AN OVERVIEW OF PHOTOVOLTAIC CELLS: THEIR WORKING PRINCIPLES, MATERIALS, FABRICATION METHODS, CHALLENGES AND REMEDIES

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ABSTRACT

One of the primary causes of climate variability is the frequent use of non-renewable energy resources, highlighting the imperative need for sustainable substitutes. At the vanguard of this shift are photovoltaic (PV) cells, semiconductor components that directly transform solar energy into electricity. This paper offers an overview of PV cells, highlighting their working principles, materials, fabrication techniques, current technological status, research and development (R&D) trends, and challenges with recommended remedies. Emphasis is on crystalline silicon (c-Si), thin-film technologies, perovskite solar cells (PSCs) and hybrid tandem configurations. Although some challenges still exist, recent developments have greatly increased efficiency and lowered costs. These consist of integration into current grids, operational instability, environmental issues, and high material expenses. Amongst other research remedies are the development of lead-free perovskites, improved passivation techniques, nanostructuring, recycling methods, and circular economy policies. Supported by International partnerships and policy incentives, ongoing research and development (R&D) projects, seek to move laboratory-scale innovations to commercially viable solutions. This article, therefore, highlights the necessity of continuous innovation to utilize solar energy as a main driver of the global energy balance.

Keywords: Photovoltaic cells, Solar Energy, Research and Development, Challenges, Remedies.

NOMENCLATURE

A/W	Ampere-Watt
AC	Alternating current
AIMD	*ab initio* molecular dynamics
AFM	Atomic Force Microscopy
APTES	Amino-propyl-trimethoxy-silane
CAS	Chinese Academy of Sciences
CdTe	Cadmium telluride
CIGS	Copper indium gallium selenide
COHP	Crystal orbital Hamilton population
CVD	Chemical vapor deposition

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CZTS	Copper zinc tin sulfide
DC	Direct current
DER	Distributed Energy Resources
DFT	Density functional theory
DMII	1-3-methylImidazole iodized salt
DMSO	Dimethyl sulfoxide
DSSCs	Dye-sensitized solar cells
EIA	Energy Information Administration
EQE	External quantum efficiency
ETLs	Electron transport layers
EVA	Ethylvinlyacetate
ExtRa Trees	Extremely Randomized Trees
FE-SEM	Field Emission Scanning Electron Microscope
FF	Fill factor
FFE	Front floating emitter
FSF	Front surface field
FTO	Fluorine-doped tin oxide
GaAs	Gallium arsenide
GCL	Golden Concord Holdings Limited
GFF	Geometric fill factor
HJT	Heterojunction
HTLs	Hole transport layers
IBC	Interdigitated-back-contact
IEA	International Energy Agency
ISE	Institute for Solar Energy
ITRPV	International Technology Roadmap for Photovoltaics
Jsc	Short-circuit current density
KNN	k-nearest neighbor
LAOSS	Large-area organic semiconductor simulation
LGBM	Light gradient boosting machine
MACL	Methylammonium chloride.
ML	Machine learning
MOAI	Multi-objective immune algorithms
MPP	Maximum power point
NREL	National Renewable Energy Laboratory
OCV	Open-circuit voltage
OPV	Organic Photovoltaics
OTES	n-octyl-trimethoxy-silane
PCE	Power conversion efficiency
POE	Polyoefin elastomer
PERC	Passivated Emitter and Rear Cell
PID	Potential Induced Degradation
PLQY	Photoluminescence quantum yield
PSCs	Perovskite solar cells
PV	Photovoltaic
PVCs	Photovoltaic cells

PVPS	Photovoltaic Power Systems Program
QDSCs	Quantum dots solar cells
QFLS	Quasi-Fermi-level-splitting
R&D	Research and Development
RH	Relative humidity
RRF	Random forest regression
RSPP	Rapid spray plasma processing
SAM	Self-assembled monolayer
SCAPS–1D	Solar Cell Capacitance Simulator in One Dimension
SVR	Support vector regression
TBP	4-*tert*-butylpyridine
TOPcon	Tunnel Oxide Passivated Contact
TWp	Terawatts peak
UV	Ultraviolet
Voc	Open-circuit voltage
XRD	X-ray Diffraction

INTRODUCTION

Photovoltaic (PV) solar cells are vital to the change to a sustainable energy future; their technology is at the cutting edge of decarbonization. PV technology has advanced into one of the fastest-growing renewable energy sectors (EIA, 2024). In 1839, the Photovoltaic effect was first discovered by Becquerel (Becquerel A E, 1839). Bell Laboratories in 1954 created the first practicable silicon solar cell (Chapin, Fuller, and Pearson, 1954) and it was theoretically refined by Shockley and Queisser in 1961 (Shockley, and Queisser, 1961). PV development has advanced through numerous generations, formed by advances in material science, device architecture, and manufacturing methods, from crystalline silicon to thin-film, dye-sensitized, organic, quantum-dot, and perovskite-based tandems, each tackling trade-offs between efficiency, cost, flexibility, and sustainability and are vital to meeting climate goals (NREL, 2025); (Dongyang et al., 2025). As a result of its established manufacturing methods, reliability and high efficiency, crystalline silicon remains conspicuous (Green et al., 2023). Thin-film technologies such as CdTe and CIGS provide lesser material usage and flexibility but present resource availability and scalability challenges (Meillaud et al., 2015). Lately, perovskite solar cells (PSCs) have demonstrated prompt efficiency increase; reaching over 25% in laboratory settings (Afre, and Pugliese 2024); Samantaray et al., 2024), providing low-cost fabrication techniques like solution processing due to their tunable bandgaps, low-temperature manufacturing, and high absorption coefficients (Mohsin et al., 2025); (Mokabane et al., 2025). Poised for tandem integration with silicon to surpass the Shockley–Queisser limit (Kirchartz et al., 2025); (Raitani, and Nair, 2025), PSCs have risen from roughly 3.5% in 2009 to 29. 5% by 2025 (Valerie T, 2025). Notwithstanding this, the existence of poisonous lead and inadequate long-term stability constitute obstacles to commercial adoption (Mokabane et al., 2025); (Mary O'Kane 2024). This brought about the exploration into lead-free perovskites, especially those employing tin and germanium as substitutes (Al Atem, and Makableh, 2025); (Mishra et al., 2024). Similarly, quantum dot and organic PV technologies target niche applications requiring lightweight, flexible, semi-transparent applications (Shilpa et al., 2023); (Wang, and Wang, 2024). Also, by enhanced utilization of the solar spectrum, tandem solar cells combine silicon and perovskites with the goal of exceeding single-junction efficiency boundaries (Sunita S, 2025); (Liu et al., 2025). Among other techniques for PV cell fabrication, inkjet printing, spin coating, chemical vapor deposition, and atomic layer deposition are used in the manufacture of PV cells (Gao et al., 2024); (Liu et al., 2019). Each method affects device performance, scalability, and stability. New studies are concentrated on stability improvements via surface passivation, encapsulation, and compositional engineering (Yi et al., 2024); (Mokabane et al., 2025). Recycling and circular economy policies are becoming more crucial to reduce toxic substance issues (Mirletz et al., 2024); (Leug et al., 2025); (Xiao et al., 2025). Dynamic load management, smart inverters, and real-time data systems help PV integration into modern smart grids on the system level (Chen, and Heilscher, 2024); (Rajendran, Raute, and Caruana, 2025); (BusinessWire 2025). Amidst growing issues about climate change and fossil fuel dependency, grid compatibility, intermittency and cost-effectiveness pose some challenges (Wu et al., 2023); (Zhang, and Park, 2024). Therefore, the application of sustainable, effective, and scalable PV technologies has become a notable element in decarbonization initiatives globally (Samantaray et al., 2024); (Xueyu et al., 2025). Driven by material science innovation, better manufacturing techniques, and global supportive policy frameworks, PV technology is braced for expansion despite the challenges (Mdallal et al., 2025); (Anika et al., 2025).

