_{3n+1}$) interleave bulky organic cations or rock-salt layers to produce natural quantum wells. Lower dimensionality increases exciton binding, enhances environmental stability, and enables color-pure emission[21]. Common representative perovskites and their properties, along with their applications, are listed in Table 1.

Oxides: BaTiO₃/SrTiO₃ (dielectric/ferroelectric), Pb(Zr,Ti)O₃ (PZT), La_{1-x}Sr_xCoO_{3-d} and LSCF (SOFC electrodes), La_{1-x}Sr_xMnO₃ (colossal magnetoresistance), high-T_c cuprates (derived structures).

- **Halides:** MAPbI₃, FAPbI₃, CsPbBr₃, mixed-halides (FA/MA/Cs with I/Br/Cl), and lead-free (Sn²⁺, Ge²⁺) or double perovskites (A₂B'B''X₆, e.g., Cs₂AgBiBr₆).

- **Nitrides/oxynitrides and oxyhalides:** Emerging chemistries for stability and band-edge tuning[22].

Table 1. Representative perovskites and applications.

Family	Example	Property	Application
Halide 3D	FAPbI ₃	Direct ~1.5 eV bandgap	PV, detectors
Halide 2D	(PEA) ₂ (FA) _{n-3} 1PbnBr _{3n+1}	High exciton binding	LEDs
Oxide ferroelectric	BaTiO, PZT	High permittivity	Capacitors
Oxide ionic	LSCF, BSCF	Mixed ionic–electronic	SOFC cathodes

3. Defects, Ion Transport, and Electronic Structure

3.1 Point defects and their roles

Vacancies (V_X, V_{Pb}, V_I), interstitials, and antisites shape carrier lifetime, doping, and hysteresis. In halide perovskites, many dominant defects are shallow; in oxides, oxygen non-stoichiometry (δ in ABO_{3- δ}) controls mixed ionic–electronic conduction and catalytic activity[23]. Mobile halide ions and organic fragments migrate along low-barrier paths (0.1–0.6 eV), causing current–voltage hysteresis, phase segregation in mixed-halide films, and slow transients in detectors/LEDs. Grain boundaries and interfaces concentrate fields and vacancies; compositional and passivation strategies mitigate drift[24].

3.2 Band structure essentials

Halides: Direct bandgaps (\approx 1.2–2.4 eV), strong spin–orbit coupling (Pb, Sn), small effective masses, long carrier diffusion lengths, exciton binding energies \approx 10–50 meV (3D) and $>$ 100 meV (2D).

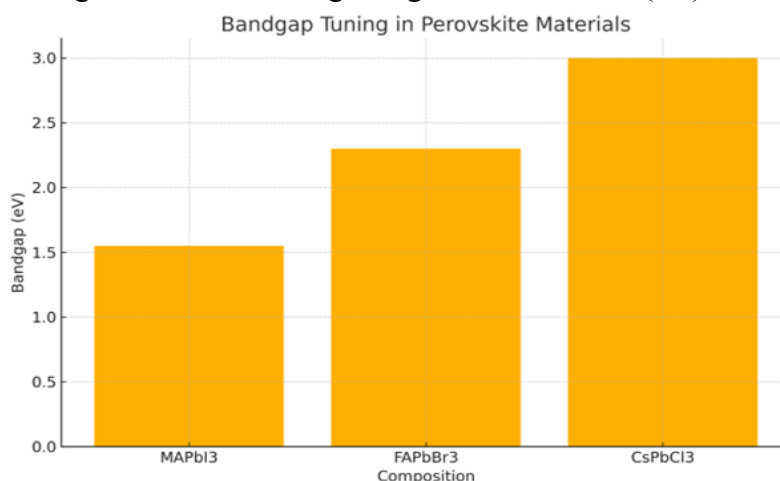


Fig. 3. Bandgap tuning in different perovskite compositions.

Oxides: Typically, wider gaps; d-electron physics yields ferroelectricity, magnetism, Mott behavior, or superconductivity upon doping/strain[25]. Bandgap tuning is illustrated in Figure 3 and Common defect types and their effects are summarized in Table 2.

