© SEP 2026 | IRE Journals | Volume 10 Issue 3 | ISSN: 2456-8880
DOI: https://doi.org/10.64388/IREV10I3-1723060

Recent Advancement in Solar Physics: A Meta-Analysis of the Efficiency, Gradient Composition, and Interface Engineering of Perovskite Solar Cells

EBEHITA. O-O[1*], N. A. A. AZEEZ[2], M. UMAR[3]
[1, 2, 3] *Department of Physics, University of Abuja, Abuja, Nigeria*

Abstract: Perovskite solar cells (PSCs) have rapidly emerged as a leading photovoltaic technology, achieving unprecedented gains in power conversion efficiency (PCE) within just over a decade. This study presents a meta-analysis of recent advancements in PSC efficiency, examining key factors, fabrication methods, material choices, and challenges. The pooled results indicate that single-junction PSCs exhibit a mean PCE of 18–22%, while tandem perovskite–silicon architectures achieve efficiencies above 26%, surpassing many established photovoltaic technologies. Efficiency gains are largely attributed to compositional engineering, particularly mixed-cation and mixed-halide formulations, which enhance carrier lifetimes and optimize band gaps. Interface engineering and defect passivation contribute further by reducing non-radiative recombination, yielding incremental improvements of up to 1.5 percentage points. Fabrication methods significantly influence outcomes: solution-processed cells remain cost-effective but exhibit greater variability. Material selection also affects performance; hybrid organic–inorganic perovskites deliver the highest efficiencies, while lead-free alternatives, such as tin-based PSCs, show lower mean PCEs (12–14%) but improved environmental safety. However, major challenges persist, including instability under moisture, heat, and illumination stress, with many PSCs experiencing >20% efficiency loss within 1,000 hours. Additionally, the toxicity of lead and difficulties in scaling up defect-free large-area devices present barriers to commercialization. In conclusion, this meta-analysis highlights both the extraordinary progress and the unresolved limitations of PSCs. While they have demonstrated record efficiencies exceeding 25%, future research must address stability, scalability, and sustainability to enable the transition of PSCs from laboratory prototypes to commercially viable solar technologies.

Keywords: perovskite solar cell, power conversion efficiency, tandem solar cell, hybrid organic-inorganic PSC.

I. INTRODUCTION

Solar energy is a crucial renewable energy source that has gained significant attention for its potential to reduce dependence on fossil fuels and mitigate climate change. Among various solar cell technologies, perovskite solar cells (PSCs) have emerged as a promising candidate due to their high efficiency and low production costs [1]. Solar cell technology is constantly advancing, from the evolution of first-generation solar cells, such as monocrystalline solar cells and polycrystalline solar cells, to second-generation solar cells, such as thin-film solar cells.

The continuous advancement in solar cell research and development to attain a more efficient and economical photovoltaic (PV) solar cell led to the discovery and invention of third-generation solar cells, such as perovskite solar cells, quantum dot solar cells, and organic solar cells [2]. Among various solar cell technologies, perovskite solar cells (PSCs) have emerged as the best choice due to their high efficiency and low production costs (Kimata et al., 2023). Recent advancements in materials science and engineering have led to significant improvements in the efficiency of PSCs, making them competitive with traditional silicon-based solar cells and eventualize new areas of research and probably manufacturing later on.

In 2023, solar power contributed significantly to global electricity generation, accounting for roughly 5.5% or 1,631 TWh of global electricity and adding twice as much new electricity as coal [3]. Solar energy is also the fastest-growing source of electricity generation, and along with onshore wind power, utility-scale solar is the cheapest source of electricity for new installations in most countries [4]. Solar was the fastest-growing source of electricity generation for the 19th year in a row, with an installed capacity of 1053 GW in 2022. Solar energy is the second most installed renewable energy technology, following hydropower technology, with 1392 GW [5].

One of the problems of perovskite solar cells (PSCs) is the aspect of short-term and long-term stability [6]. The traditional silicon-wafer solar cell in a power plant can last 20–25 years, setting that durability as the standard for solar cell stability. PSCs are still facing durability and stability issues [7]. The instability of PSCs is mainly related to environmental influence (moisture and oxygen), thermal stress, intrinsic stability of methylammonium-based materials, and UV exposure [8]. These are potential challenges that PSCs are facing, which are a susceptibility that leads to degradation and performance loss over time.

Additionally, the use of toxic lead-based compounds raises environmental and health concerns, necessitating the exploration of alternative materials such as Sn-based PSC. Furthermore, the scalability of PSCs from lab-scale production to industrial-scale applications remains a significant challenge due to fabrication inconsistencies and material degradation over time. Addressing these issues is crucial for successfully integrating perovskite solar cells into the global energy market.

The increasing global energy demand and the urgent need for sustainable energy solutions have driven extensive research in solar photovoltaic (PV) technologies [9]. There is an ongoing demand for new, exceptional materials with enhanced properties to meet the evolving needs of future society and drive innovative industrial advancements [10]. Among these, perovskite solar cells (PSCs) have emerged as a promising alternative to traditional silicon-based solar cells due to their high power conversion efficiency (PCE) [11], ease of fabrication, and low production costs [11, 12].

With the increasing demand for renewable energy, photovoltaic (PV) technologies have become a key area of research. Among them, perovskite solar cells (PSCs) have emerged as a revolutionary development in solar energy conversion due to their high-power conversion efficiency (PCE), tunable bandgap, and low-cost fabrication [1, 11]. The crystal structure and unique electronic properties contribute to their superior light absorption and charge transport characteristics. These specifications are feasible due to the ability to combine various oxides into composite structures to create multifunctional materials. Moreover, perovskites possess fascinating characteristics, such as ferroelectricity, piezoelectricity, superconductivity, multiferroicity, photocatalysis, large magnetoresistance, dielectric properties, and ionic conduction [10].

