International Journal of Materials Science and Applications
2026, Vol. 15, No. 5, pp. 163–174
https://doi.org/10.11648/j.ijmsa.20261505.11

Review Article

Multi-Criteria Comparative Review of Photovoltaic Materials and Technologies: Performance, Stability, Resources, Circularity, and Technological Maturity

Mamadou Traore[1, *], Amadou Sidibe[1], Abdoulaye Tall[2], Moussa Camara[2], Abdourahmane Diallo[3, 4], Abdoul Kadri Diallo[4], Saliou Bolarinwa Ogou[1]

[1]Departement of Physics, University of Julius Nyerere of Kankan, Kankan, Guinea

[2]Faculty of Sciences, Gamal Abdel Nasser University of Conakry, Conakry, Guinea

[3]Department of Mechanical Design and Manufacturing, Higher Institute of Technology of Mamou, Mamou, Guinea

[4]Department of Energy, Higher Institute of Technology of Mamou, Mamou, Guinea

Abstract

The increasing diversification of photovoltaic technologies generates more and more questions about their performance, dependability and sustainability. This review is centered on a comparative overview of nine families of photovoltaic technologies: crystalline silicon (c-Si), CdTe, CIGS, kesterites (CZTS/CZTSSe), III-V semiconductors, perovskites, organic photovoltaics (OPV), dye-sensitized solar cells (DSSC) and tandem architectures. The study takes a qualitative approach based on seven criteria, including photovoltaic performance and optoelectronic qualities, stability, manufacturing costs and complexity, resource availability and criticality, toxicity and environmental implications, recyclability, and technological maturity. The comparison demonstrates that c-Si presents the best compromise between performance, stability and industrial maturity, whereas III–V and tandem technologies are known for their high efficiencies but suffer from cost, manufacturing or stability issues. Emerging technologies have the potential to complement each other, but their implementation is still limited by technological and industrial challenges. This cross-cutting approach further emphasizes the connection of these criteria, in particular between stability, resource use and sustainability. It also states that performance data acquired under different testing conditions may not always allow a straight comparison between technologies. These results emphasize the need for a holistic study of the trade-offs among performance, dependability, material limitations, and environmental impact to guide future developments of solar technology.

Keywords

Photovoltaics Materials, Photovoltaic Technologies, Multi-criteria Analysis, Stability, Critical Resources, Circularity, Sustainability

*Correspondence: Mamadou Traore (mamadoutraore1uadb@gmail.com)

Received: 22 October 2026; **Accepted:** 2 November 2026; **Published:** 16 November 2026

Copyright: © The Author(s), 2026. Published by Science Publishing Group. This is an **Open Access** article, distributed under the terms of the Creative Commons Attribution 4.0 License (http://creativecommons.org/licenses/by/4.0/), which permits unrestricted use, distribution and reproduction in any medium, provided the original work is properly cited.

1. Introduction

Photovoltaic (PV) technologies are expanding in response to energy transition objectives, climate concerns, declining costs, and continued technological progress. This expansion has diversified absorber materials and device architectures, ranging from crystal-line silicon to emerging perovskite, organic, and tandem technologies [1-4].

The photovoltaic performance relies on the optoelectronic properties of the materials, in particular the bandgap, absorption and charge transport. However, efficiency alone is not a sufficient indicator. Other criteria including stability, manufacturing costs and complexity, availability of resources, toxicity, environmental implications and recyclability also dictate the application of these technologies [4-6]. The necessity of substitution, reduction of material intensity and recycling is pointed out by important elements (Ag, In, Ga and Te) and possibly poisonous ones (Pb and Cd) constraints [6-8].

Photovoltaics get many assessments, although the analysis is frequently limited to certain technology or characteristics. Therefore, it is essential an integrated assessment of the main mature and emerging technologies to identify their techno-economic and environmental trade-offs.

In this context, this research provides a multi-criteria comparative analysis of nine photovoltaic families: c-Si, CdTe, CIGS, CZTS/CZTSSe kesterites, III-V semiconductors, perovskites, OPV, DSSC and tandem structures. It is based on seven complementary dimensions and aims to identify trade-offs between performance, stability, manufacturing, resources, environmental impacts, recyclability and technological maturity, so as to define research priorities for high-performance, economically viable and sustainable photovoltaic technologies.

2. Methodology for the Comparative Analysis of Photovoltaic Materials

The potential of a photovoltaic technology is not limited to its performance, but also to its stability, its manufacturing, its resources mobilized and its compatibility with environmental and industrial requirements for a large-scale deployment [9]. In particular, the growth of the sector reinforces the issues related to critical raw materials and end-of-life material recovery [6, 10]. The adopted framework is shown in Figure 1.

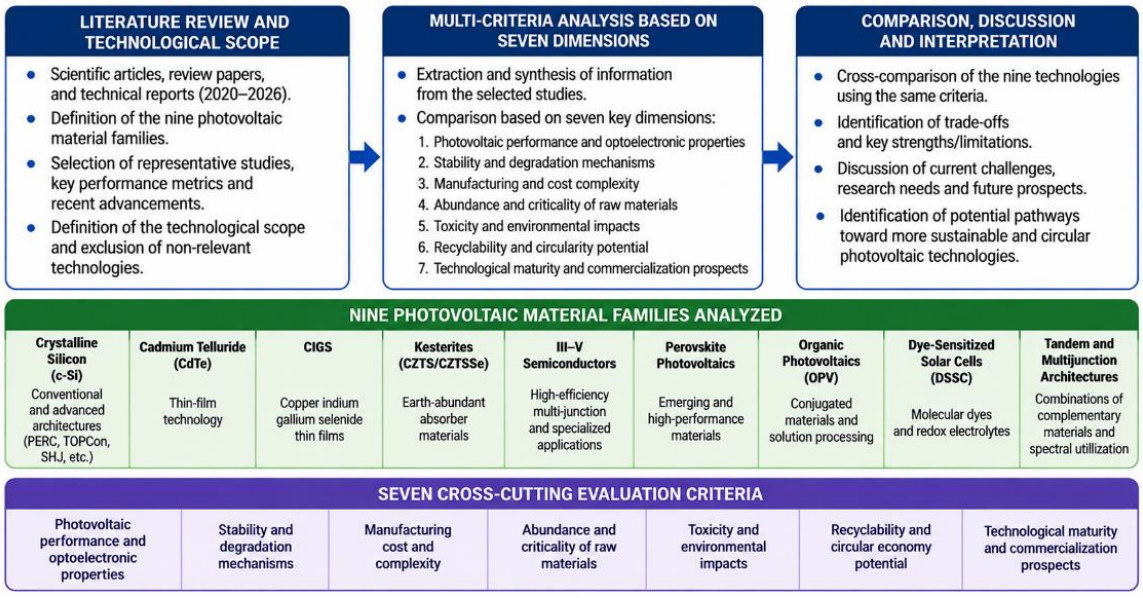


Figure 1. *Methodological framework for the comparative analysis of photovoltaic material technologies.*

2.1. Review Approach and Technological Scope

The review considers eight material/device families (c-Si, CdTe, CIGS, CZTS/CZTSSe, III–V semiconductors, perovskite, OPV, and DSSC) and separately evaluates tandem architectures as cross-cutting device configurations that combine two or more technologies.

2.2. Comparative Analysis Criteria

The analysis is based on seven complementary dimensions: (i) photovoltaic performance and optoelectronic properties [9]; (ii) stability and degradation mechanisms; (iii) manufacturing costs and complexity; (iv) raw material abundance and criticality [6]; (v) toxicity and environmental impacts; (vi) recy-

clability and circular economy potential [11]; and (vii) technological maturity and commercialization prospects. This paradigm enables to identify the main trade-offs between photovoltaic systems.