Table 2. Common defects and typical effects in halide vs oxide perovskites.

Defect Type	Halide Perovskites	Oxide Perovskites
Halide vacancy (V_X)	Ion migration, hysteresis	Not relevant
Cation vacancy	Deep traps, recombination	Controls carrier density
Interstitials	Shallow traps, ionic conduction	O^{2-} transport
Antisite defects	Occasional recombination centers	Alter ordering
Oxygen vacancy	Not applicable	Controls conductivity, catalysis

4. Synthesis and Processing

4.1 Bulk oxides and ceramics

Solid-state reaction, sol-gel/Pechini, combustion, spark plasma sintering (SPS), tape casting, hot pressing—targeting dense, textured ceramics for capacitors, piezoelectrics, SOFCs, and MEMS [26]. Solution processing: Spin/dip blade coating, slot-die, inkjet; antisolvent techniques; hot-casting for large grains.

Vapor routes: Thermal co-evaporation, hybrid CVD, close-space sublimation—better stoichiometry control and uniformity.

Single crystals: Inverse-temperature crystallization (ITC), Bridgman—lower trap densities for detectors [27].

4.2 Nanocrystals & quantum dots and 2D perovskites and quasi-2D mixtures

Hot-injection or ligand-assisted reprecipitation produce monodisperse $CsPbX_3$ nanocrystals (NCs) with narrow linewidths and high photoluminescence quantum yields (PLQYs), enabling LEDs, displays, and lasers. Surface chemistry (oleylamine/oleic acid; zwitterionic ligands) controls stability and charge balance [28]. Tuning the n-value in $(A')_2A_{n-1}B_nX_{3n+1}$ stacks yields phase distributions serving as energy funnels in LEDs and stable caps in solar cells. Solution vs vapor processing routes are compared in Figure 4.

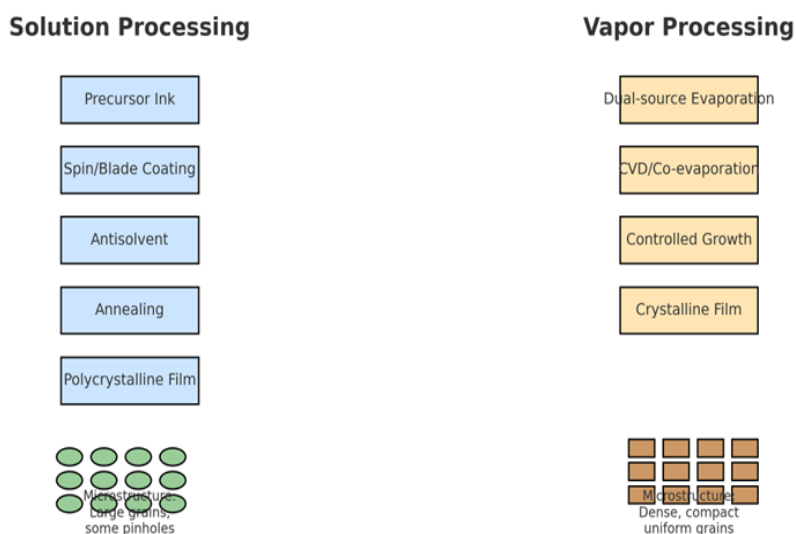


Fig. 4. Process flow for perovskite solar cells (solution vs vapor) with microstructure.

5. Characterization Toolbox

Structure & phases: XRD (Rietveld), GIWAXS, pair distribution function (PDF), electron diffraction.

- Morphology: SEM/TEM, AFM, EBSD, tomography for grain size and texture.
- Optoelectronics: UV-Vis, PDS, TRPL, TAS, THz spectroscopy for lifetimes, diffusion lengths, and recombination kinetics.
- Electrical: Hall, SCLC, impedance spectroscopy (extracting ionic vs electronic contributions), temperature-dependent measurements.
- Defects & chemistry: XPS/UPS, ToF-SIMS, DLTS, ESR/EPR.
- In-situ/operando: Illumination/thermal/environmental cells to observe phase segregation, ion drift, and electrode reactions under bias [29].