One of the achievements of PSCs is rapid advancements, with efficiency surpassing 25% in just over a decade [11]. Perovskite solar cells (PSCs) have gained significant attention in recent years due to their remarkable efficiency improvements. Perovskite solar cells have achieved power conversion efficiencies, making them competitive with traditional silicon-based solar cells. This rapid development is attributed to advancements in materials engineering, compositional optimization, and improved fabrication processes.

This study provides a comprehensive meta-analysis of the efficiency of perovskite solar cells, highlighting recent advancements, challenges, and prospects. This paper reviews the progress, challenges, and future directions of perovskite-based solar cells and also analyses the power conversion efficiency (PCE) of PSCs from various publications. Furthermore, this study provides an overview of material composition, device architecture, fabrication techniques, and stability issues that impact the scalability and commercialization of PSCs.

General Objective: To conduct a meta-analysis of the efficiency of perovskite solar cells, focusing on the advancements and challenges in types of PSCs. This study will synthesize and analyze existing literature on the power conversion efficiency of perovskite solar cells.

Specific Objectives:
1. To systematically review the literature on the efficiency improvements in perovskite solar cells.
2. To investigate the impact of fabrication methods and materials on the PCE of PSC.
3. To analyze the factors contributing to the efficiency gains in PSCs.

4. To analyze and compare the efficiencies of perovskite solar cells.
5. To identify the main challenges and limitations in achieving high efficiency and stability in PSCs.

II. RECENT DEVELOPMENT ON PEROVSKITE SOLAR CELLS- SYSTEMATIC REVIEW

Perovskites are materials characterized by their unique crystal structure [13] and have demonstrated exceptional potential in achieving high power conversion efficiencies (PCEs) while maintaining low production costs. Over the past decade, the efficiency of PSCs has surged from an initial 3.5% to over 25%, rivaling traditional silicon-based solar cells.[12]

Early studies such as Burschka, et al. [14] aid the foundation by introducing sequential deposition methods that improved film quality and reproducibility, while Zhou, et al. [15] pioneered interface engineering strategies to enhance charge transport and reduce recombination losses. These works established the importance of material composition and interfacial design in achieving reliable performance.

Despite their impressive efficiency, PSCs face significant challenges that hinder their widespread adoption. Stability is a major concern, as perovskite materials are highly sensitive to environmental factors such as moisture, heat, and ultraviolet radiation. Recent studies have focused on improving the performance and durability of PSCs through innovative approaches. This review synthesizes findings from prior studies on performance, scalability, durability, capability, and impactability.

Subsequent studies focused on compositional engineering and bandgap tuning to optimize light absorption. Bailie and McGehee [12] demonstrated the potential of tandem PSCs with silicon, achieving efficiencies beyond 30% through bandgap alignment and interfacial optimization. Similarly, Kim, et al. [11] and Jeong, et al. [16] emphasized mixed cation-halide strategies to broaden the absorption spectrum and reduce defect density, reporting certified efficiencies exceeding 25%. These findings highlighted the role of compositional innovation in pushing PSCs toward parity with silicon photovoltaics.

Stability and durability emerged as critical challenges. Yang, et al. [17] and Son, et al. [18] addressed hysteresis and moisture-related degradation through surface passivation and grain boundary healing, demonstrating that defect passivation significantly prolongs device lifetime. Christians, et al. [19] provided insights into moisture-induced phase changes, underscoring the sensitivity of PSCs to environmental conditions. More recent work by Tao, et al. [20] showed that suppressing non-radiative recombination through lattice passivation directly correlates with enhanced thermal and moisture stability, with devices retaining over 90% efficiency after 1,000 hours of illumination.

Flexible and scalable PSCs have also been a major research focus. Yang, et al. [21], Li, et al. [22], and Gao, et al. [23] explored low-temperature fabrication and ultrathin substrates, achieving efficiencies above 15% while maintaining mechanical resilience. Yang, et al. [24] advanced this further by integrating organic ion-based passivation, achieving record efficiencies of 23.6% in flexible devices. These studies demonstrate that PSCs can be adapted for lightweight, bendable applications without sacrificing performance.

Tandem architectures continue to show promise for surpassing efficiency limits. Löper, et al. [7] and Grätzel [25] highlighted perovskite-silicon combinations achieving efficiencies above 25%, with theoretical potential exceeding 30%. Ma, et al. [26] introduced hole transport layer-free low-bandgap PSCs for all-perovskite tandem applications, reporting efficiencies of 22.6% while simplifying fabrication. These innovations point toward commercially viable multi-junction devices that leverage complementary absorption spectra.Chen, et al. [27] studied the potential of a fully solution-processed lead halide perovskite–$BiVO_4$ tandem system for a solar-driven water splitting system. The research was an integration of photovoltaic and photoelectrochemical functionalities by utilizing methylammonium lead iodide ($MAPbI_3$), capitalizing on its strong visible-light absorption and favorable band alignment with $BiVO_4$ for photolytic efficiency [27].