SOLAR CELLS AND THEIR WORKING PRINCIPLE

A solar cell works in the same way as a junction diode, but its construction varies to some extent from characteristic p-n junction (connected) diodes. The actual slim sheet of p-type semiconductor is built using a fairly heavier n-type semiconductor as presented in Figure 1. On the p-type semiconductor sheet, a few finer electrodes are placed. These electrodes allow light to penetrate the slim p-type sheet. Just below the p-type sheet, there is a connection known as a p-n junction. A current-receiving electrode is provided at the base of the n-type sheet. The entire setup is encapsulated with a thin layer of glass to guard it from any mechanical damage (Al-Ezzi, and Ansari, 2022).

Working Principle of Photovoltaic Cells (PVC)

By absorbing photons, PV cells generate electron-hole pairs by exciting electrons from the valence to the conduction band in semiconducting materials. Charge separation driven by the built-in electric field of a p-n junction generates external current flow (Zih-Lie et al., 2024). Critical performance indicators include power conversion efficiency (PCE), fill factor, open-circuit voltage, and short-circuit current density (EIA, 2024). Only photons with energies equal to or above the bandgap of the semiconductor add to charge carrier generation upon photon absorption. Through thermalization, excess energy is lost and some photons are reflected or transmitted without absorption—underscoring the need for optical management. Voltage results from the electron-hole separation at the junction; the external circuit link enables current generation. PV efficiency—that is, output relative to incident photon power—relies on material characteristics (mobility, bandgap, recombination rates), lighting-incidence conditions, and cell design (Kurisinkai et al., 2023); (Mokabane et al., 2025)

Loss processes include:

i. Reflection losses, which are alleviated by anti-reflective coatings and textured surfaces, is key in advanced Si cells for maximizing light absorption

ii. R**ecombination losses** like Shockley–Read–Hall, radiative, and Auger lower efficiency and carrier lifetime

iii. **Thermal losses,** heat is dissipated essentially by photon-energy above the bandgap

iv. Series and shunt resistances, which damage fill factor and result in power losses.

Photon management strategies—such as front and rear coatings, surface texturing, and back reflectors—are continually optimized to address these losses

To mitigate these losses, photon management techniques like back reflectors, front and rear coatings, and surface texturing are constantly improved (Hossain, Sun, and Davis, 2024).

Parts of a solar power system

A photovoltaic system consists of a solar panel, an inverter, and super supercapacitor. The solar panel receives a certain quantum of light energy and converts it into electricity. The supercapacitor backup is employed to offer added energy. The direct current (DC) power produced is converted into alternating current (AC) for domestic use (Floyd T L, 2011); (Arefeen, and Dallas, 2021). The essential parts of a PV system are presented in Figure 2.

PV cell: p-n junction and creation of the depletion region

A PVC is a semiconductor diode, developed to produce power from solar rays. A diode is a mono-crystal semiconductor substance, for instance, silicon, with pentavalent impurities doped on one side and trivalent impurities on the other side to form p-type and n-type, respectively. The doping process generates more mobile carriers in the respective distinctive region. Once the semiconductors in both regions interact, electrons will move to the p-section, thereby creating a positively charged region of donor atoms in the p-n interface around the n-zone. Similarly, a negatively charged resultant acceptor atom is abandoned around the p-n junction; hence, the holes (as p-zone) move from p to the n-region. The resultant valence electron jump could be noticed as hole movement. Electrons and holes would now generate a diffusion current and a depletion region. At the depletion area, the electrons and holes are taken away by the electric field produced, which prevents more charge carriers from flowing (Wang, Liu, and Gao, 2019). The process is shown in Figure 3.

OVERVIEW OF PV MATERIALS

PV technologies can typically be divided into four generations according to their material composition and architecture. Figure 4 shows the different generations.

PV technology categories derived from Figure 4 are as follows:

1. First Generation (Silicon-Based PV Cells): Monocrystalline and polycrystalline silicon cells are still the most often used because of their well-known supply networks and high efficiency (Muhammad, Zeeshan, and Shayan, 2024). With heterojunction (HJT) and Passivated Emitter and Rear Cell (PERC) techniques providing record module efficiencies greater than 25% and bifacial energy benefits (Will N, 2025); (Jäger-Waldau A, 2024), monocrystalline and polycrystalline varieties make up roughly 70–80% of the installed PV market (NREL, 2025); (Green et al., 2023). Enhanced passivation and texture techniques like black silicon have lowered recombination losses and surface reflectance (Machín, and Márquez, 2024); (Maoz et al., 2025), thereby increasing light absorption and performance by 22% (Sharma, and Mishra, 2025); (Mdallal et al., 2025), though economic restrictions come from wafering charges and high-temperature processes.

Gallium Arsenide (GaAs): Having a wide bandgap and excellent optical properties, GaAs is more effective than silicon solar panels, it also uses far less semiconductor material than silicon solar cells and runs better even at higher temperatures; it has a smaller short-circuit current density, higher open-circuit voltage, and superior conversion efficiency though GaAs is costlier and employed in specialized uses as as in space (Ranabhat et al., 2016).

2. Second-Generation (Thin-Films): Thin films PVs like cadmium telluride (CdTe), copper indium gallium selenide (CIGS), and copper zinc tin sulfide (CZTS) provide lesser material usage, intermediate efficiency (roughly 18–22%), simpler fabrication, flexible deposition but suffer from environmental issues regarding toxic components buffer-layer effects (Ghulam et al., 2024); (Mahesh, Wahidul, and Chithirai, 2025). With the use of low-temperature processes, these materials can be deposited on metals, glasses or plastic substrates (Maoz et al., 2025); (Sharma, and Mishra, 2025).