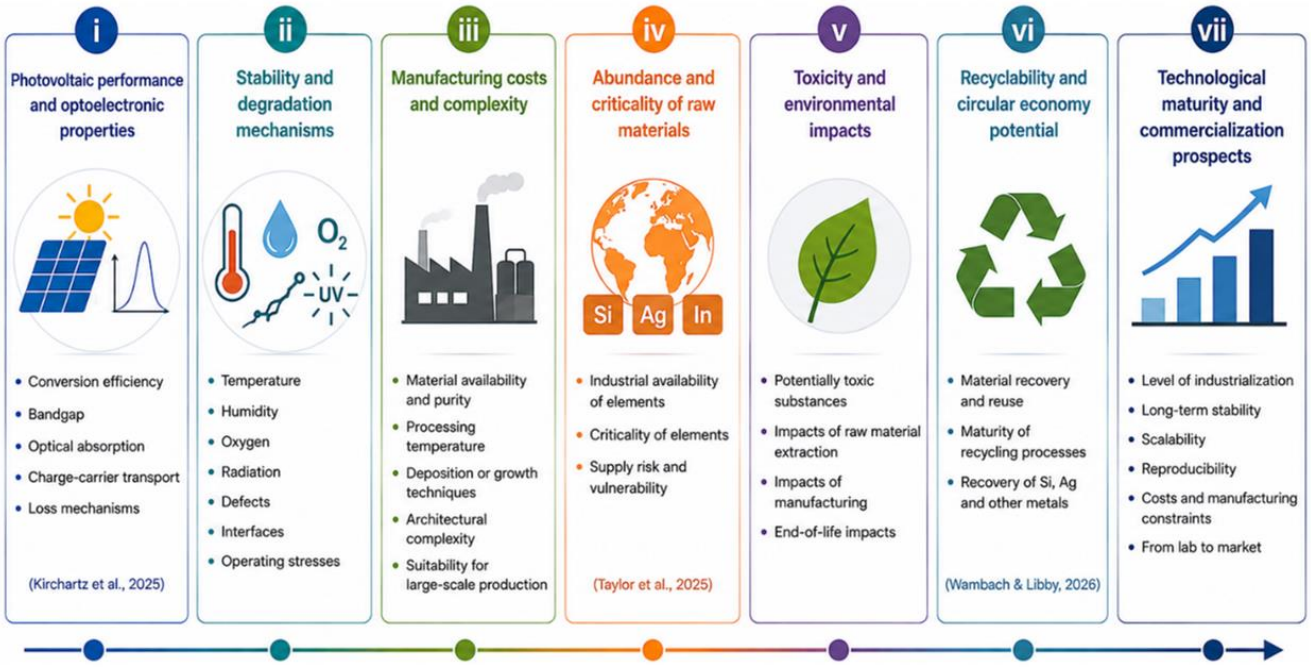


Figure 2. *Multi-criteria assessment framework for photovoltaic technologies.*

2.3. Comparison and Interpretation Procedure

The comparison is based on the application of a common framework—comprising seven criteria—to the nine families of solar technologies under study. These families are analyzed to determine their key characteristics, advantages, and limitations across various evaluation dimensions. The information provided is qualitative, accounting for the diversity of the technologies, their level of technical maturity, and the conditions under which their performance is measured. The results are compared across the different technology families to identify similarities, differences, and trade-offs. This analysis draws on trends observed in the literature and on the qualitative assessments compiled in the comparative table. In experimental settings, the size of the devices and the availability of data limit the direct comparison of certain results. Quantitative scores are not used in this approach. The objective is not to establish an absolute ranking of photovoltaic technology families, but rather to highlight technological, economic, and environmental trade-offs, as well as the interactions between the various evaluation factors.

3. Conventional and Thin-film Photovoltaic Technologies

This group includes crystalline silicon (c-Si), CdTe, CIGS and CZTS/CZTSSe kesterites with maturity levels ranging from industrialisation to emerging research.

3.1. Silicium Cristallin

Crystalline silicon (c-Si), accounting for approximately 95% of the photovoltaic market, dominates due to its maturity, reliability and performance. Its PERC, TOPCon and SHJ/HJT architectures rely on various strategies for passivation and contact optimization [12-14].

With an indirect bandgap of approximately 1.12 eV, c-Si requires effective optical trapping. PERC architectures employ rear-side passivation, TOPCon uses tunnel-oxide passivated contacts and SHJ/HJT utilizes hydrogenated amorphous silicon layers [12-14]. These advancements have enabled efficiencies of 26.81% for SHJ cells, with a short-circuit current of 41.45 mA cm^{-2} [13], and 27.09% for back-contact heterojunction cells.

Despite its stability, c-Si remains susceptible to LID, LeTID and PID degradation, the extent of which varies depending on doping and architecture [15]. SHJ cells also face risks of c-Si/a-Si: H interface degradation [16], while accelerated testing has revealed specific vulnerabilities in TOPCon and HJT technologies [17, 18].

Manufacturing involves purification, wafer production, texturing, doping, passivation and metallization. Although industrialization has reduced costs, TOPCon and SHJ require spe-

cific processes [12, 13, 16]. Metallization optimization remains essential to limit the consumption of conductive materials [19]. Although silicon is abundant, certain architectures rely on silver and indium; annual demand for these materials could increase four- to twenty-seven-fold and thirty-eight- to two-hundred-and-eighty-six-fold, respectively, between 2022 and 2050, depending on the scenarios analyzed [20]. Environmental impacts stem primarily from energy-intensive manufacturing processes and depend on the electricity mix [21].

At the end-of-life stage, glass and aluminum are relatively easy to recover, unlike silicon and valuable metals, which require specific processing methods [22]. Electrochemical processes and closed-loop recycling offer prospects for improving material recovery and reducing the need for primary resources [20, 23].

Thus, despite efficiencies exceeding 27%, the scope for further improvement in c-Si technology is narrowing as it approaches its fundamental limit [14, 24].

3.2. CdTe

CdTe is the leading commercial thin-film technology, with over 30 GW installed and efficiencies reaching 18.6% for modules and over 22% in the laboratory [25, 26]. Its direct bandgap (1.45–1.50 eV) and high absorption coefficient allow for the use of active layers just a few micrometers thick. Advances rely notably on $CdSe_xTe_{1-x}$ absorbers, passivation, interface optimization and Group V element doping to reduce recombination and the open-circuit voltage deficit [26].

Stability depends on interfaces, contacts and encapsulation [27]. Copper diffusion from the back contact can promote degradation, driving the development of more stable contacts and alternative doping strategies [26, 28]. Despite low absorber material usage, manufacturing requires precise control over deposition, composition and interfaces [26].

Dependence on Te, primarily recovered as a copper industry by-product, poses a supply constraint, reinforcing the importance of reducing its use and developing recycling methods [29]. Although Cd presents environmental risks, encapsulation limits potential emissions and the technology offers advantages across several environmental impact categories [25]. Te recovery relies notably on delamination processes and hydro- or pyro-metallurgical treatments, which vary in efficiency [30].

Thus, the industrial maturity of CdTe is accompanied by persistent challenges regarding stability, performance improvement and resource availability [26].