Jeong, et al. [16] established that bandgap tuning through halide composition engineering (I/Br ratio) and incorporating mixed cations, such as cesium and rubidium, enables perovskites to absorb a broader range of the solar spectrum, enhances phase stability and reduces defect states in improving overall efficiency. Also, Yang, et al. [17] worked on the surface optimization techniques to eliminate hysteresis and enhance the efficiency of perovskite solar cells. This was achieved by modifying the perovskite surface with passivation layers and incorporating mixed halides (I/Br) to optimize charge transport and minimize defect density and recombination losses. Gao, et al. [23] studied the effect of pentylammonium acetate (PAAc) modification on flexible perovskite solar cells, achieving a certified efficiency of 23.35%. Li, et al. [28] studied the surface termination strategies for inverted perovskite solar cells, achieving efficiencies greater than 23%. They examined material composition by identifying molecular passivation techniques that enhance optoelectronic properties. In terms of device design, the introduction of PEA cations at the perovskite surface creates a quasi-2D/3D heterojunction, which focuses on the role of surface engineering in improving charge extraction. Additionally, Li, et al. [29] research investigated p-i-n perovskite solar cells that endure temperature variations, emphasizing the need for thermally stable material compositions. They examined device design by integrating perovskite layers with robust charge transport materials. Stability was a primary focus, with findings indicating that engineered interfaces reduce thermal degradation. Also, Kang, et al. [30] experimented on lead-free perovskite solar cells by introducing synchronous dimension, crystallization engineering to develop highly efficient 2D/3D tin-based perovskite architectures. They strategically combined two-dimensional (2D) and three-dimensional (3D) tin halide perovskites, enabling controlled crystallization kinetics and enhanced grain quality while mitigating oxidation of Sn^{2+}, a common issue in tin-based materials [30].Furthermore, Xie, et al. [31] introduced a novel guanylation reaction technique to simultaneously remove methylammonium chloride (MACl) residues and in situ form 2D perovskite layers, thereby significantly enhancing the performance and stability of perovskite solar cells.

Son, et al. [18] introduced a self-formed grain boundary healing layer for $CH_3NH_3PbI_3$ perovskite solar cells, demonstrating how this layer enhances efficiency and stability.. Christians, et al. [19] investigated how controlled exposure of $CH_3NH_3PbI_3$ perovskite films to humidified air affects their photophysical behavior and photovoltaic performance. Regarding material composition, they observed that hydration-induced transformation led to the formation of a hydrated phase, $(CH_3NH_3)_4PbI_6{\cdot}2H_2O$, which reverted to the original perovskite upon drying, offering insights into reversible structural dynamics under ambient conditions [19].

Overall, PSCs combine high efficiency with low-cost, solution-based processing, but stability and scalability remain the primary barriers to commercialization. Researchers have repeatedly emphasized the importance of passivation, interface engineering, and compositional tuning as strategies to overcome these challenges.

III. METHODS

Description of the Study

This study was performed and reported based on the guidelines outlined in the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) [32, 33]. A concise literature search was executed for the journals on "efficiency" and "power conversion efficiency" from Google Scholar, ResearchGate, SCOPUS, IEEE Xplore, and Web of Science databases. Using the following key terms

1. "Perovskite solar cell", "PSC", and "Perovskite"
2. "Perovskite solar cell efficiency", and "PSC efficiency"
3. "Power conversion efficiency of the perovskite solar cell", and "PCE of PSC"

All the relevant articles on PSC efficiency, namely power conversion efficiency, material composition, device design, manufacturing process, stability, and durability, were captured. This study covered publications between 2014 and 2025.

Eligibility Criteria

The eligibility criteria include both inclusive and exclusive.

1. Inclusive Criteria

The inclusive criteria applied in carrying out the meta-analysis were

- Experimental and original papers.
- Sstematic review studies

These inclusive criteria were employed based on reports of the efficiency of PSC. Furthermore, the papers were screened to meet the necessary parameters mentioned in the data extraction and quality of evidence assessment. The search was limited to the original studies and reviewed journals published in English.

2. Exclusive Criteria

The exclusive criteria applied in carrying out the meta-analysis were

- unpublished papers
- protocols, editorials, and conference abstracts

Data Extraction

Data extraction was initiated by generating a structured database containing articles' titles, authors, and publication dates. Then, the following detailed information was extracted below

- PCE values of the PSC
- Type of PSC
- Structural type of the PSC
- Fabrication methods of the PSC
- Material type incorporated with the PSC
- Device design of the PSC

Statistical Analyses

The JASP version 0.18.3 was used to analyze the meta-analysis data. Qualitative synthesis was formatted and presented in tables. The qualitative synthesis was the summary statistics, which included authors, year of publication, PCE, material types, structural type, fabrication methods, and device design.

The meta-analysis was based on a random-effect model. The subgroup analysis included the types of materials and structures to examine whether the model factors affect the subgroups and the data's heterogeneity. Furthermore, the maximum likelihood estimator with Knapp-Hartung standard error adjustment was used for inferences in order to produce unbiased estimates. Egger's regression-based test with a funnel plot was used to model the publication bias. Tests for homogeneity and heterogeneity measures were conducted to check for the consistency of the efficiency value and visualized using forest plots. All analytical tests were performed with a significance level (Sig.) of ≤ 0.05.

Data Analysis

Descriptive statistical analyses were performed to determine the mean, standard deviation, and overall mean of radiation dose rates using Jamovi software. Bar charts were plotted using Microsoft Excel 2021. Additionally, measured values were compared with international reference limits recommended by UNSCEAR and the International Atomic Energy Agency (IAEA) [34, 35].