3. Third Generation: Emerging Materials

Emerging materials among which are organic PV (OPV), quantum dots solar cells (QDSCs) and dye-sensitized solar cells (DSSCs), Although still in early phases, they have potentials for low-cost, flexibility, and semi-transparent uses (Kirchartz et al., 2025); (Shilpa et al., 2023). They offer solution-processing, lightweight, and bandgap tunability advantages (Shilpa et al., 2023); (Lee et al., 2020). With efficiencies exceeding 18.1%, quantum-dot solar cells (QDSCs) feature tunable bandgaps, multiple exciton generation and potential thermodynamic ceiling of about 66% [79, 89,]. Enhancement of performance and stability is achieved by the integration of two-dimensional materials like graphene as electrodes and passivation layers (Mahesh, Wahidul, and Chithirai, 2025).

Perovskite Solar Cells (PSCs) have briskly attained efficiencies over 25% (Antonio A, 2023); (Mdallal et al., 2025), profiting from facile solution processing as well as tunable bandgaps (Yang et al., 2024).

4. Fourth Generation (Hybrid systems)

Hybrid PV technologies, including perovskite-silicon tandems are getting much interest. In tandem cells with silicon, especially perovskites with lead halide, have certified efficiencies exceeding 33% (NREL, 2025); (Dongyang et al., 2025). With certified tandem efficiencies reaching 34. 85%, halide perovskites and perovskite–silicon tandems combining perovskites' great absorption with silicon's stability have shot up (*Emiliano, and Vincent, 2025).* Low-temperature and solution-based processes are made possible by cost-effective compounds including methylammonium and formamidinium (Muhammad, Zeeshan, and Shayan, 2024); (Zhang, and Park, 2024).

FABRICATION METHODS

Depending on the material and technology employed, photovoltaic cell fabrication methods differ. Some fabrication methods are listed below:

1. c-Si wafer treatment: Using Czochralski or float-zone methods, silicon wafers are produced, then wafering, doping, surface texturing (to increase efficiency and lower reflection), passivation, and metallization follow. Black silicon texturing methods help to increase light absorption (Lameirinhas et al., 2022); (Yadav et al., 2024). High-temperature techniques like Czochralski crystal growth, photolithography, and metallization define silicon-based PV construction.

2**. Thin-Film Deposition**: Offering scalability and lower cost, thin films are applied through physical vapor deposition (on substrates at high temperatures), sputtering, chemical bath deposition, or solution processing (Bellani et al., 2021); (Siphelo, Thelma, and Mpfunzeni, 2025).

3. Perovskite layer construction: Common solutions-based methods are spray coating, spin coating, slot-die printing and inkjet with additives improving film morphology and stability (Njema, and Kibet, 2023); (Ashwani et al., 2024)

4. 2D Materials Integration: To grow 2D materials like graphene for use in transparent electrodes and interfacial layers, chemical vapor deposition (CVD) is employed, hence improving charge transport and durability (Shi et al., 2024).

SIMULATION OF SOLAR CELLS AND MODULES USING SCAPS–1D This is a unidimensional simulation software program for thin film PVCs developed at the Department of Electronic and Information Systems, University of Gent, Belgium. SCAPS–1D software can generate numerous forms of perovskite solar cells (PSCs) and other thin-film PV gadgets, with broad utilization in the validation of experimental data (Ksouri et al., 2024); (NREL, 2025). Several researchers who contributed to SCAPS–1D software development are Alex Niemegeers, Marc Burgelman, Stefaan Degrave, Johan Verschraegen and Koen Decock. It was initially programmed for use in studying cell pattern of the $CuInSe_2$ and the CdTe family. It runs by solving essential physical equations and it ensures self-reliability before convergence is attained. It's solution procedure is shown in Figure 5, which comprises of successive phases such as cell geometry definition and incorporation of material characteristics or properties (Rezini et al., 2025).

The finite difference method could be used for assessment, with the Scharfetter–Gummel procedure adapted to perfect the current densities. The procedure iteratively calculates the electron and hole amount (n and p) at grid areas (Yuan et al., 2019). Through sequential repetitions, physical quantities such as solar-induced carrier generation (G) and electrostatic potential (U) are refined. Lastly, several characteristics such as current density–voltage (JV) curves, capacitance–frequency (CF) responses, capacitance-voltage (CV) profiles, and external quantum efficiency (QE) can be examined. Other physical parameters such as the generation rate (G), energy band diagrams and recombination rate (U) can also be taken out to model the current densities [(Lee, and Ebong, 2017).Again, Figure 7 shows a typical methodology that was used by (Lee, and Ebong, 2017), where integration of DFT computations with SCAPS replications was used to improve the process of PSCs. Firstly, the procedure started with the implementation of density functional theory DFT computations, which were meant to obtain essential electronic and optical characteristics of Cs_2SnI_6-xBrx PSCs for varying Br contents. These computations involved the evaluation of structural parameters, density of states, electronic band structures, optical properties (for instance, absorption coefficient), effective masses, and bandgap energies. Based on the information given by DFT computations, the procedure advanced to run SCAPS –ID simulations. These simulations were related to experimental studies, which took advantage of the calibration of similar PVC structures to authenticate the replicas used. Based on validation, the PSC designs were developed; where Cs_2SnI_6-xBrx was used as an absorber film. Through the replication process, major parameters including absorber doping concentration and thickness, Br content, carrier transportation materials (electron transport layers [ETLs and hole transport layers HTLs]), and bulk flaws were accurately examined and improved.

CURRENT TECHNOLOGY AND RESEARCH, AND DEVELOPMENT (R&D) STATUS

With improvements in cost reductions, cell efficiencies, and new materials, the PV sector is rapidly developing; Accounting for almost 97% of installations, silicon-based technologies are still dominant (Anoop et al., 2024); (Ayaydah, Raddad, and Hawash, 2023), new passivation and contact techniques like PERC (Passivated Emitter and Rear Cell) (Hacke et al., 2024), TOPCon (Tunnel Oxide Passivated Contact) (Ullah et al., 2023); (ITRPV, 2025), and heterojunction (HJT) (Arriaga et al., 2023) with intrinsic thin layer are pushing efficiency limitations (Hacke et al., 2024); (ITRPV, 2025); (Li et al., 2025). Lead toxicity and moisture instability present major hurdles that drive R&D in tin-based perovskites with chemicals like SnF_2 to enhance film formation and durability (Mishra et al., 2024); (Wan et al., 2024). With improved stability and lead reduction techniques under intensive research and development, perovskite solar cells are nearing commercialization. [(Rice News, 2024); (Al Atem, and Makableh, 2025); (Ren et al., 2025)

Studies on ligand-based passivation, such as amidinium treatments, have yielded stable perovskite layers with 26. 3% efficiency and T_{90} stability exceeding 1,100 hours under stress, indicating looming commercial feasibility (Ma et al., 2022); (Amanda Morris, 2024); (Shi et al., 2024)

With high efficiency and durability, cutting-edge R&D concentrates on tandem architectures. New efficiency records have been set by tandem solar cells combining perovskite and silicon, achieving above 33.9% efficiency on small-area cells and material engineering to increase operational lifetimes hence, they are a key topic of interest Raitani, and Nair, 2025); (Utility Dive, 2025).