3.3. CIGS

CIGS [Cu (In, Ga) Se_2] is a direct band-gap semiconductor with an adjustable band-gap (1.04-1.68 eV) with high absorption and low active material consumption [31]. Efficiencies of up to 23.64% have been achieved for a (Ag, Cu)(In, Ga) Se_2 cell using alkali treatments (KF, RbF, CsF) and interface optimization, although losses related with recombination and open-circuit voltage deficit continue [31, 32].

It is stabilized by flaws in the absorber and at interfaces and by thermal and light-induced strains. Potential-induced deterioration (PID), especially related to ion migration, is still a reliability concern for modules [33, 34]. CIGS may be fabricated by co-evaporation, sputtering and selenization, including on flexible substrates, despite heat restrictions and the possibility of impurity diffusion [31, 35].

The dependence on indium and gallium is a major barrier for the implementation at large scale [36]. The possible usage of silver increases material limitations even further [32]. The implications from an environmental point of view are mainly related to the metal extraction, the manufacturing processes and the possible use of CdS as buffer layer [31]. However, recycling allows recovering precious metals, including In, Ga and Cu [37, 38].

Finally, efficiency could be improved toward the 25% mark through optimization of the compositional profiles and reduction of optical losses [32]. Its variable bandgap and versatility also allow for easy incorporation in tandem systems, especially perovskite/CIGS [39, 40].

3.4. Kesterites of CZTS/CZTSSe

These kesterites CZTS/CZTSSe offer an alternative to CIGS by replacing In and Ga with more plentiful elements, in particular Zn and Sn. They have significant absorption and an adjustable direct bandgap from ~1.0 to 1.5 eV depending on the S/Se ratio [41-43]. But the structural flaws, secondary phases and recombination are still limiting their performances. Improvements in crystallization and defect engineering have permitted verified efficiencies of 13.44% and subsequently 14.2% with recent breakthroughs above 15% [42].

Their stability is mainly determined by composition, interfaces, Cu migration and chalcogenization conditions, which affect device microstructure and ageing [42-46]. Vacuum and solution techniques can provide lower cost manufacture, but require strict control of crystallization and composition [42, 46, 47]. Notably, a verified efficiency of 10.1% was obtained on a CZTSSe module with an area of 10.48 cm^2 [48].

While the dependence on Se for specific compositions is a limitation, the relative abundance of Zn and Sn is a significant advantage [42]. Concerning the absorber, it is free of Cd and Pb, but the massive usage of a CdS buffer layer has prompted the development of cadmium-free options, particularly Zn (O, S) and Zn-Sn oxides [49, 50]. The environmental consequences and the recyclability also rely on the procedures and the auxiliary materials utilized [51].

Hence, kesterites are still an emerging technology but with resource availability benefits. Their commercialization mostly requires improvements in efficiency, stability and scalability [38, 46, 48].

4. III–V Semiconductor-based Photovoltaic Technologies

III–V semiconductors (GaAs, GaInP, InP, AlGaAs and InGaAs) have excellent opto-electronic characteristics and high efficiencies. GaAs has a straight bandgap of around 1.42 eV and multi-junction topologies reduce transmission and thermalisation losses [52]. Under non-concentrated conditions, efficiencies of 37.9% for InGaP/GaAs/InGaAs [53], 38.8% for a five-junction cell and 35.9% for GaInP/GaInAsP/Si have been certified [53].

III–V cells are nevertheless subject to radiation-induced faults [52], but have good dependability (especially for space applications). Their synthesis using epitaxy (MOVPE/MOCVD, MBE) needs expensive equipment and substrates [54]. Substrate reuse with techniques such as epitaxial lift-off (ELO), spalling or sonic lift-off and integration into silicon provide routes for lowering costs and material usage [54, 55].

Environmental and material constraints include the use of elements such as Ga, In and Ge, the toxicity of arsenic-based compounds and the energy requirements for manufacturing. III–V technologies are mature for space uses, but are still limited for terrestrial applications because to their expense. Development of these devices is strongly dependent on advancement in epitaxial techniques, substrate circularity and III–V/Si designs [52, 54].

5. Emerging Photovoltaic Technologies

OPV and DSSCs are listed here as emerging technologies, but they are unique in operating principles and materials from perovskites.

5.1. Perovskites

The ABX 3 halide absorbers of perovskite solar cells (PSCs) possess significant absorption, variable bandgap and verified efficiencies of up to 26.1% in single-junction setups. These qualities are beneficial for their integration in perovskite/Si tandem cells [56, 57].

Their stability is still limited by humidity, temperature, light and ion migration and an improved passivation and encapsulation is needed [57, 58]. Issues such as the cost of auxiliary materials, film homogeneity and cell-to-module losses despite potentially cost-effective deposition techniques limit the industrialization of these materials [59-61].

Pb existence is a serious environmental problem. Sn-based alternatives are still challenged by instability, although encapsulation and closed-loop recycling are promising avenues for risk mitigation and material recovery [62].

Therefore, despite the encouraging performance of PSCs, they are still far from showing long-term reliability and suitability for large-scale industrial production [57, 59].

5.2. Organic Photovoltaics (OPV)

Organic photovoltaic (OPV) cells are lightweight, flexible, semi-transparent and fabricated by solution based processes. The rise of non-fullerene acceptors (NFAs), especially the Y-series and the optimisation of bulk heterojunctions (BHJs) have pushed efficiencies to almost or above 20% [63].

Their stability is limited by photochemical, photo-oxidative and morphological deterioration. Oligomeric acceptors may enhance the lifetime of the devices [64, 65]. Yet, the complexity of the synthesis of NFAs increases the prices, but they are compatible with large-area manufacturing. Hence, non-fused ring electron acceptors (NFREAs) have been developed [65, 67].

However, the environmental impact of OPVs is also dependent on the solvents, electrodes and functional layers, as well as their operational life [68, 69]. OPVs minimize dependence on some of the key metals. The commercialization, however, is still limited by the problems of stability, cost and scalability, while the prospects for creating integrated photovoltaics and stretchy devices are attractive [65, 66, 68, 70-72].

5.3. Dye-sensitized Solar Cells (DSSCs)

DSSCs consist of a TiO_2 photo-anode, a dye, a redox electrolyte and a counter-electrode [73-75]. Their efficiencies are 15.2% under AM 1.5G and 35.6% under indoor lighting, under not precisely comparable conditions [76, 77].

Their stability is limited by the degradation of dyes and liquid electrolytes, motivation for the creation of quasi-solid electrolytes and deep eutectic solvents [73, 78, 79]. Despite production complexity, the costs of Ru and Pt motivate their replacement with more abundant elements, while natural dyes are low-performing [80, 83].

Environmental implications depend on the materials, solvents and efficiency, whereas recycling is still underdeveloped [73, 82, 84, 85]. DSSCs are appealing for indoor applications, IoT sensors and building integrated photovoltaics while they are still commercially immature [73, 86, 87].

6. Tandem Architectures

Tandem architectures combine different sub-cells with complementary bandgaps to increase the utilization of the solar spectrum. Notable examples include perovskite/Si, perovskite/CIGS, perovskite/organic, all-perovskite tandems and III–V multi-junction devices [40, 88]. In 2015, the perovskite/Si tandem had an efficiency of 13.7%, which rose to 34.6% in 2024, mostly because to interface and passivation optimization [68]. Other combinations, such as perovskite/CIGS and perovskite/organic, are promising for thin and flexible devices [89, 90].

The stability relies on absorbers, interfaces and interconnections, which are components particularly prone to ion migration, moisture and heat stress in perovskite tandems [56,

80]. Manufacturing is still complicated: 2T configurations require current matching and 4T designs have a larger number of contacts [40, 88].