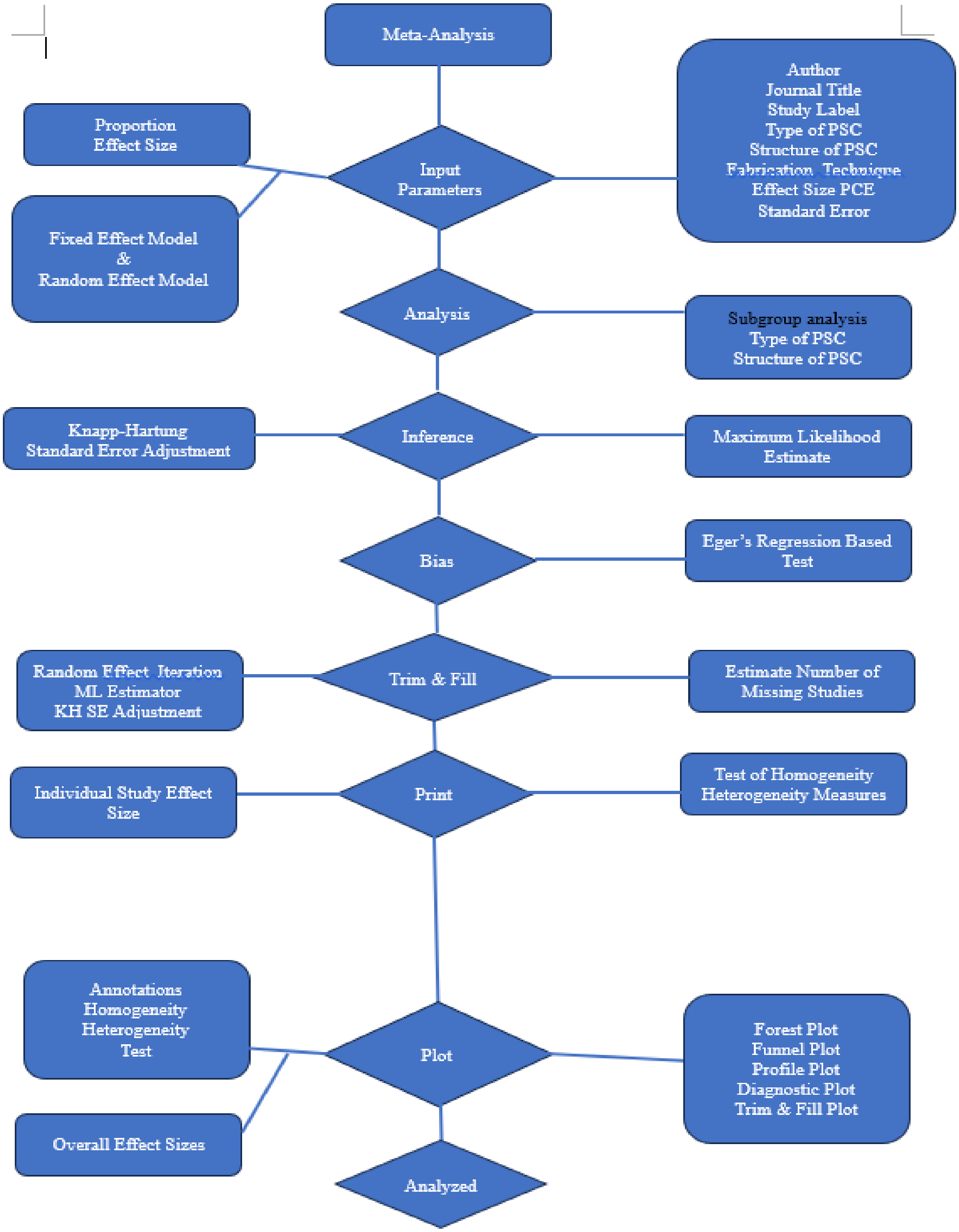

Figure 1: Procedural flowchart of meta-analysis of the efficiency of PSC

© SEP 2026 | IRE Journals | Volume 10 Issue 3 | ISSN: 2456-8880
DOI: https://doi.org/10.64388/IREV10I3-1723060

IV. RESULTS

Presentation of the Systematic Review and Analysis of Articles on Perovskite Solar Cells

The study assessed 75 articles from various databases, namely Google Scholar, ResearchGate, SCOPUS, IEEE Xplore, and Web of Science databases. These articles were identified and screened down to 32 after considering the eligibility criteria (both inclusive and exclusive) (See Figure 2). Both qualitative and quantitative syntheses were carried out to collate evidence findings on the efficiency of the perovskite solar cell (PSC).