Stability studies define important degradation pathways (moisture, ion migration, UV, thermal stress) and suggest remediation via encapsulation, 2D templates, and plasma-polymer passivation (Shi, and Zhang, 2023); (Shi et al., 2024). Breakthroughs comprise double-layer encapsulation, amidinium-based passivation, and scalable roll-to-roll printing (Solak, and Irmak, 2023); (Yi et al., 2024); (Ashwani et al., 2024). New materials like tin- or germanium-based perovskites are being investigated to replace hazardous lead compounds (Dey et al., 2023); (Azizman et al., 2023); (Al Atem, and Makableh, 2025).

Scalable, consistent thin films are investigated for sophisticated production methods including atomic layer deposition and inkjet printing (Ashwani et al., 2024); (Gao et al., 2024). Furthermore, integrating PV modules into smart networks using cutting-edge inverter technologies helps improve real-time performance and grid stability (Chen, and Heilscher, 2024); (Rajendran, Raute, and Caruana, 2025); (BusinessWire 2025).

Record efficiencies include; OPV15.8%, CdTe 21%, CIGS 23.4%, Si multi 24.4%, Si mono 27.8%, Perovskite 26.9%, Perovskite-Si tandem 34.9%, III-V on Si (2-terminal) 36.1%, III-V multi-junction concentrator solar cells 47.6% (Fraunhofer ISE, 2025), China's National Institute of Metrology certified that GCL Optoelectronics unit has achieved 29.51% power conversion efficiency for a 2,048 cm² perovskite-silicon tandem solar module in June 2025 *(Vincent S, 2025).* Shanghai Institute of Microsystem and Information Technology under the Chinese Academy of Sciences (CAS) confirmed that JinkoSolar has achieved a 33.84% power conversion efficiency for a perovskite-silicon tandem solar cell based on n-type wafers in January 2025 surpassing the former 33.24% achieved (*Emiliano B, 2025).*

U.S. Department of Energy's National Renewable Energy Laboratory (NREL) confirmed that Longi's recent laboratory development used bilayer passivation (lithium fluoride + ethylenediammonium diiodide) to achieve 34.85% efficiency in April 2025 surpassing the former 34.6% efficiency in November 2023 (*Emiliano, and Vincent, 2025).* PV capacity surpassed 1.6 TWp at the close of 2023 and grew to significantly over 2.2 TWp at the end of 2024, underscoring its dominant role in climate mitigation. (IEA-PVPS, 2025). Major investments support scaling initiatives; Japan, for instance, has a billion-dollar project to create ultra-thin flexible perovskite modules intended at achieving up to 1 GW/year by 2027 (Harry D, 2025). These milestones indicate the trend is moving from R&D to market production.

CHALLENGES AND REMEDIES

PV technologies face some challenges such as availability of materials, environmental effects, long-term stability, and production scalability, even with the aforementioned progresses. Silicon cells need energy-intensive manufacturing; thin-film cells may include poisonous compounds like cadmium or lead. For perovskites, lead toxicity, stability and degradation under actual circumstances are major problems. Remedies comprise recycling methods, encapsulation technologies, lead-free perovskite alternatives, and low-energy fabrication developments. Below are some challenges faced by PV technology and their remedies:

Efficiency Restrictions

1) Intermittency of solar irradiance limits reliable power supply (Dzobo, Tivani, and Mbatha, 2024).
2) Intrinsic losses like recombination, thermalization, and material defects limit efficiency (Suo et al., 2024); (Al-Ali, Olabi, and Mahmoud 2025)

Remedies

1) Nanostructuring and passivation (like **SnF_2 , alumina nanoparticles addition**, and **Lewis base passivators** to reduce defect density and enhance film uniformity) (Kurisinkai, 2023); (Mishra et al., 2024); (Wan et al., 2024).
2) Tandem architectures (such as incorporating **2D/3D layered structures,** Atomic layer deposition passivation, and hybrid perovskite architectures for increased environmental resistance) (Yadav et al., 2024); (Zhang, and Park, 2024); (Tanko et al., 2025)
3) Reducing vapor environments during manufacturing to suppress Sn^{4+} formation are all main remedies (Mohsin et al., 2025); (Jake, Holger, and John, 2025).

Stability and Degradation

1) Moisture (Mohsin et al., 2025); (Mokabane et al., 2025)

2) UV exposure (Shilpa et al., 2023); (Mary O'Kane, 2024); (Mokabane et al., 2025)

3) Temperature swings (Zih-Lie et al., 2024); (Tanko et al., 2025)

4) Soiling causes PV modules to degrade, thereby leading to output losses over operational lifetimes (Kazem et al., 2024); (Sharma, and Mishra, 2025)

Remedies

1) Anti-soiling coatings (Badran, and Dhimish, 2023); (Amanda M, 2024)
2) Advanced encapsulation (Ning et al., 2023); (Kazem et al., 2024)
3) 2D capping sulfonium/sulfur ligands (Suo et al., 2024); (Shi et al., 2024); (Yi et al., 2024)
4) Controlled module environments can be employed (Dey et al., 2023); (Kazem et al., 2024); (Li et al., 2025)

Environmental Impact (Waste and Toxicity)

1) Substantial wastes are generated by end-of-life PV modules (Lee, Duffy, and Allen, 2025)
2) c-Si wafering incurs **30–40% kerf loss**, thereby increasing resource consumption and carbon footprint**.** (Yadav et al., 2024)
3) **Cadmium (CdTe), lead (perovskites), as well as indium in high-performing PV materials** create significant environmental hazards and regulatory issues [8, 9, 13]

Remedies

1) **Kerf-free wafering** ((Jiang et al., 2024); (Yadav et al., 2024)
2) **Thin-glass laminates (**Glassonweb, 2025)
3) Recycling methods such as green solvents, chemical recovery and mechanical shredding can improve material recovery rates (Emily W, 2024); (Aktas et al., 2022).
4) Promote modular designs that assist recycling, encapsulate recovery (Gerold, and Antrekowitsch, 2024); (Badran, and Lazarov, 2025)
5) Create programs **for end-of-life recycling** for metal, glass, and implement **extended producer responsibility**, policy initiatives are being put in place (Badran, and Lazarov, 2025); (Xiao et al., 2025)
6) Eco-friendly changes and circular design (such as **lead-free perovskites** like Sn, Bi, Ge alloys) and tandem scalability (Al Atem, and Makableh, 2025); (Mishra et al., 2024); (Rezini et al., 2025).