6. Halide Perovskites for Optoelectronics

6.1 Photovoltaics (PV)

-Device architectures:

- N-i-P: TCO / compact-TiO₂ or SnO₂ / perovskite / Spiro-OMeTAD or PTAA / metal.
- P-i-N: TCO / NiO_x or SAM/perovskite / fullerene (C₆₀/PCBM) or polymer ETL / metal.
- Monolithic tandems: Perovskite/Si or perovskite/perovskite stacks.

Performance enablers: Composition engineering (FA/Cs, Br/I), cation/anion alloying for bandgap tuning; additives (MAI, Rb⁺, K⁺); passivation (Lewis bases, quaternary ammonium halides, ionic liquids); interfacial dipoles and self-assembled monolayers (SAMs); low-defect crystallization via antisolvent timing and gas quenching[30].

Stability strategies: Inorganic A-site cations (Cs), 2D capping layers, cross-linked HTLs, robust electrodes (carbon, transparent conductive oxides), moisture/oxygen getters, encapsulation; minimizing migration-prone halides at contacts.

Scalability: Slot-die and roll-to-roll coating; blade-coated modules; vapor co-evaporation for uniformity; perovskite/Si tandem modules with industrially compatible stacks[31].

6.2 Light-Emitting Diodes (PeLEDs) & Lasers and Amplifiers

Perovskite LEDs leverage high PLQY and narrow emission (FWHM 15–25 nm). Quasi-2D mixtures (n-graded phases) and NCs serve as emissive layers with improved color purity and operational half-lives. Key challenges: ion migration under high fields, Auger heating at high current density, and electrode diffusion. Strategies include robust transport layers, compositional confinement (Br-rich for green), and defect-healing ligands[32]. Low threshold amplified spontaneous emission in single crystals and NC films arises from high gain and low trap density. Distributed feedback (DFB) gratings and microcavities have produced room-temperature lasing with tunable wavelengths (blue–NIR). Thermal management and photostability remain active topics[33]. Various methods for producing white light from LEDs are shown in Figure 5. These techniques include a single chip with white EL, a blue LED chip coated with yellow or green and red emission layers (phosphor), or a UV or violet LED chip and emission layer (phosphor) combined.

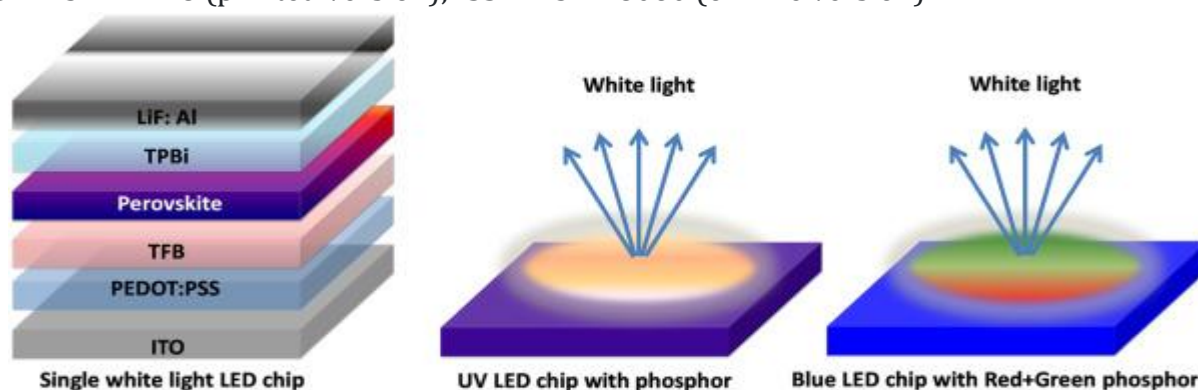


Fig.5. Single white light LED chip & UV and Blue LED with various phosphor

6.3 Photodetectors and X-ray/ γ -ray detectors

Single-crystal halides show high $\mu\tau$ products and excellent stopping power. Applications include medical imaging and security screening. Defect control, trap passivation, and electrode engineering reduce dark current and afterglow[34].