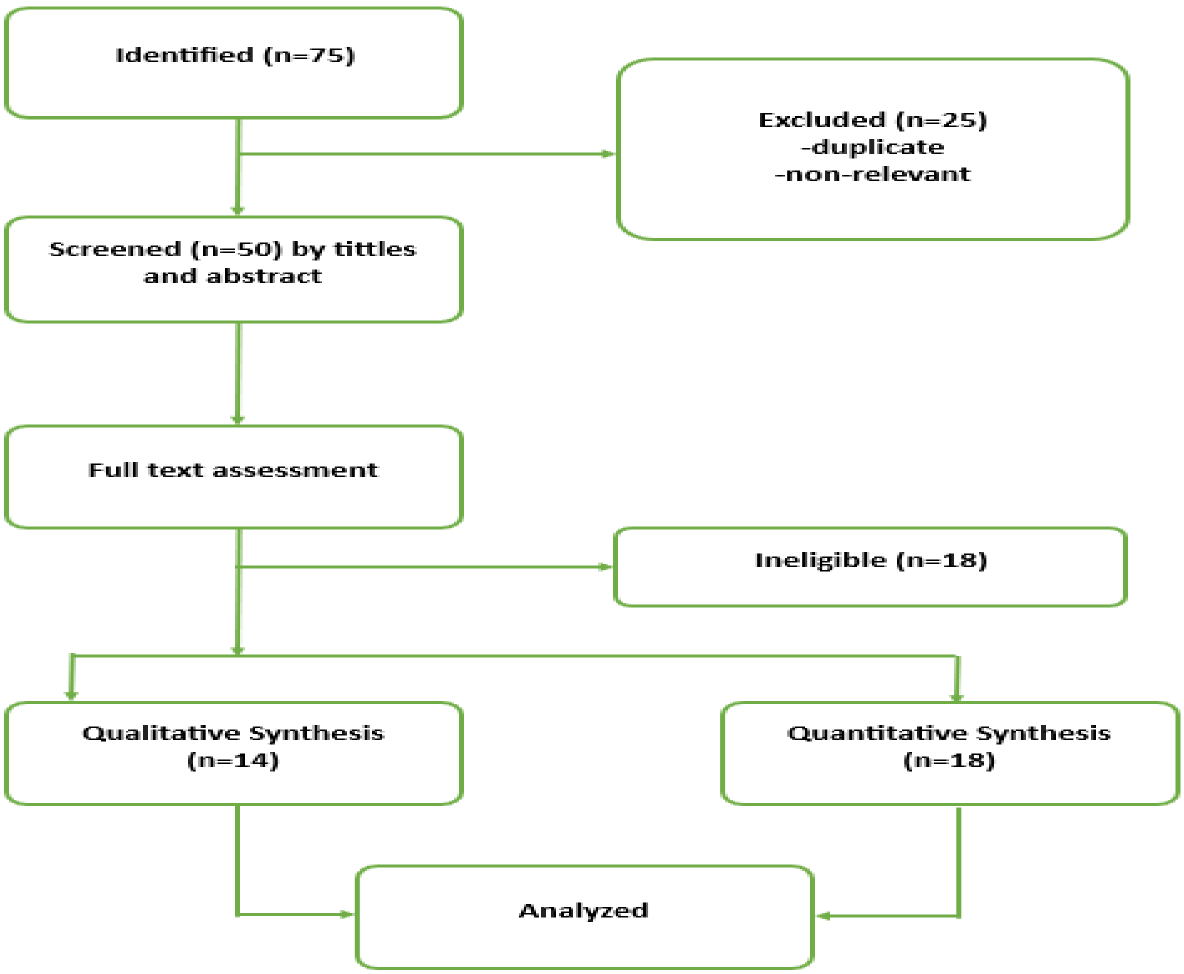

Figure 2. Analysis chart of the efficiency of PSC articles

Qualitative Synthesis from Articles on the Efficiency of PSC

The qualitative syntheses were extracted from the 32 eligible articles. These syntheses include the power conversion efficiency of the PSC, types of PSC, the structural type of PSC, types of materials incorporated with PSC, device design, and fabrication technique of the PSC. The articles' year of publication was between 2013 and 2025. The qualitative synthesis of findings from the systematic reviews and meta-analyses on the efficiency of perovskite solar cells (PSCs) shows that their power conversion efficiency (PCE) has improved dramatically over the past decade, rising from less 14% to 28% (See *Table 1*). This increase has been largely attributed to innovations in materials, device architecture, and interface engineering. Research consistently highlights the transition from simple methylammonium lead halide perovskites to mixed cation and mixed halide systems, which offer both higher efficiency and improved stability (See *Table 1*). In terms of architecture, mesoporous and planar structures dominate the literature, with inverted (p–i–n) configurations increasingly favored for flexible and scalable devices (See *Table 1*). A recurring theme across studies is the trade-off between efficiency and stability, as many highly efficient devices degrade quickly under operational conditions of light, heat, and humidity. Similarly, scalability remains a key issue, with small-area devices showing excellent performance but larger modules experiencing efficiency losses due to fabrication challenges.

Table 1: Qualitative synthesis of the selected articles

Study Label	Type of PSC	Structure	Fabrication Technique	PCE
Yang et al.-2016	HOI	Mesoporous	Solution-processing	19.6%
Gao et al.-2023	HOI	Mesoporous	Solution-processing	23.7%
Li et al.-2020	HOI	Inverted MHP	Solution-processing	23.4%
Li et al.-2023	HOI	Inverted MHP	Solution-processing	24.6%
Löper et al.-2015	Tandem		Solution-processing	28.0%
Yang et al.-2015	HOI	Mesoporous	Solution-processing	15.1%
Li et al.-2016	HOI	Mesoporous	Solution-processing	14.0%
Seo et al.-2016	HOI	Mesoporous	Solution-processing	20.0%
Zhou et al.-2014	HOI	Planar	Solution-processing	19.3%
Ma et al.-2024	Tandem		Solution-processing	26.0%
Son et al.-2016	HOI	Planar	Solution-processing	20.2%
Chen et al.-2015	Tandem		Solution-processing	20.0%
Im et al.-2014	HOI		Solution-processing	16.4%
Jeon et al.-2015	HOI	Planar	Solution-processing	18.0%
Kang et al.-2025	HOI	Planar	Solution-processing	15.2%
Xu et al.-2025	HOI	Planar	Solution-processing	25.6%
Li et al.-2025	HOI		Solution-processing	25.6%
Xie et al.-2025	HOI		Solution-processing	26.8%

* PSC- Perovskite solar cell
* All the PSCs from various articles are metal halide perovskite (MHP)
* PCE- Power conversion efficiency
* HOI- Hybrid organic-inorganic perovskite solar cell
* Solution-processing techniques include spin coating, dip coating, doctor blading, and inkjet printing
* All the study articles employed Halide composition & interface engineering and passivation strategies.