Raw Material Supply, Scalability, and Cost

1) Market volatility and scarcity affect PV materials like indium, tellurium, gallium, and high-purity Sn. (Mirletz et al., 2022); (Heath et al., 2020).
2) Uniformity, reliability, and cost optimization problems arise in translating laboratory-scale devices to mass production (Kirchartz et al., 2025).

Remedies:

1) Encouraging recycling of scarce elements from decommissioned modules (Su et al., 2020).
2) Recycling lead-based modules and embracing circular designs (Emily W, 2024); (Xueyu et al., 2025)
3) Use of PV materials that are abundant (copper-based, organics) (Ashwani et al., 2024)
4) Bridge the distance between laboratory-scale efficiency and industrial-scale dependability (Baumann et al., 2024); (Rice News, 2024); (Siphelo, Thelma, and Mpfunzeni, 2025).

Standardization & Grid Integration

1) IEC testing procedures lack structures for emerging PV types (perovskite, tandems) (Rajendran, Raute, and Caruana, 2025)
2) Integration into existing electrical grids requires addressing harmonics, voltage fluctuations, and regulatory compliance (Kaur, and Bath, 2025)
3) High PV penetration challenges grid stability and requires advanced storage and control systems (Chen, and Heilscher, 2024); (Rajendran, Raute, and Caruana, 2025)

Remedies

1) Update IEC standards to include humidity, PID, and combined aging tests (BusinessWire, 2025); (Utility Dive, 2025).
2) Deployment of **smart inverters,** dynamic pricing models, DC/AC advances, DER controls (Dzobo, Tivani, and Mbatha, 2024); (Rajendran, Raute, and Caruana, 2025)
3) **Grid-scale storage** is essential for PV penetration to boost dispatchability (Lusis et al., 2020); (Kaur, and Bath, 2025)

CONCLUSION

Photovoltaic (PV) cells symbolize a technologically diverse and fast-developing field poised to play a major role in decarbonization globally. The following major conclusions can be drawn from the review:

Latest developments

- A global PV cumulative capacity grew to significantly over 2.2 TWp at the end of 2024.
- Use of novel materials like tin- or germanium-based perovskites is being explored to replace toxic lead variants
- Use of advanced fabrication techniques like atomic layer deposition and inkjet printing for scalable, uniform thin films is also being explored
- Integration of PV modules into smart grids with advanced inverter technologies that supports real-time performance optimization and grid stability, tandem cells that combine different materials to broaden light absorption and engineered perovskite structures with improved defect tolerance and longer operational lifetimes achieving over 33.9% efficiency on small-area cells, are being used

- Longi's recent laboratory development used bilayer passivation (lithium fluoride + ethylenediammonium diiodide) to achieve 34.85% efficiency.
- Fraunhofer Institute for Solar Energy (ISE)'s record efficiencies include; OPV15.8%, CdTe 21%, CIGS 23.4%, Si multi 24.4%, Si mono 27.8%, Perovskite 26.9%, Perovskite-Si tandem 34.9%, III-V on Si (2-terminal) 36.1%, III-V multi-junction concentrator solar cells 47.6%

Challenges

Despite these developments, some challenges persist. These include;

- Efficiency limitations
- Standardization and grid integration
- Economic scalability and cost
- Stability and degradation
- Waste and toxicity

Remedies

To mitigate these concerns, researchers and engineers are exploring a series of remedies. These include;

- nanostructuring and passivation (like **SnF_2 , alumina nanoparticles addition**, and **Lewis base passivators** to reduce defect density and enhance film uniformity)
- tandem architectures (such as incorporating **2D/3D layered structures**, ALD passivation, and hybrid perovskite architectures for increased environmental resistance)
- reducing vapor environments during manufacturing to suppress Sn^{4+} formation
- anti-soiling coatings
- advanced encapsulation
- 2D capping sulfonium/sulfur ligands, and controlled module environments
- **kerf-free wafering** and **thin-glass laminates**
- recycling methods such as green solvents, chemical recovery and mechanical shredding
- To promote modular designs that assist recycling, encapsulant recovery, programs **for end-of-life recycling** for metal, glass, and implement **extended producer responsibility,** policy initiatives, use of eco-friendly changes and circular design
- bridging the distance between laboratory-scale efficiency and industrial-scale dependability
- update IEC standards to include humidity, PID, and combined aging tests,
- deployment of **smart inverters,** dynamic pricing models, DC/AC advances, DER controls as well as **grid-scale storage** for PV penetration

In summary, continual multidisciplinary research and industry teamwork will move PV technology to commercial maturity. With continued R&D investments, global partnership, and planned technological deployment, PV cells are poised to be a keystone of the sustainable energy network for years to come.

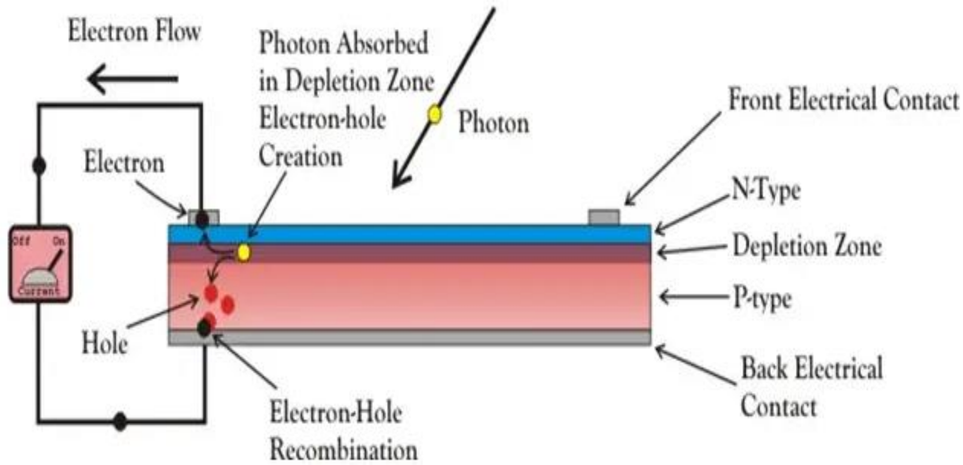

Figure 1. A simple solar cell and its components.
Source: (Electrical4U, 2024b).