7. Oxide Perovskites: Ferroelectrics, Piezoelectrics, Ionics, and Superconductivity

7.1 Ferroelectrics and dielectrics

BaTiO₃ and PZT underpin capacitors, actuators, and non-volatile memories. Domain engineering, acceptor/donor doping, and thin-film strain tuning produce large piezoelectric coefficients (d_{33}) and high permittivities. Lead-free alternatives—(K,Na)NbO₃ (KNN), Ba(Zr,Ti)O₃–(Ba,Ca)TiO₃ (BZT–BCT)—are advancing rapidly[35].

7.2 Solid-oxide fuel cells (SOFCs) and mixed conductors

Perovskites such as La_{1-x}Sr_xCo_{1-y}Fe_yO_{3- δ} (LSCF) and Ba_{0.5}Sr_{0.5}Co_{0.8}Fe_{0.2}O_{3- δ} (BSCF) exhibit high oxygen vacancy concentrations and surface exchange rates, enabling cathodes and oxygen separation membranes. Interface stability with electrolytes (YSZ, GDC) and Sr segregation management are central.[36]

7.3 Catalysis and electrocatalysis

Transition-metal oxides (LaNiO₃, LaCoO₃, SrTiO₃) serve as catalysts for OER/ORR/CO oxidation and photocatalysis. Activity descriptors include e_g occupancy, oxygen vacancy formation energy, and covalency; strain and A-site deficiency modulate surface termination and adsorption energetics[37].

7.4 Colossal magnetoresistance and multiferroics

Doped manganites (La_{1-x}Sr_xMnO₃) exhibit double-exchange-mediated conductivity and large MR near Curie temperature. Multiferroic perovskites and superlattices combine ferroelectric and magnetic orders for spintronic and memory concepts[38]. Cuprate high-T_c families (e.g., YBCO-related) share perovskite-derived layered blocks; epitaxy and oxygen stoichiometry control T_c and critical current density in coated conductors.

8. Interfaces, Microstructure, and Reliability

8.1 Grain boundaries and texture & Contact engineering

In halides, large grains reduce recombination and ion migration pathways; in oxides, boundaries can pin domains or provide fast ion pathways. Texturing (e.g., via solvent-engineered crystallization or templated substrates) enhances carrier transport and piezoelectric response[39]. Energy-level alignment using SAMs, dipole layers, and doped transport layers minimizes barriers and nonradiative recombination. In oxides, electrode reactivity and diffusion (e.g., Ag, Au) require barrier layers[40].

8.2 Degradation pathways

Halides: Moisture ingress, oxygen/photo-oxidation, thermal phase transitions (δ -phase FA), ion migration and halide segregation, light-induced halide exchange.

- Oxides: Redox cycling, cation segregation (e.g., Sr to the surface), grain growth, and phase decomposition at high temperatures. Encapsulation, compositional engineering, cross-linking, and defect passivation are the main mitigation strategies[41].

Reliability testing protocols are summarized in Table 3.

Test Category	Protocol/Condition	Purpose
PV (ISOS-D)	Dark storage	Intrinsic stability
PV (ISOS-L)	Light soaking	Photostability
PV (ISOS-T)	Thermal stress	Heat resistance
PV (ISOS-O)	Outdoor exposure	Real-world durability
LED stress	Constant current	Operational lifetime (T50)
LED stress	High current	Overdrive robustness
SOFC	Redox cycling	Start–stop durability
SOFC	Thermal cycling	Mechanical integrity

Table 3. Reliability test matrices for PV, LEDs, and SOFCs.

9. Lead-Free and Low-Lead Strategies

Sn-based perovskites (ASnX₃): Direct bandgaps and high mobility but prone to Sn²⁺ → Sn⁴⁺ oxidation; use reducing atmospheres, SnF₂ additives, and antioxidant ligands.

- **Double perovskites (A₂B'B''X₆):** Pb-free but often indirect gaps; alloying and vacancy-ordered variants can improve absorption.

- **Bismuth/antimony halides and chalcogenides:** Defect-tolerant alternatives for detectors and PV.

- **Oxide routes:** For piezoelectrics and dielectrics, KNN and BZT–BCT lead the lead-free landscape[42].