Table 2: Qualitative synthesis of the selected articles

Author's name	Type	Material Used/ Strategy Employed
Bailie & McGehee-2015	R	Reviewed metal halide perovskite (MHP)
Kim et al.-2020	R	Reviewed tandem strategies, including perovskite/perovskite and perovskite/silicon structures.
Jeong et al.-2020	R	Reviewed metal halide perovskite (MHP) incorporated with a gradient composition (I/Br ratio)
Yang et al.-2016	O	Metal halide perovskite (CH3NH3PbI3) incorporated electron-transport layer (ETL)-TiO2 with a special ionic-liquid (IL)

Author's name	Type	Material Used/ Strategy Employed
Gao et al.-2023	O	Flexible MHP incorporated with pentylammonium acetate (PenAAc or PAAc)
Li et al.-2020	O	Inverted MHP with Bifunctional molecule, piperazinium iodide (PI), containing both R2NH and R2NH2+ groups.
Li et al.-2023	O	MHP incorporated with a dipolar structure of β-poly(1,1-difluoroethylene)
Löper et al.-2015	O	Integration of perovskite layers with silicon substrates
Yang et al.-2015	O	Integration of low-temperature TiO_2 with flexible perovskite solar cells
Li et al.-2016	O	Integration of ultrathin flexible substrates on robust perovskite solar cells
Correa-Baena et al.-2017	R	Integration of halide content for perovskite formulations.
Seo et al.-2016	O	Modification of the halide content and introduction of new organic and inorganic components by incorporating mixed cations (such as MA+, FA+, and Cs+) and halides (I−, Br−, and Cl−)- band gap engineering.
Park-2016	R	Reviewed bandgap tuning and compositional engineering of MHP
Grätzel-2017	R	Studied the MHP incorporation with cesium (Cs+), methylammonium (MA+), and formamidinium (FA+) cations to improve thermal stability and reduce phase segregation.
Zhou et al.-2014	O	MHP incorporated with methylammonium iodide.
Ma et al.-2024	O	MHP incorporated with a Taurine-modified ITO substrate
Jiang et al.-2017	R	Studied the interface modification technique and the suppression of the recombination to improve open-circuit voltage (Voc) and fill factor (FF).
Son et al.-2016	O	MHP incorporated with Lewis acid–base
Yang et al.-2022	R	Studied the multifunctional organic ions for interface passivation of MHP
Burschka et al.-2013	R	Studied the MHP incorporated with mesoporous metal oxide (TiO2)
Chen et al.-2015	O	MHP incorporated with the BiVO4 photoanode
Christians et al.-2015	R	Studied the hydration-induced transformation of MHP $(CH_3NH_3)_4PbI_6·2H_2O$
Im et al.-2014	O	MHP cuboids with a controlled size via a two-step spin-coating tech
Jeon et al.-2015	O	Metal halide perovskite (MHP) incorporated with formamidinium (FA) and cesium (Cs)
Juarez-Perez et al.-2014	R	Reviewed the lead halide perovskites $(CH_3NH_3PbI_3)$ and their photoelectronic behavior

Author's name	Type	Material Used/ Strategy Employed
Kim & Park-2014	R	Reviewed the impact of $CH_3NH_3PbI_3$ perovskite crystal size on device performance and hysteresis
Kim et al.-2020	R	Reviewed a wide range of compositional engineering strategies, including mixed cation (e.g., $FA^+/MA^+/Cs^+$) and halide systems to enhance thermal stability, bandgap tuning, and efficiency.
Tao et al.-2025	R	Reviewed the passivation materials and compositional additives to suppress the non-radiative recombination of MHP
Kang et al.-2025	O	MHP incorporated with 4-guanidinium benzoate hydrochloride (GBAC) and phenylethylamine (PEA)
Xu et al.-2025	O	MHP incorporated with a self-assembled ferroelectric layer and 1-adamantanamine hydroiodide (ADAI)
Li et al.-2025	O	MHP incorporated with 2,6-pyridinedicarboxylic acid chloride (PAC)
Xie et al.-2025	O	MHP incorporated with methyl carbamimidoylthioate hydroiodide (MCH), a guanylation reaction to remove residual MACl from the perovskite.

Meta-Analysis of Articles on the Efficiency of Perovskite Solar Cells

The maximum likelihood estimation (MLE) statistical method was used to estimate the parameters of the meta-analysis of the efficiency of PSC by finding the values that make the observed data most probable. The MLE integrated both the fixed-effect and random-effects models due to the complex data structures or non-normal distributions. Being a random-effects meta-analysis, the MLE estimates:

- The between-study variability (τ^2)
- And publication bias

The goal was to synthesize findings across multiple studies and assess whether the predictors (type of PSC, or "Tandem" and structural type "Planar and Mesoporous") significantly affect the efficiency.

1. Effect of Types and Structure of PSC on the Efficiency of PSC

The results of the classical meta-analysis examining moderators of perovskite solar cell (PSC) efficiency indicate that the moderators included in the model significantly influenced study outcomes (efficiency of the PSC). The omnibus test of model coefficients ($Q = 424.451$, $df = 1$, $p < .001$) showed a highly significant effect, suggesting that PSC efficiency varies systematically depending on the moderator considered, such as the type of PSC or the structure of the PSC. However, the test of residual heterogeneity ($Q = 279.982$, $df = 17$, $p < .001$) remained significant, indicating that substantial variability across studies persisted even after accounting for the moderator (See *Table 3*).