While tandem devices can potentially cut cost per watt, material-related restrictions involving Pb, Sn, In and Ga can be an issue based on the particular architecture [56]. Thus, its industrialization is based on long-term stability, cost control, large-area manufacturing and recyclability [56-88].

7. Integrated Comparative Analysis

In this part we evaluate the nine photovoltaic families along the seven specified dimensions to determine their significant technological, economic and environmental trade-offs [3, 4, 91].

7.1. Performance, Stability and Manufacturing

The most efficient are III-V and tandem cells whereas c-Si are reliable, mature and easily available. CdTe and CIGS are proven thin-film alternatives, whereas kesterites are still constrained by flaws. Particularly interesting are low-light circumstances for DSSCs and the perovskites and OPVs are moving fast [3, 4, 91].

Conventional technologies and III–V materials have a more established stability than new approaches [92]. Furthermore, the industrial methods for c-Si, CdTe and CIGS are different from the expensive epitaxy needed for III–V materials and the scaling-up problems of developing technologies and tandem cells [3, 4, 91].

7.2. Resources, Environmental Impacts and Circularity

The main material restrictions are Ag and In for c-Si, Te for CdTe, In and Ga for CIGS and III-V materials and Ru and Pt for some DSSCs. Kesterites make use of more plentiful elements and tandem cells combine the material requirements of their constituent sub-cells [4, 6].

The environmental consequences rely heavily on the energy consumed in production, the potentially harmful compounds (Cd, Pb, As) and the solvents involved [3, 92, 93]. Recycling is more advanced for c-Si, CdTe and CIGS, but it still has to be improved for other technologies to increase material recovery and circularity [14, 22, 94].

7.3. Technological Maturity and Commercialization Prospects

c-Si and CdTe are the dominant players in the industrial environment, with CIGS and III–V materials used in specialized industries. Kesterites, perovskites, OPV and DSSC are still in their infancy. The perovskite/Si tandem cells are close to industrialization, however they are still limited by dependability, prices and large-scale production [3, 4, 91].

7.4. Multi-criteria Summary and Fundamental Trade-offs

The seven dimensions are summarized in comparative tables (Tables 1 &2) which show that no single technology is better than all others on all criteria at the same time. Mature technologies target industrial reliability, III-V materials and tandem cells for performance, whereas certain developing technologies bring advantages of materials or integration [3, 4, 91]. Therefore, in tandem cells, the complexity of which imposes limitations on manufacturing and end-of-life, the selection of a technology must consider not only efficiency but also variables like longevity, cost, resource availability and recyclability [6, 22, 92].

7.5. Critical Analysis of the Interactions Between Photovoltaic Selection Criteria

Beyond the differences noted among various photovoltaic families, an overall analysis of the findings reveals that the seven studies examined are not independent. Improved performance may come at the cost of increased manufacturing complexity, the use of certain critical materials, or new stability requirements. This interdependence is particularly evident in advanced architectures, where efficiency gains are achieved by modifying interfaces, contacts, or material composition. Consequently, progress made regarding one criterion must be interpreted in light of its potential impact on other dimensions.

One key implication concerns the relationship between efficiency, stability, and resource consumption. The fact that some technologies use only a small amount of active material does not necessarily mean they have a low overall resource footprint throughout their operational lifespan. Accelerated degradation may necessitate more frequent replacements, thereby increasing cumulative material requirements and the volume of waste generated. Conversely, greater stability can partially offset a higher initial consumption of materials. This relationship suggests that resource use should be evaluated in relation to the energy actually produced over the device's lifetime, rather than solely based on the quantity of materials required for its manufacture.

Furthermore, the level of technological performance may vary depending on whether it is measured using laboratory cells, commercial modules, or under different illumination conditions. Similarly, the results of aging tests can be highly dependent on the specific protocols and experimental conditions employed. These discrepancies hinder direct comparison and may lead to an overestimation of the advantages of certain technologies if the measurement conditions are not sufficiently distinguished. A second point concerns the comparability of performance data reported in the literature. Efficiencies measured for laboratory cells, commercial modules, or under varying illumination conditions do not necessarily represent the same level of technological performance. Furthermore, the results of aging tests can be highly dependent on

specific experimental protocols and conditions.

Finally, the analysis shows that material-related constraints cannot be assessed solely based on natural abundance or intrinsic toxicity. Their significance depends on the quantities used, manufacturing processes, the potential for substitution and recovery, and the operational lifespan of the devices. Consequently, two technologies with different material constraints may result in comparable environmental trade-offs, depending on their specific production and operating conditions.

These observations highlight a limitation of qualitative comparison: while it helps identify the advantages and constraints of each technology family, it is not sufficient on its own to determine the relative importance of these constraints for a given application. Our analysis therefore underscores the value of an assessment based on comparable indicators at the device and life-cycle level—one that integrates the complex interplay between efficiency, degradation, and resource use. This perspective would make it possible to better gauge the scope of technological advancements and to distinguish between gains in intrinsic performance and the benefits actually realized under operational conditions.

Table 1. *Comparison of photovoltaic performance, stability, manufacturing and technological maturity.*

Technology	Performance	Stability	Manufacturing / Cost	Technological Maturity	Key References
c-Si	Very high	Very high	Highly competitive	Very high	[4, 6, 22]
CdTe	High	High	Competitive	High	[25, 26, 29]
CIGS	High	High	Relatively complex	High / Intermediate	[31-34]
CZTS/CZTSSe	Intermediate	Requires further improvement	Potentially favorable	Emerging	[38, 42, 46]
III–V	Exceptional	Very high	Very expensive	High, specialized markets	[52-54]
Perovskites	Very high	Requires further improvement	High potential	Pre-industrial	[56, 58]
OPV	High	Needs improvement	Potential for printing-based manufacturing	Pre-commercial	[65, 71, 72]
DSSC	Moderate under sunlight**	Intermediate	Potentially simple	Niche applications	[73, 75, 87]
Perovskite/Si tandem	Exceptional	Requires further improvement	More complex	Approaching industrialization	[56, 58]

Table 2. *Comparison of material resources, environmental impacts and recyclability.*

Technology	Material Resources	Environmental Considerations	Recyclability	Key References
c-Si	Abundant Si; Ag/In supply requires monitoring	Relatively favorable	Highly advanced	[4, 6, 22]
CdTe	Te supply constraints	Cd-related concerns require management	Advanced	[25, 26, 29, 30]
CIGS	In/Ga supply constraints	Possible use of CdS	High potential	[31, 32, 36, 37]
CZTS/CZTSSe	More abundant Zn/Sn	Potentially favorable	Limited development	[38, 42, 46, 48, 51]
III–V	Ga/In supply constraints	As-related concerns depending on architecture	Limited; substrate reuse is possible	[52-55]
Perovskites	Low absorber material requirements	Pb-related concerns require management	Under development	[3, 91, 92]

Technology	Material Resources	Environmental Considerations	Recyclability	Key References
OPV	Relatively favorable	Solvent use and synthesis processes must be considered	Poorly documented / limited development	[14, 65, 66, 71]
DSSC	Ru/Pt depending on architecture	Variable	Limited development	[75]
Perovskite/Si tandem	Abundant Si; Pb and contact materials require monitoring	Pb-related concerns depending on composition	Emerging	[56, 57, 80, 88]

8. Research Challenges and Priorities

Research priorities are dependent on level of development. For mature technologies the focus is on minimizing losses, material intensity and reliance on vital resources whereas for new technologies stability, reproducibility and the scale-up from cell to module remain central [3, 4, 91]. In parallel, substitution or recovery of Ag, Te, In, Ga, Pb and Cd should be increased together with design techniques for recycling and circularity [14, 6, 22, 93, 94].