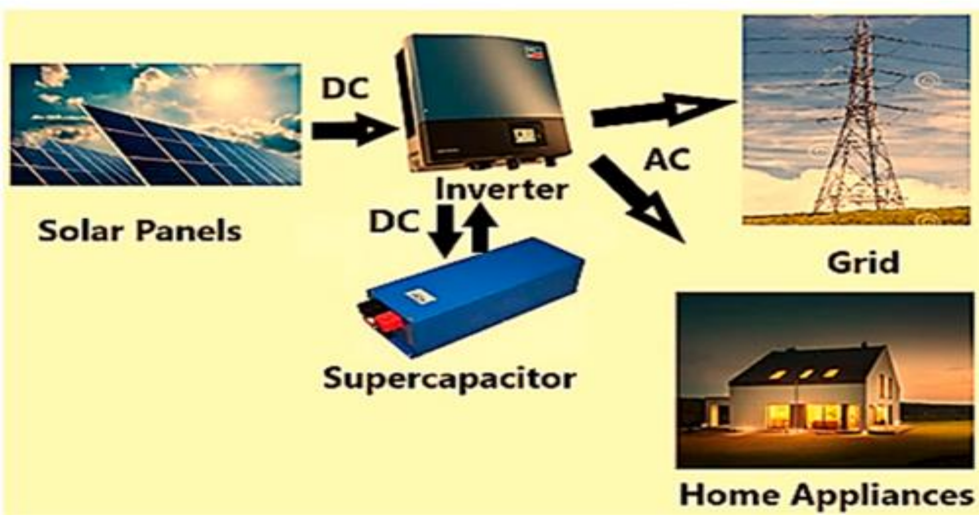

Figure 2. The fundamental parts of a photovoltaic system.
Source: (Arefeen, and Dallas, 2021).

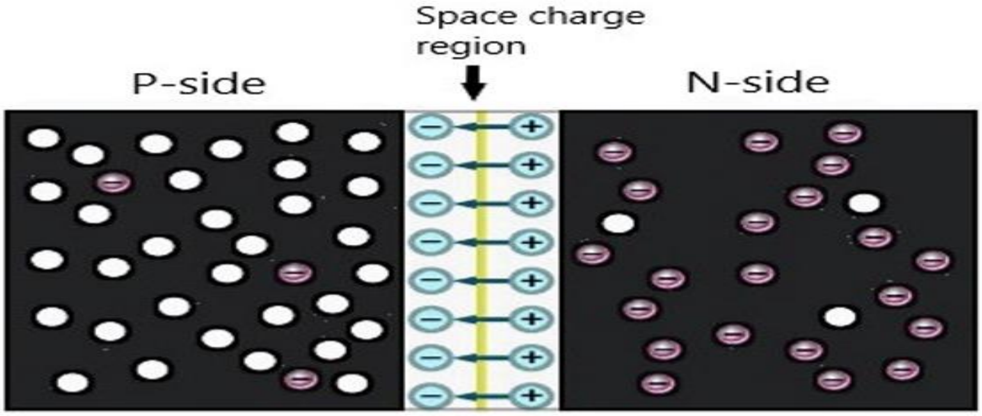

Figure 3. Production of the electric field in between p-, and n-side (the space charge area).
Source: (Wang, Liu, and Gao, 2019)

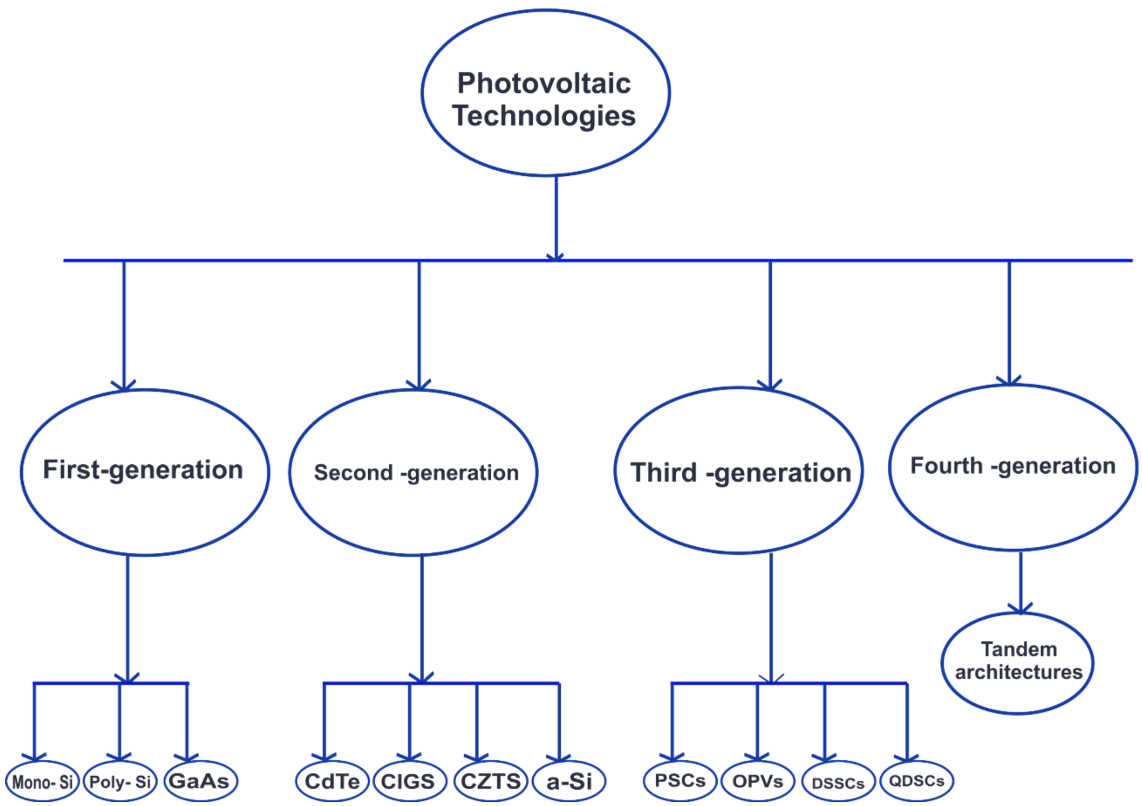

Figure 4. Schematic diagram of the classification of PV technologies.
Source: (author).

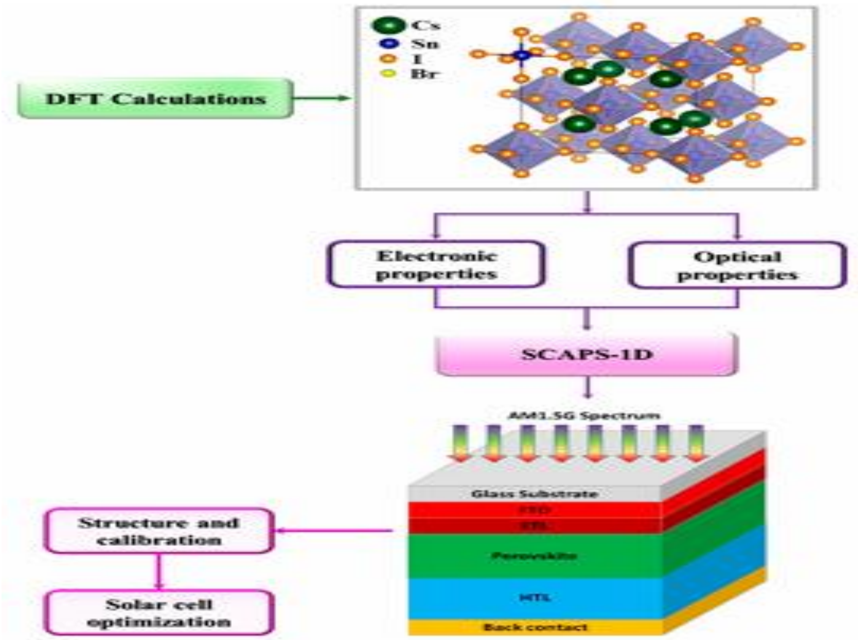

Figure 5. Organizational workflow for augmenting Cs_2SnI_6-xBrx PVCs performance utilizing density functional theory (DFT) and SCAPS–1D.
Source: (Rezini et al., 2025).