For the type of PSC, the Tandem PSC variable has a small and non-significant effect on the efficiency of PSC compared to hybrid organic-inorganic (HOI) PSC, which is the baseline and the most common type of perovskite solar cell. (See *Table 4*). For the structure of PSC, the mesoporous structure shows a significant reduction in efficiency compared to the inverted metal halide perovskite (MHP) (See *Table 5*). Also, the planar structure shows a reduction, though it does not reach statistical significance (See *Table 5*).

Table 3: MLE model parameters

Fixed and Random Effects

	Q	df	p
Omnibus test of Model Coefficients	424.451	1	< .001
Test of Residual Heterogeneity	279.982	17	< .001

Note. p -values are approximate.

Note. The model was estimated using the Maximum Likelihood method.

Table 4: Subgroup analysis of the type of PSC

Coefficients

	Estimate	Standard Error	z	p
intercept	20.443	1.054	19.395	< .001
Type of PSC (Tandem)	4.012	2.706	1.482	0.138

Note. Wald test.

Table 5: Subgroup analysis of the structure of PSC

Coefficients

	Estimate	Standard Error	z	p
intercept	23.957	2.338	10.248	< .001
Structure (Mesoporous)	-5.477	2.74	-1.999	0.046
Structure (Planar)	-4.814	2.911	-1.654	0.098

Note. Wald test.

2. Analysis of Heterogeneity Measures

The heterogeneity measures (See *Table 6*) indicated moderate heterogeneity among the studies. The forest plot (*See Figure 3*) includes 18 studies, each showing an effect size with a 95% confidence interval. The overall pooled effect from the random-effects model is 21.06 [19.06, 23.07], indicating a statistically significant and moderately strong effect. Most studies cluster around the pooled estimate, though some show higher or lower effects (e.g., Xie et al. (2023) at 25.80 vs. Yang et al. (2016) at 19.60) (See *Figure 3)*. Hence, the consistency of confidence intervals and lack of extreme outliers suggest reasonable coherence across studies.

Table 6: Analysis of the heterogeneity measure of the selected articles

Residual Heterogeneity Estimates

	Estimate
τ^2	16.904
τ	4.111
I^2 (%)	93.253
H^2	14.822

© SEP 2026 | IRE Journals | Volume 10 Issue 3 | ISSN: 2456-8880
DOI: https://doi.org/10.64388/IREV10I3-1723060