9. Conclusion

This analysis has contrasted nine families of photovoltaic systems using seven parameters, encompassing performance, stability, manufacturing challenges, resource needs, environmental effects, recyclability, and technological readiness. The assessment verifies that no solitary technique delivers the most advantageous features across all these dimensions. Crystalline silicon possesses a clear superiority in reliability and industrial sophistication, while other material families have other opportunities—its importance is contingent upon the particular performance aims and restrictions of each application.

In addition to these variances, this analytical critique emphasizes the interconnectedness of the selection criteria. Notably, the benefits of high efficiency or reduced initial material consumption should be considered in relation to device stability, operational lifespan, and the resources necessary for eventual replacement. The assessment additionally emphasizes the shortcomings of comparisons founded on results acquired at disparate scales or in various experimental settings. Thus, the qualitative analyzes included in this study focus on recognizing essential trade-offs rather than creating a conclusive rating of the technologies.

These conclusions imply that future developments ought to be measured not just by increased conversion efficiency, but also by their contributions to reliability, mitigation of material restrictions, and effective environmental impact management. Establishing equivalent indicators—at the device level and across the full life cycle—would constitute a crucial advancement in this analysis and improve the guidance of technology selections for sustainable solar deployment.

Abbreviations

ACV / LCA	Life Cycle Assessment
BHJ	Bulk Heterojunction
c-Si	Crystalline Silicon
CIGS	Copper Indium Gallium Selenide
CZTS	Copper Zinc Tin Sulfide
CZTSe	Copper Zinc Tin Selenide
CZTSSe	Copper Zinc Tin Sulfur Selenide
DSSC	Dye-Sensitized Solar Cell
ELO	Epitaxial Lift-Off
HJT	Heterojunction Technology
LeTID	Light and Elevated Temperature-Induced Degradation
LID	Light-Induced Degradation
MBE	Molecular Beam Epitaxy
MOCVD	Metal-Organic Chemical Vapor Deposition
MOVPE	Metal-Organic Vapor Phase Epitaxy
NFA	Non-Fullerene Acceptor
NFREA	Non-Fused Ring Electron Acceptor
OPV	Organic Photovoltaics
PERC	Passivated Emitter and Rear Cell
PID	Potential-Induced Degradation
PSC	Perovskite Solar Cell
PV	Photovoltaic
SHJ	Silicon Heterojunction
TOPCon	Tunnel Oxide Passivated Contact

Author Contributions

Mamadou Traore: Investigation, Resources, Writing – original draft

Amadou Sidibe: Conceptualization, Formal Analysis, Investigation, Methodology, Writing – original draft

Abdoulaye Tall: Formal Analysis, Validation, Writing – review & editing

Moussa Camara: Investigation, Resources, Writing – review & editing

Abdourahmane Diallo: Formal Analysis, Methodology, Writing – review & editing

Abdoul Kadri Diallo: Supervision, Validation, Writing – review & editing

Saliou Bolarinwa Ogou: Investigation, Validation, Writing – review & editing

Conflicts of Interest

The authors declare no conflicts of interest.

References

[1] A. O. Ali et al., « Advancements in photovoltaic technology: A comprehensive review of recent advances and future prospects », Energy Conversion and Management: X, vol. 26, p. 100952, avr. 2025, https://doi.org/10.1016/j.ecmx.2025.100952

[2] D. Intal et A. Ebong, « Thin-Film Solar Photovoltaics: Trends and Future Directions », in 2024 IEEE 21st International Conference on Smart Communities: Improving Quality of Life using AI, Robotics and IoT (HONET), Doha, Qatar: IEEE, déc. 2024, p. 135-142. https://doi.org/10.1109/HONET63146.2024.10822947

[3] A. Machín et F. Márquez, « Advancements in Photovoltaic Cell Materials: Silicon, Organic, and Perovskite Solar Cells », Materials, vol. 17, no 5, p. 1165, mars 2024, https://doi.org/10.3390/ma17051165

[4] A. M. Oni, A. S. M. Mohsin, Md. M. Rahman, et M. B. Hossain Bhuian, « A comprehensive evaluation of solar cell technologies, associated loss mechanisms, and efficiency enhancement strategies for photovoltaic cells », Energy Reports, vol. 11, p. 3345-3366, juin 2024, https://doi.org/10.1016/j.egyr.2024.03.007

[5] M. Cellura, L. Q. Luu, F. Guarino, et S. Longo, « A review on life cycle environmental impacts of emerging solar cells », Science of The Total Environment, vol. 908, p. 168019, janv. 2024, https://doi.org/10.1016/j.scitotenv.2023.168019

[6] N. Taylor, K. Teodor, C. Anatoli, et S. Carrara, Deep dive on critical raw materials for solar photovoltaics in the EU. LU: Publications Office, 2025. https://doi.org/10.2760/0883326

[7] H. Akram Cheema, S. Ilyas, H. Kang, et H. Kim, « Comprehensive review of the global trends and future perspectives for recycling of decommissioned photovoltaic panels », Waste Management, vol. 174, p. 187-202, febr 2024, https://doi.org/10.1016/j.wasman.2023.11.025

[8] K. Komoto et al., « Status of PV Module Recycling in IEA PVPS Task 12 Countries », IEA Photovoltaic Power Systems Programme, 2025. https://doi.org/10.69766/XLFG7020

[9] T. Kirchartz, G. Yan, Y. Yuan, B. K. Patel, D. Cahen, et P. K. Nayak, « The state of the art in photovoltaic materials and device research », Nat Rev Mater, vol. 10, no 5, p. 335-354, mars 2025, https://doi.org/10.1038/s41578-025-00784-4

[10] Y. H. Sim, M. J. Yun, L. Fauzan, H. Choi, D. Y. Lee, et S. I. Cha, « Design strategies for energy-harvesting photovoltaics in diverse environments », iScience, vol. 28, no 9, p. 113312, sept. 2025, https://doi.org/10.1016/j.isci.2025.113312

[11] K. Wambach et C. Libby, « Advances in Photovoltaic Module Recycling: Third Update to Empirical Life Cycle Inventory Data », International Energy Agency Photovoltaic Power Systems Programme, 2026. https://doi.org/10.69766/PJOW5359

[12] C. Ballif, F.-J. Haug, M. Boccard, P. J. Verlinden, et G. Hahn, « Status and perspectives of crystalline silicon photovoltaics in research and industry », Nat Rev Mater, vol. 7, no 8, p. 597-616, mars 2022, https://doi.org/10.1038/s41578-022-00423-2

[13] H. Lin et al., « Silicon heterojunction solar cells with up to 26.81% efficiency achieved by electrically optimized nanocrystalline-silicon hole contact layers », Nat Energy, vol. 8, no 8, p. 789-799, mai 2023, https://doi.org/10.1038/s41560-023-01255-2

[14] G. Wang et al., « 27.09%-efficiency silicon heterojunction back contact solar cell and going beyond », Nat Commun, vol. 15, no 1, p. 8931, oct. 2024, https://doi.org/10.1038/s41467-024-53275-5

[15] L. Ning, L. Song, et J. Zhang, « Research progress of light and elevated temperature-induced degradation in silicon solar cells: A review », Journal of Alloys and Compounds, vol. 912, p. 165120, aug. 2022, https://doi.org/10.1016/j.jallcom.2022.165120