Table 1: Related works on PSCs showing factors relied on and results obtained

Researcher's name	Title of research	Year of publication	Factors relied on	Results obtained
Saliba et al.	Incorporation of rubidium cations into perovskite solar cells improves photovoltaic performance. Science	2016	Rubidium (Rb^+) cation incorporation in PSCs; cation cascade integration; polymer-impregnated encapsulation; lattice stability & oxidation resistance	PCE up to 20.2%, electroluminescence 3.8%, OCV 1.24 V; potential loss 0.39 V, polymer PVCs retained 95% performance at 85°C for 500 h
Giles et al.	Perovskite-perovskite tandem photovoltaics with optimized band gaps.	2016	Narrow and wide-bandgap perovskite combination (FA/Cs Sn–Pb & FA/Cs Pb-halide); monolithic and 4-terminal tandem architectures	Narrow-bandgap PSC 14.8%, monolithic 2T tandem 17.0%, 4T tandem 20.3%, with high thermal and environmental stability

Yang et al.	Perovskite ink with wide processing window for scalable high-efficiency solar cells	2017	Solvent tuning and chlorine for $MAPbI_3$ catalyst preparation; antisolvent treatment; blade- and spin-coating deposition; large-area module fabrication	High-quality perovskite films; 18.55% (0.12 cm^2), 17.33% (1.2 cm^2); 13.3% stabilized active-area efficiency for 12.6 cm^2 module with 88% GFF
Chang et al.	Controlled deposition and performance optimization of perovskite solar cells using ultrasonic spray-coating of photoactive layers	2017	Ultrasonic spray deposition; ink formulation (concentration, solvent ratio); drying kinetics; film crystallinity and alignment	PSC PCE 11.30%, fill factor 73.6%, Jsc 19.7 mA/cm^2, OCV 0.78 V
Jia et al.	Improved perovskite morphology and crystallinity using porous PbI2 layers for efficient planar heterojunction solar cells	2017	Permeable PbI_2 films with polystyrene pore-generating agents; organic solvent washing; improved interfacial contact with CH_3NH_3I	Perovskite films with 17% efficiency, uniform surface coverage, no residual PbI_2
Amruta, and Sheela	Solution process for fabrication of thin film CdS/CdTe photovoltaic cell for building integration	2017	Chemical bath deposition of TiO_2/CdS/CdTe layers; controlled thickness; UV–Vis, FE-SEM, AFM, XRD characterization	Semi-transparent PSCs (~43% crystal clear); reduced leakage current, enhanced Jsc
Martin et al.	Opto-electronic characterization of third-generation solar cells	2018	Multiple opto-electronic evaluation techniques (charge extraction, transient photovoltage, impedance spectroscopy); drift-diffusion simulations; parameter extraction	Identified charge injection barriers, low mobilities, traps; reduced parameter correlation; achieved complete, precise parameter extraction for bulk-heterojunction PSCs
Li et al.	Scalable fabrication of	2018	Use of abundant earth elements; low-	PSCs suitable for tera-watt scale, low

	perovskite solar cells		temperature fabrication; roll-to-roll scalability	cost, scalable, and improved stability compared to thin-film PVs
Chou et al.	Scalable ultrasonic spray-processing technique for manufacturing large-area $CH_3NH_3PbI_3$ perovskite solar cells.	2018	Ultrasonic spray deposition for large-area perovskite layers; controlled precursor volume and spray passes	PCE 12.3% for 1 cm^2, 10.18% (2 cm^2), 7.01% (3 cm^2); reduced hysteresis; good exposure stability
Yao et al.	The impacts of PbI_2 purity on the morphology and device performance of one-step spray-coated planar heterojunction perovskite solar cells	2018	PbI_2 purity variation (98% vs. 99.9%); unit-step ultrasonic spray deposition; grain size control	99.9% PbI_2: PCE 12.6%, high crystal quality; 98% PbI_2: PCE 4.9%; hysteresis minimized with two-step spin-casting
Detao et al.	Improved crystallinity of perovskite via molecularly tailored surface modification of SnO_2	2019	SnO_2 surface modification with APTES and OTES; enlarged perovskite crystal grains	Increased grain size; reduced non-radiative recombination; extended charge lifetime; PCE enhanced 18.21 → 20.3%
Lin et al.	Monolithic all-perovskite tandem solar cells with 24.8% efficiency exploiting comproportionation to suppress Sn (ii) oxidation in precursor ink	2019	Sn void reduction in narrow-bandgap Pb–Sn perovskites using metallic Sn; charge-carrier diffusion enhancement	Monolithic all-perovskite tandem PCEs: 24.8% (0.049 cm^2) and 22.1% (1.05 cm^2); 90% performance after 463 h at 1-sun illumination
Lee et al.	Control of crystal growth toward scalable fabrication of	2019	Large-area deposition strategies (blade, slot-die, evaporation, post-treatment); minimize PCE loss in scaling	PCE loss rate $1.4 \times 10^{-2}\%\ cm^{-2}$, projected PCE >20% with optimized upscaling

	perovskite solar cells			
Su et al.	Perovskite ink with an ultrawide processing window for efficient and scalable perovskite solar cells in ambient air.	2020	Precursor toner optimization; antisolvent extraction; methylamine chloride addition; single-pass spraying	Rigid PSC: 18.5%, flexible PSC: 16.15%; cm^2-scale PCEs: 15.07% (rigid), 13.21% (flexible); 540 m h^{-1} deposition rate viable for commercialization
Zhengyang et al.	Design of (C3N2H5) (1-x) CsxPbI3 as a novel hybrid perovskite with strong stability and excellent photoelectric performance: A theoretical prediction.	2021	Cation doping (Cs) in $ImPbI_3$; DFT, AIMD, XRD, COHP, tolerance factor analysis	$Im_{0.5}Cs_{0.5}PbI_3$: robust thermodynamic/structural stability, lower optical bandgap, excellent optical absorption
Bingyu et al.	Improved perovskite crystallization via antisolvent-assisted processed using additive engineering for efficient perovskite solar cells	2021	DMII additive in precursor; anti-solvent-aided deposition	Improved perovskite crystallinity, larger grains, smoother surface; PCE 14.56% vs. 12.80% for pristine cell
Jeong et al.	Pseudo-halide anion engineering for α-FAPbI3 perovskite solar cells.	2021	Anion engineering using pseudo-halide formate ($HCOO^-$); surface defect passivation	PSC PCE 25.6%, 450 h operational stability, electroluminescence QE >10%
Ho et al.	Grain transformation and degradation mechanism of formamidinium and cesium lead iodide perovskite	2021	Cation alloying in $FA_{0.85}Cs_{0.15}PbI_3$; photothermal infrared microscopy	Degradation mechanism identified: δ-$CsPbI_3$, δ-$FAPbI_3$, PbI_2 formation under high humidity/light exposure; FA