10. Computation, Data, and AI-Accelerated Discovery

High-throughput DFT screening uses tolerance factors, formation energies, octahedral factors, and defect thermodynamics to identify stable phases with targeted bandgaps and effective masses. Machine-learning models predict processing–structure–property relationships (e.g., solvent/antisolvent maps, crystallization kinetics), and Bayesian optimization accelerates composition and process tuning in the lab. Multiscale simulations (ab initio MD → drift–diffusion device models) connect ion migration and recombination to stability metrics and hysteresis[43].

11. Sustainability, Toxicology, and Lifecycle

11.1 Lead stewardship in halides & 2 Energy and materials footprint

Risk is dominated by soluble Pb salts and end-of-life leaching. Strategies: robust encapsulation, polymer/zeolite scavengers, glass lamination, lead-capture layers under module glass, and recycling processes recovering Pb and halides[44]. Regulatory frameworks require RoHS awareness and TCLP testing for modules. Low-temperature processing reduces embodied energy vs. vacuum-processed semiconductors. Solvent selection (green solvents, solvent-recovery), abundance of precursors, and scalable deposition (roll-to-roll) lower environmental cost. For oxides, sintering energy is the main lever; SPS and microwave sintering decrease thermal budgets[45].

12. Application Case Studies

12.1 Perovskite/Si tandem photovoltaics & High-brightness green/red PeLEDs

Top perovskite ($\approx 1.65\text{--}1.8$ eV) + bottom Si (1.12 eV) reach near-Shockley–Queisser-limited utilization of the solar spectrum. Critical elements: UV/thermal stability, recombination layers (TCO/oxide/SAM stacks), and current matching via optical modeling and graded halides. Industrial pathways focus on sputtered TCOs, robust HTLs (NiOx), and scalable perovskite deposition[46]. Quasi-2D perovskites with controlled n-distribution funnel excitations to low-n emissive phases. Additives (e.g., bulky ammonium halides) stabilize phases; NC films enable Rec.2020-grade color. Encapsulation and electrode blocking layers extend T_{50} lifetimes[47].

12.2 Oxide electrocatalysts for OER & Solid-oxide ionics and membranes

A-site deficiency and strain in LaNiO_3 -type perovskites tune e_g occupancy and oxygen binding, improving turnover frequency. Surface reconstruction under bias (formation of oxyhydroxide layers) is now recognized as part of the active state; operando XAS and Raman track these changes[48]. BSCF membranes enable oxygen separation with high permeation flux; microstructural control (grain size, pore architecture) and cation-segregation suppression are key for durability[49]. One major obstacle to the widespread use of perovskite materials in solar applications is their stability. Although perovskite solar cells (PSCs) have shown impressive efficiencies of over 25%, one of their key drawbacks is still their long-term operational stability in practical settings [50]. Perovskites suffer from both intrinsic and extrinsic degradation mechanisms, which lead to performance deterioration and reduced device lifetimes. Intrinsic factors, although extrinsic variables like moisture, UV light, and heat stress hasten material degradation, extrinsic factors like ion migration and phase segregation can change the perovskite's crystal structure and electrical characteristics [51].

13. Industrial Roadmap for Perovskite Commercialization

The excellent efficiency, low cost of production, and potential for scaling of perovskite solar cells (PSCs) have made them a prospective substitute for conventional silicon photovoltaics [52, 53]. But even after attaining a power conversion efficiency (PCE) of more than 25% in lab settings, transitioning PSCs from the research stage to large-scale commercial deployment presents significant challenges, including scalability, long-term stability, and cost-effectiveness [54]. An industrial roadmap for perovskite commercialization requires addressing pilot-scale production, real-world performance testing, and economic feasibility to ensure that PSC technology meets the standards

required for mass adoption in the photovoltaic (PV) industry [55]. Cost per watt (CPW) analysis, stability improvement tactics, and large-area production processes are the subject of numerous research projects and are essential to the effective integration of PSCs into the global energy market [56]. Uneven film deposition, repeatability, and material degradation are some of the major engineering hurdles associated with the switch from lab-scale, small-area perovskite devices to large-area commercial modules [57]. Atomic layer deposition (ALD) and chemical vapor deposition (CVD) are two vapor deposition techniques that have also been investigated to increase device stability and perovskite film homogeneity in industrial manufacturing settings [58]. The Industrial Roadmap for Perovskite commercialization mentioned in figure 6. Real-world performance testing of perovskite modules is also crucial for evaluating operational stability and degradation rates under outdoor conditions, as perovskites are known to degrade under moisture, oxygen, UV exposure, and thermal stress [59].