[16] A. Diggs et al., « Hydrogen-induced degradation dynamics in silicon heterojunction solar cells via machine learning », Commun Mater, vol. 4, no 1, p. 24, avr. 2023, https://doi.org/10.1038/s43246-023-00347-6

[17] C. Sen et al., « Accelerated damp-heat testing at the cell-level of bifacial silicon HJT, PERC and TOPCon solar cells using sodium chloride », Solar Energy Materials and Solar Cells, vol. 262, p. 112554, oct. 2023, https://doi.org/10.1016/j.solmat.2023.112554

[18] C. Sen et al., « Buyer aware: Three new failure modes in TOPCon modules absent from PERC technology », Solar Energy Materials and Solar Cells, vol. 272, p. 112877, aug. 2024, https://doi.org/10.1016/j.solmat.2024.112877

[19] S. Tepner et A. Lorenz, « Printing technologies for silicon solar cell metallization: A comprehensive review », Progress in Photovoltaics, vol. 31, no 6, p. 557-590, juin 2023, https://doi.org/10.1002/pip.3674

[20] C. Xu, O. Isabella, et M. R. Vogt, « Future material demand for global silicon-based PV modules under net-zero emissions target until 2050 », Resources, Conservation and Recycling, vol. 210, p. 107824, nov. 2024, https://doi.org/10.1016/j.resconrec.2024.107824

[21] M. Fan, Z. Yu, W. Ma, et L. Li, « Life Cycle Assessment of Crystalline Silicon Wafers for Photovoltaic Power Generation », Silicon, vol. 13, no 9, p. 3177-3189, sept. 2021, https://doi.org/10.1007/s12633-020-00670-4

[22] S. Preet et S. T. Smith, « A comprehensive review on the recycling technology of silicon based photovoltaic solar panels: Challenges and future outlook », Journal of Cleaner Production, vol. 448, p. 141661, avr. 2024, https://doi.org/10.1016/j.jclepro.2024.141661

[23] J. Lee, N. Duffy, et J. Allen, « A Review of End-of-Life Silicon Solar Photovoltaic Modules and the Potential for Electrochemical Recycling », Adv Energy and Sustain Res, vol. 6, no 2, p. 2400254, febr. 2025, https://doi.org/10.1002/aesr.202400254

[24] Z. Xie et al., «27%-efficiency silicon heterojunction cell with 98.6% cell-to-module ratio driving new momentum towards the 29.4% limit », Nat Commun, vol. 16, no 1, p. 9421, oct. 2025, https://doi.org/10.1038/s41467-025-64465-0

[25] V. Fthenakis, C. Athias, A. Blumenthal, A. Kulur, J. Magliozzo, et D. Ng, «Sustainability evaluation of CdTe PV: An update », Renewable and Sustainable Energy Reviews, vol. 123, p. 109776, mai 2020, https://doi.org/10.1016/j.rser.2020.109776

[26] M. A. Scarpulla et al., « CdTe-based thin film photovoltaics: Recent advances, current challenges and future prospects », Solar Energy Materials and Solar Cells, vol. 255, p. 112289, juin 2023, https://doi.org/10.1016/j.solmat.2023.112289

[27] J. Kettle et al., «Review of technology specific degradation in crystalline silicon, cadmium telluride, copper indium gallium selenide, dye sensitised, organic and perovskite solar cells in photovoltaic modules: Understanding how reliability improvements in mature technologies can enhance emerging technologies », Progress in Photovoltaics, vol. 30, no 12, p. 1365-1392, déc. 2022, https://doi.org/10.1002/pip.3577

[28] V. Narayanan et R. Ks, « CdTe Photovoltaics in Superstrate Geometry–Back-Contact Materials: A Review », ACS Appl. Energy Mater., vol. 6, no 17, p. 8644-8659, sept. 2023, https://doi.org/10.1021/acsaem.3c00947

[29] N. T. Nassar, H. Kim, M. Frenzel, M. S. Moats, et S. M. Hayes, «Global tellurium supply potential from electrolytic copper refining », Resources, Conservation and Recycling, vol. 184, p. 106434, sept. 2022, https://doi.org/10.1016/j.resconrec.2022.106434

[30] D. Ravikumar et al., «Environmentally improved CdTe photovoltaic recycling through novel technologies and facility location strategies », Progress in Photovoltaics, vol. 28, no 9, p. 887-898, sept. 2020, https://doi.org/10.1002/pip.3279

[31] N. H. Suhaimi et al., « Chronological progress in enhancing CIGS solar cell performance through window layer development: Fundamentals, synthesis, optimization », Surfaces and Interfaces, vol. 54, p. 105145, nov. 2024, https://doi.org/10.1016/j.surfin.2024.105145

[32] J. Keller et al., «High-concentration silver alloying and steep back-contact gallium grading enabling copper indium gallium selenide solar cell with 23.6% efficiency », Nat Energy, vol. 9, no 4, p. 467-478, febr. 2024, https://doi.org/10.1038/s41560-024-01472-3

[33] P. Yilmaz et al., «In-depth analysis of potential-induced degradation in a commercial CIGS PV module », Progress in Photovoltaics, vol. 31, no 6, p. 627-636, juin 2023, https://doi.org/10.1002/pip.3670

[34] P. Yilmaz, J. Schmitz, et M. Theelen, «Potential induced degradation of CIGS PV systems: A literature review », Renewable and Sustainable Energy Reviews, vol. 154, p. 111819, febr. 2022, https://doi.org/10.1016/j.rser.2021.111819

[35] C. Zhang et al., «High efficiency CIGS solar cells on flexible stainless steel substrate with SiO2 diffusion barrier layer », Solar Energy, vol. 230, p. 1033-1039, déc. 2021, https://doi.org/10.1016/j.solener.2021.11.006

[36] D. Teng et al., « Advances in the Recovery of Critical Rare Dispersed Metals (Gallium, Germanium, Indium) from Urban Mineral Resources », ACS Omega, vol. 10, no 1, p. 76-92, janv. 2025, https://doi.org/10.1021/acsomega.4c08689

[37] D. Hu, B. Ma, X. Li, Y. Lv, Y. Chen, et C. Wang, «Innovative and sustainable separation and recovery of valuable metals in spent CIGS materials », Journal of Cleaner Production, vol. 350, p. 131426, mai 2022, https://doi.org/10.1016/j.jclepro.2022.131426

[38] H. Li, S. Liu, X. Wu, S. Yao, X. Hu, et Y. Chen, «Advances in the device design and printing technology for eco-friendly organic photovoltaics », Energy Environ. Sci., vol. 16, no 1, p. 76-88, 2023, https://doi.org/10.1039/D2EE03246E

[39] X. Liu et al., «Over 28% efficiency perovskite/Cu (InGa) Se2 tandem solar cells: highly efficient sub-cells and their bandgap matching », Energy Environ. Sci., vol. 16, no 11, p. 5029-5042, 2023, https://doi.org/10.1039/D3EE00869J

[40] A. Saeed, L. Wang, et Q. Miao, « High-Performance Perovskite-Based Tandem Solar Cells: Recent Advancement, Challenges, and Steps toward Industrialization », Solar RRL, vol. 8, no 17, p. 2400172, sept. 2024, https://doi.org/10.1002/solr.202400172

[41] M. He et al., «Kesterite Solar Cells: Insights into Current Strategies and Challenges », Advanced Science, vol. 8, no 9, p. 2004313, mai 2021, https://doi.org/10.1002/advs.202004313

[42] X. Xu et al., « Controlling Selenization Equilibrium Enables High-Quality Kesterite Absorbers for Efficient Solar Cells », Nat Commun, vol. 14, no 1, p. 6650, oct. 2023, https://doi.org/10.1038/s41467-023-42460-7