	under humidity and light.			migration/evaporation
Castro, Duarte, and Andrade	Perovskite Solar Modules: Design Optimization	2022	Upscaling design optimization using LAOSS simulation; interconnection width control	Demonstrated energy retention in upscaled modules; highlighted critical role of laser accuracy and design for minimized losses
Khanzadeh et al.	Structural optimization of a perovskite solar cell using single- and multi-objective particle swarm optimization method	2022	Particle swarm optimization integrated with SCAPS-ID; single- and multi-objective optimization; layer thickness and efficiency parameters	Optimized layers increased PCE from 6.69% → 23.76%; enhanced FF, OCV, Jsc
Noh et al.	Facile tuning of PbI_2 porosity via additive engineering for humid air processable perovskite solar cells	2022	4-tert-butylpyridine (TBP) additive to configure PbI_2 morphology; ambient air deposition (RH 30–40%)	Optimal TBP (10 vol%) → porous PbI_2, high-quality perovskite layer; PCE 15.1%, improved ambient stability
Jikui et al.	Design, realization and loss analysis of efficient low-cost large-area bifacial interdigitated-back-contact solar cells with front floating emitter	2022	Front floating emitter (FFE) replacing FSF; double-side boron diffusion; ion implantation; unit-step mask/opening	IBC cell PCE 22.92%; low recombination; simplified fabrication; identified metal contact and surface recombination losses
Lin et al.	All-perovskite tandem solar cells with improved grain surface passivation.	2022	Ammonium-cation passivation of Pb–Sn perovskites; molecular dynamics simulations	Tandem absorber width ~1.2 μm; carrier diffusion doubled; certified PCE 26.4%, >90% performance retention after 600 h
Xiao et al.	Scalable processing for	2022	Blade coating; cesium ratio tuning; diffusion	Tandem modules PCE 21.7%, 20 cm^2

	realizing 21.7%-efficient all-perovskite tandem solar modules		barrier between sub-cells	area; retained 75% of original efficiency after 500 h at 1-sun
Lu et al.	Crystallization and defect regulation in Sn–Pb perovskite solar cells via optimized anti-solvent passivation strategy	2022	Anti-solvent passivation (isopropanol, MACl); defect and crystal formation control	MACl-aided Sn–Pb PSCs: Jsc 26.49 mA/cm^2, OCV 0.70 V, FF 16.05%
Ning et al.	Stable passivation of cut edges in encapsulated n-type silicon solar cells using Nafion polymer	2023	Edge passivation with Nafion polymer; module cutting techniques; boundary repassivation	Repassivated boundaries reduced recombination; stable for 1000 h at 85% RH/85°C; EVA encapsulants better than POE
Yanyan et al.	High-performance UV–visible photodetectors based on ZnO/perovskite heterostructures	2023	ZnO/perovskite heterostructure; sputtering and sol-gel spin-coating; spectral range UV–visible	EQE 940.86%, detectivity 1.09×10^{12} Jones, light-to-dark ratio 5.88×10^4, responsivity 2.73 A/W; improved visible light detection
Wenhao et al.	Performance prediction and optimization of perovskite solar cells based on the Bayesian approach.	2023	Bayesian optimization and ML; four ML models (ExtRa Trees, LGBM, KNN, RRF); parameter prediction	ExtRa Trees best R^2=0.71; Bayesian optimization → predicted PCE 23.0%; ML accelerates fabrication process
He et al.	Improving interface quality for 1-cm^2 all-perovskite tandem solar cells	2023	Self-assembled monolayer (SAM) hole-selective layer; wide-bandgap PSC; monolithic perovskite tandem solar cell integration	Wide-bandgap sub-cells OCV 1.31 V; PCE 27%, tandem OCV 2.12 V, FF 82.6%

Chen et al.	Regulating surface potential maximizes voltage in all-perovskite tandems	2023	Diammonium surface treatment (1,3-propane diammonium); quasi-Fermi-level splitting analysis	QFLS improved by 90 meV; monolithic tandem PCE >27%, OCV 2.19 V; retained ≥86% PCE after 500 h
Yan et al.	Fabrication of perovskite solar cells in ambient air by blocking perovskite hydration with guanabenz acetate salt	2023	Guanabenz acetate salt for vacancy passivation; ambient air PSC fabrication; defect-controlled crystallization	PCE 25.08%; non-encapsulated: 96% after 2000 h; encapsulated: 85% after 300 h (85°C/85% RH); high-quality films
Swagata et al.	Cerium-based halide perovskite derivatives: A promising alternative for lead-free narrowband UV photodetection	2024	Lead-free Cs_3CeBr_6 perovskite; low-temperature eco-friendly synthesis; optoelectronic device fabrication	PLQY ~89%, PL lifetime 28.3 ns; responsivity 2.05 A/W, detectivity 10^{13} Jones; long-term stability, high PCE
Ksouri et al.	DFT Study of structural, elastic, electronic, and thermodynamic properties of compounds Cs_2TiCl_6 and Cs_2TiBr_6	2024	Br substitution in Cs_2SnI_6; DFT and SCAPS-1D simulations; $FTO/TiO_2/Cs_2SnI_6$/P3HT/Ag architecture	Bandgap 1.33 → 2.24 eV; absorption in visible range; PCE 0.47–3.07% depending on Br content; validated simulation methodology
Yunwu et al.	Accelerating the design and manufacturing of perovskite solar cells using a one-shot automated machine learning framework	2025	AutoML, SVR, MOIA, reverse engineering; RSPP fabrication; rapid parameter screening	Simulated PCE 21.83 → 31.29%; 5 optimal parameter sets identified from 166; continuous performance enhancement
Yang et al.	Understanding and manipulating the crystallization of Sn–Pb perovskites for efficient all-perovskite	2025	DMSO desorption manipulation; Sn–Pb mixed perovskite crystallization; antisolvent-free deposition	Mono-junction Sn–Pb PCE 22.88%; all-perovskite tandem PCE 28.87%; 87% retention after 450 h at 1-sun MPP

	tandem solar cells.			

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