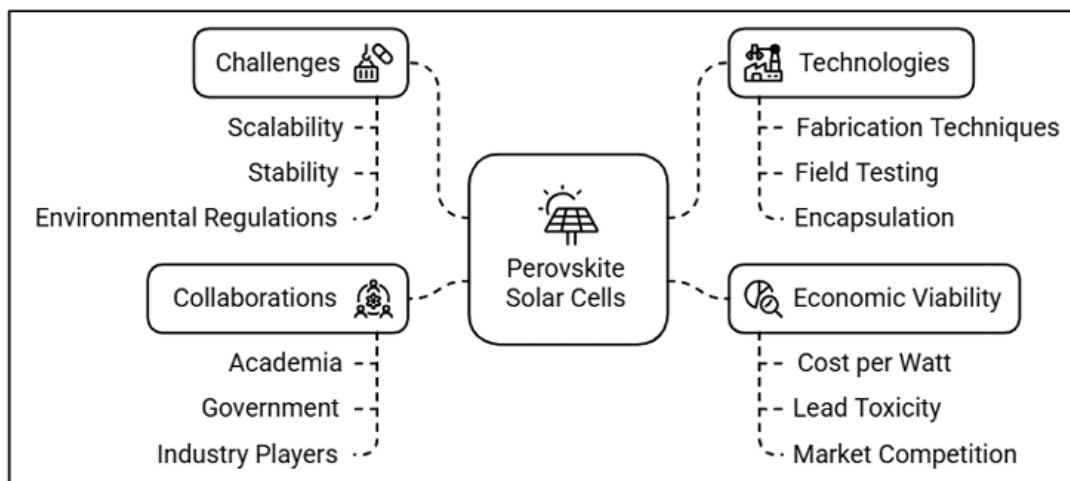


Fig.6. Industrial Roadmap for Perovskite Commercialization

The main economic barriers to perovskite commercialization include limited operational stability, concerns regarding lead toxicity, and the need to address the scalability of fabrication techniques before broad market adoption is possible [60]. PSCs' commercial appeal will be increased by research and development activities aimed at extending device lifetime through compositional engineering, encapsulating techniques, and lead-free perovskites [61]. Several startups and established solar manufacturers are actively developing commercial perovskite-based PV products, within the next ten years in order to commercialize perovskite-silicon tandem solar cells [62]. By tackling these major issues, perovskite photovoltaics could completely transform the solar market by providing an affordable, highly effective substitute for conventional PV technology.

14. Lifecycle Assessment and Environmental Impact

Concerns have been raised about the environmental impact of PSCs' rapid development, especially when compared to more conventional silicon photovoltaics (PVs). Lifecycle assessment (LCA) studies examine PSCs' carbon footprint, energy consumption, resource utilization, and end-of-life disposal to assess their overall sustainability [63, 64]. Notwithstanding the excellent power conversion

efficiencies (PCEs) and low production costs that perovskite solar cells have shown, issues with stability, recyclability, and the inclusion of hazardous lead components continue to be major obstacles to their widespread commercialization [65,66]. Perovskite solar cells' lifespan evaluation and environmental impact are depicted in Figure 7. Perovskite photovoltaics (PVs) often have a lower carbon footprint and a shorter energy payback time (EPBT) than silicon-based solar cells, according to comparative life cycle assessment (LCA) studies. This makes them a potentially more sustainable option for renewable energy generation [67, 68]. On the other hand, solution-based deposition methods including spin-coating, inkjet printing, and slot die coating can be used to produce perovskite solar cells at low temperatures (~150°C), thereby lowering energy consumption and related carbon emissions [69].