[43] A. Wang, M. He, M. A. Green, K. Sun, et X. Hao, «A Critical Review on the Progress of Kesterite Solar Cells: Current Strategies and Insights », Advanced Energy Materials, vol. 13, no 2, p. 2203046, janv. 2023, https://doi.org/10.1002/aenm.202203046

[44] M. I. Hossain, Y. Putthisigamany, A. Zekri, Y. Tong, P. Chelvanathan, et B. Aissa, «Exploring degradation mechanisms in CZTSSe solar cells for harsh environmental conditions », Solar Energy, vol. 298, p. 113699, sept. 2025, https://doi.org/10.1016/j.solener.2025.113699

[45] F. Martinho et al., «Persistent Double-Layer Formation in Kesterite Solar Cells: A Critical Review », ACS Appl. Mater. Interfaces, vol. 12, no 35, p. 39405-39424, sept. 2020, https://doi.org/10.1021/acsami.0c10068

[46] J. Shi et al., «Multinary alloying for facilitated cation exchange and suppressed defect formation in kesterite solar cells with above 14% certified efficiency », Nat Energy, mai 2024, https://doi.org/10.1038/s41560-024-01551-5

[47] J. Fu et al., « A critical review of solution-process engineering for kesterite thin-film solar cells: current strategies and prospects », J. Mater. Chem. A, vol. 12, no 2, p. 545-566, 2024, https://doi.org/10.1039/D3TA05018A

[48] C. Xiang et al., « Solution-processed kesterite solar module with 10.1% certified efficiency », Nat Energy, vol. 10, no 11, p. 1315-1322, sept. 2025, https://doi.org/10.1038/s41560-025-01860-3

[49] N. Ahmad et al., « Cadmium-Free Kesterite Thin-Film Solar Cells with High Efficiency Approaching 12% », Advanced Science, vol. 10, no 26, p. 2302869, sept. 2023, https://doi.org/10.1002/advs.202302869

[50] G. Tseberlidis, C. Gobbo, V. Trifiletti, V. Di Palma, et S. Binetti, « Cd-free kesterite solar cells: State-of-the-art and perspectives », Sustainable Materials and Technologies, vol. 41, p. e01003, sept. 2024, https://doi.org/10.1016/j.susmat.2024.e01003

[51] A. Maalouf, T. Okoroafor, S. Gahr, K. Ernits, D. Meissner, et S. Resalati, « Environmental performance of Kesterite monograin module production in comparison to thin-film technology », Solar Energy Materials and Solar Cells, vol. 251, p. 112161, mars 2023, https://doi.org/10.1016/j.solmat.2022.112161

[52] R. Verduci et al., « Solar Energy in Space Applications: Review and Technology Perspectives », Advanced Energy Materials, vol. 12, no 29, p. 2200125, aug. 2022, https://doi.org/10.1002/aenm.202200125

[53] M. A. Green et al., «Solar cell efficiency tables (Version 61) », Progress in Photovoltaics, vol. 31, no 1, p. 3-16, janv. 2023, https://doi.org/10.1002/pip.3646

[54] J. S. Mangum et al., « High-Efficiency Solar Cells Grown on Spalled Germanium for Substrate Reuse without Polishing », Advanced Energy Materials, vol. 12, no 29, p. 2201332, august. 2022, https://doi.org/10.1002/aenm.202201332

[55] A. N. Neumann et al., « Solar Cell Performance after Exfoliation Using Sonic Liftoff », Solar RRL, vol. 9, no 15, p. 2500049,aug. 2025, https://doi.org/10.1002/solr.202500049

[56] L. Duan et al., «Stability challenges for the commercialization of perovskite–silicon tandem solar cells », Nat Rev Mater, vol. 8, no 4, p. 261-281, janv. 2023, https://doi.org/10.1038/s41578-022-00521-1

[57] C. Yang et al., « Achievements, challenges, and future prospects for industrialization of perovskite solar cells », Light Sci Appl, vol. 13, no 1, p. 227, sept. 2024, https://doi.org/10.1038/s41377-024-01461-x

[58] S. Baumann et al., «Stability and reliability of perovskite containing solar cells and modules: degradation mechanisms and mitigation strategies », Energy Environ. Sci., vol. 17, no 20, p. 7566-7599, 2024, https://doi.org/10.1039/D4EE01898B

[59] G. S. Han et al., « Cutting-Edge Studies Toward Commercialization of Large Area Solution-Processed Perovskite Solar Cells », Adv Materials Technologies, vol. 8, no 20, p. 2201387, oct. 2023, https://doi.org/10.1002/admt.202201387

[60] T. Le et al., « Perovskite Solar Module: Promise and Challenges in Efficiency, Meta-Stability, and Operational Lifetime », Adv Elect Materials, vol. 9, no 10, p. 2300093, oct. 2023, https://doi.org/10.1002/aelm.202300093

[61] C. Zhang et N.-G. Park, «Materials and methods for cost-effective fabrication of perovskite photovoltaic devices », Commun Mater, vol. 5, no 1, p. 194, sept. 2024, https://doi.org/10.1038/s43246-024-00636-8

[62] A. D. Khan et al., «Advancements in the stability, protection and lead-free strategies of perovskite solar cells: a critical review », Environ. Sci.: Adv., vol. 3, no 7, p. 1004-1029, 2024, https://doi.org/10.1039/D3VA00401E

[63] S. H. Lee, H. J. Kim, J.-H. Kim, G. Y. Park, S.-K. Kim, et S.-M. Lee, «Rational strategy for power doubling of monolithic multijunction III-V photovoltaics by accommodating attachable scattering waveguides », Light Sci Appl, vol. 13, no 1, p. 261, sept. 2024, https://doi.org/10.1038/s41377-024-01628-6

[64] F. Qi, Y. Li, F. R. Lin, et A. K. -Y. Jen, «Recent Progress of Oligomeric Non-Fullerene Acceptors for Efficient and Stable Organic Solar Cells », ChemSusChem, vol. 17, no 13, p. e202301559, juill. 2024, https://doi.org/10.1002/cssc.202301559

[65] Y. Guo, D. Li, Y. Gao, et C. Li, «Recent Progress on Stability of Organic Solar Cells Based on Non-Fullerene Acceptors », Acta Physico-Chimica Sinica, vol. 40, no 6, p. 2306050, juin 2024, https://doi.org/10.3866/PKU.WHXB202306050

[66] E. D. Papkovskaya, D. O. Balakirev, J. Min, et Y. N. Luponosov, «Toward commercially viable non-fullerene organic solar cells: a critical review of recent developments in high-performance non-fused ring electron acceptors », Materials Today Energy, vol. 43, p. 101591, juill. 2024, https://doi.org/10.1016/j.mtener.2024.101591

[67] X. Du et al., «Revealing processing stability landscape of organic solar cells with automated research platforms and machine learning », InfoMat, vol. 6, no 7, p. e12554, juill. 2024, https://doi.org/10.1002/inf2.12554

[68] J. Liu et al., «Perovskite/silicon tandem solar cells with bilayer interface passivation », Nature, vol. 635, no 8039, p. 596-603, nov. 2024, https://doi.org/10.1038/s41586-024-07997-7

[69] B. Paci et al., «Semitransparent Organic Photovoltaic Devices: Interface/Bulk Properties and Stability Issues », Nanomaterials, vol. 14, no 3, p. 269, janv. 2024, https://doi.org/10.3390/nano14030269

[70] W. Song, Q. Ye, Z. Chen, J. Ge, L. Xie, et Z. Ge, «Advances in Stretchable Organic Photovoltaics: Flexible Transparent Electrodes and Deformable Active Layer Design », Advanced Materials, vol. 36, no 37, p. 2311170, sept. 2024, https://doi.org/10.1002/adma.202311170

[71] Q. Wu, S. Ding, A. Sun, et Y. Xia, «Recent progress on non-fullerene acceptor materials for organic solar cells », Materials Today Chemistry, vol. 41, p. 102290, oct. 2024, https://doi.org/10.1016/j.mtchem.2024.102290

[72] L. Zhu et al., «Progress of organic photovoltaics towards 20% efficiency », Nat Rev Electr Eng, vol. 1, no 9, p. 581-596, aug. 2024, https://doi.org/10.1038/s44287-024-00080-3

[73] B. K. Korir, J. K. Kibet, et S. M. Ngari, «A review on the current status of dye-sensitized solar cells: Toward sustainable energy », Energy Science & Engineering, vol. 12, no 8, p. 3188-3226, aug. 2024, https://doi.org/10.1002/ese3.1815

[74] N. Kumar, S. Choudhury, A. Mahajan, et V. Saxena, « Enhanced efficiency of dye-sensitized solar cells via controlled thickness of the WO3 Langmuir–Blodgett blocking layer in the Debye length regime », Mater. Adv., vol. 5, no 19, p. 7659-7670, 2024, https://doi.org/10.1039/D4MA00063C

[75] R. Sasikumar, S. Thirumalaisamy, B. Kim, et B. Hwang, « Dye-sensitized solar cells: Insights and research divergence towards alternatives », Renewable and Sustainable Energy Reviews, vol. 199, p. 114549, juill. 2024, https://doi.org/10.1016/j.rser.2024.114549

[76] C. Coppola et al., «A combined ML and DFT strategy for the prediction of dye candidates for indoor DSSCs », npj Comput Mater, vol. 11, no 1, p. 28, febr. 2025, https://doi.org/10.1038/s41524-025-01521-9

[77] S. M. Meethal et al., «Asymmetric dual species copper (II / I) electrolyte dye-sensitized solar cells with 35.6% efficiency under indoor light », J. Mater. Chem. A, vol. 12, no 2, p. 1081-1093, 2024, https://doi.org/10.1039/D3TA06046B

[78] C. L. Boldrini et al., «Top-ranked efficiency under indoor light of DSSCs enabled by iodide-based DES-like solvent electrolyte », Sustainable Energy Fuels, vol. 8, no 3, p. 504-515, 2024, https://doi.org/10.1039/D3SE00949A

[79] A. Ibrayeva, Z. Imanbekova, U. Abibulla, Y. Tashenov, B. Baptayev, et M. P. Balanay, «Enhancing the stability and efficiency of dye-sensitized solar cells with MIL-125 metal-organic framework as an electrolyte additive », Sci Rep, vol. 15, no 1, p. 5883, febr. 2025, https://doi.org/10.1038/s41598-025-89913-1

[80] S. A. U. Hasan, M. A. Zahid, S. Park, et J. Yi, «Stability Challenges for a Highly Efficient Perovskite/Silicon Tandem Solar Cell: A Review », Solar RRL, vol. 8, no 6, p. 2300967, mars 2024, https://doi.org/10.1002/solr.202300967

[81] N. Mittal et al., «Next-generation sensitizers for dye sensitizer solar cells: Molecular engineering, performance metrics, and photostability », Solar Compass, vol. 18, p. 100161, juin 2026, https://doi.org/10.1016/j.solcom.2026.100161

[82] S. S. Malhotra, M. Ahmed, M. K. Gupta, et A. Ansari, «Metal-free and natural dye-sensitized solar cells: recent advancements and future perspectives », Sustainable Energy Fuels, vol. 8, no 18, p. 4127-4163, 2024, https://doi.org/10.1039/D4SE00406J

[83] W. Vallejo, M. Lerma, et C. D áz-Uribe, «Dye sensitized solar cells: Meta-analysis of effect sensitizer-type on photovoltaic efficiency », Heliyon, vol. 11, no 1, p. e41092, janv. 2025, https://doi.org/10.1016/j.heliyon.2024.e41092

[84] A. Błaszczyk, K. Joachimiak-Lechman, S. Sady, T. Tański, M. Szindler, et A. Drygała, « Environmental performance of dye-sensitized solar cells based on natural dyes », Solar Energy, vol. 215, p. 346-355, febr. 2021, https://doi.org/10.1016/j.solener.2020.12.040

[85] G. Salerno, N. Manfredi, A. Abbotto, et O. Bettucci, «Sustainable Electrolyte Media in Dye-Sensitized Solar Cells: From Water-Based to Deep Eutectic Solvents and Biopolymeric Approaches », Molecules, vol. 31, no 12, p. 2037, juin 2026, https://doi.org/10.3390/molecules31122037

[86] H. Michaels et al., «Dye-sensitized solar cells under ambient light powering machine learning: towards autonomous smart sensors for the internet of things », Chem. Sci., vol. 11, no 11, p. 2895-2906, 2020, https://doi.org/10.1039/C9SC06145B

[87] I. O. Abdulsalami, I. A. Omobhude, B. A. Abdulsalami, M. Younas, B. Semire, et I. A. Bello, «Dye-sensitized solar cells: a systematic review of progress, challenges, and future perspectives », Discov. Chem., vol. 3, no 1, p. 87, febr. 2026, https://doi.org/10.1007/s44371-026-00548-1

[88] Z. Ying, X. Yang, X. Wang, et J. Ye, « Towards the 10-Year Milestone of Monolithic Perovskite/Silicon Tandem Solar Cells », Advanced Materials, vol. 36, no 37, p. 2311501, sept. 2024, https://doi.org/10.1002/adma.202311501

[89] K. O. Brinkmann et al., «Perovskite–organic tandem solar cells », Nat Rev Mater, vol. 9, no 3, p. 202-217, janv. 2024, https://doi.org/10.1038/s41578-023-00642-1

[90] P. Procel et al., « Opto-electrical modelling and roadmap for 2T monolithic Perovskite/CIGS tandem solar cells », Solar Energy Materials and Solar Cells, vol. 274, p. 112975, aug. 2024, https://doi.org/10.1016/j.solmat.2024.112975

[91] A. A. Ugochukwu et al., «Recent enhancement in photovoltaic cell efficiency performance, stability, and cost reduction: a review », Solar Energy, vol. 300, p. 113853, nov. 2025, https://doi.org/10.1016/j.solener.2025.113853

[92] K. J. Prince et al., «Sustainability pathways for perovskite photovoltaics », Nat. Mater., vol. 24, no 1, p. 22-33, janv. 2025, https://doi.org/10.1038/s41563-024-01945-6

[93] W. Akram, X. Li, S. Ahmed, Z. Ouyang, et G. Li, «A review of life cycle assessment and sustainability analysis of perovskite/Si tandem solar cells », RSC Sustainability, vol. 3, no 1, p. 21-36, 2025, https://doi.org/10.1039/D4SU00431K

[94] P. S. Silveira Camargo, P. A. Petroli, R. Andrade De Souza, F. S. Kerpen, et H. M. Veit, «CdTe photovoltaic technology: An overview of waste generation, recycling, and raw material demand », Current Opinion in Green and Sustainable Chemistry, vol. 47, p. 100904, juin 2024, https://doi.org/10.1016/j.cogsc.2024.100904