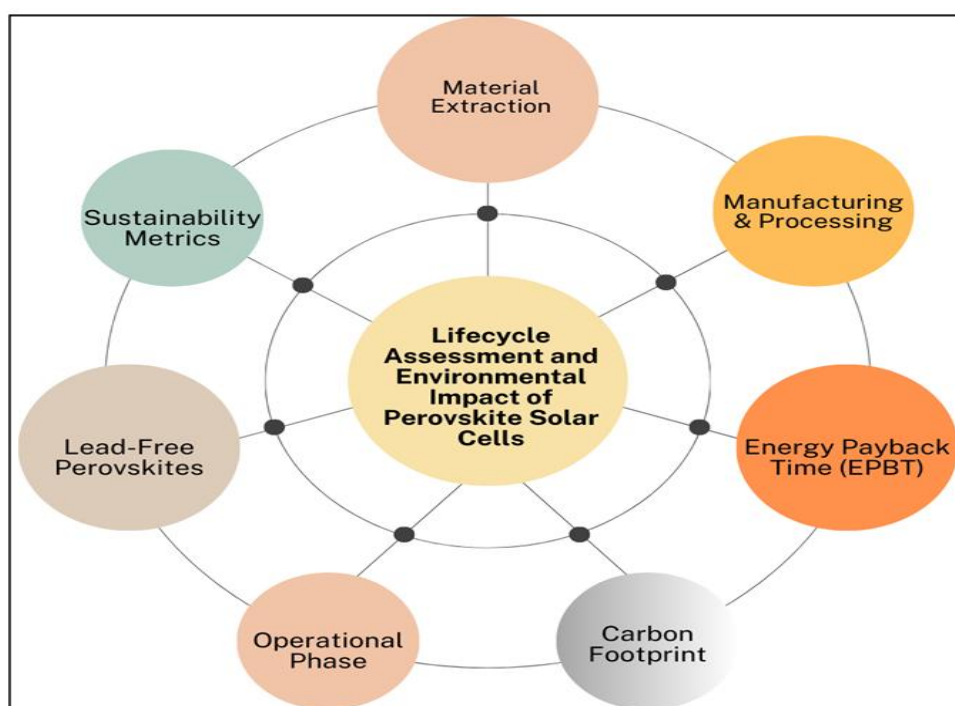


Fig.7. Lifecycle Assessment & environment Impact of Perovskite Solar Cells

One of the primary environmental concerns associated with perovskite solar cells is their end-of-life management, particularly regarding lead-containing perovskite materials [70]. Perovskite PVs require new strategies for material recovery and disposal to prevent potential environmental contamination [71]. As the photovoltaic industry moves toward more sustainable practices, integrating circular economy principles into the design and recycling of perovskite solar cells will be essential for ensuring their long-term environmental viability [72].

15. Conclusion

Perovskites unite structural versatility, benign defect landscapes (for halides), and rich correlated physics (for oxides). Rapid advances in scalable deposition, interface passivation, and encapsulation are pushing perovskite photovoltaics, LEDs, detectors, and tandem modules toward commercial viability, while oxide perovskites continue to power electroceramics, catalysis, and ionics. Future

progress hinges on stability-by-design, green chemistry, AI-guided discovery, and standardized reliability metrics—ensuring that perovskites remain a cornerstone of multifunctional materials and devices. The findings of this systematic review underscore the remarkable progress in perovskite solar cell (PSC) technology, highlighting significant advancements in efficiency improvements, stability enhancements, tandem integration, light management strategies, and commercialization prospects. Concerns about lead toxicity and end-of-life recycling need to be resolved before full-scale deployment, even though perovskite PVs have a substantially smaller carbon footprint and a shorter energy payback time (EPBT) than silicon PVs. In order to standardize manufacturing procedures, create sustainable material solutions, and apply scalable production techniques, researchers, industry leaders, and legislators will need to work together to overcome the last obstacles to commercialization. With further research and industry assistance, perovskite solar cells have the potential to revolutionize the renewable energy industry and, in the near future, become a widely used photovoltaic option.

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