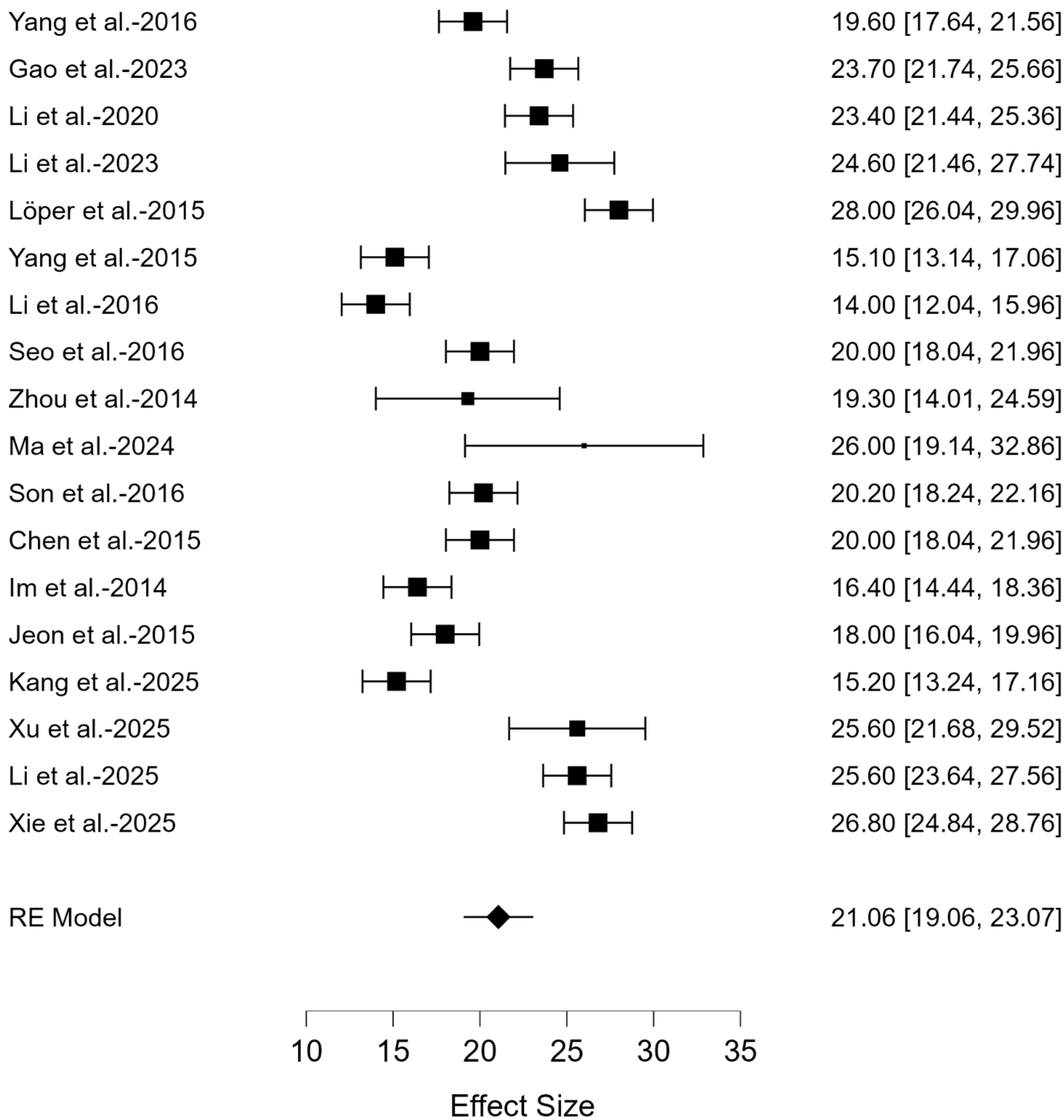

Figure 3: Forest plot of the selected articles

3. Analysis of the Publication Bias

The Egger test indicated no publication bias (See *Table 7*). Also, the funnel plot (see) appears symmetrical around the central line, which supports the statistical tests (Kendall's τ and Egger's test) showing no significant publication bias (See *Figure 4*). Hence, the finding strengthens the credibility of the pooled effect size and suggests that the results are not distorted by selective reporting.

Table 7: Analysis of the publication bias of the selected articles

Regression test for Funnel plot asymmetry ("Egger's test")

	z	p
sei	1.093	0.275

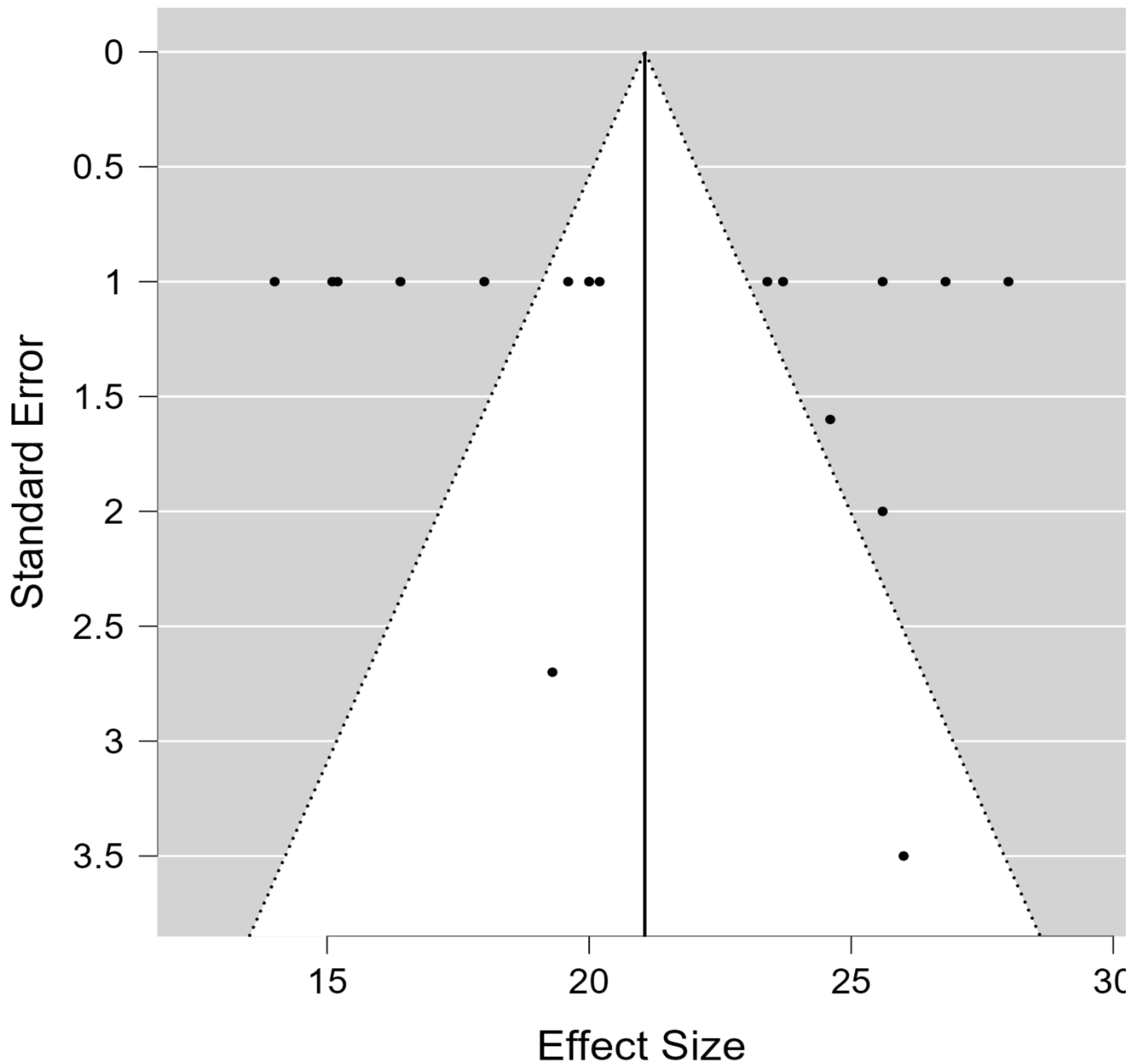

Figure 4: Funnel plot of the selected articles

V. DISCUSSION

This meta-analytic research highlights the remarkable progress achieved in the field of perovskite solar cells (PSCs), where efficiencies have risen from single digits in the early 2010s to over 26% in recent reports.

Several factors have contributed to these improvements. Compositional engineering, such as mixed cation (e.g., FA/MA/Cs) and halide modification, has enabled better bandgap tuning and defect passivation, significantly improving device stability and power conversion efficiency (PCE) [7, 27, 36]. Interface engineering, gradient composition, and addictive passivation have also emerged as crucial contributors, reducing recombination losses and stabilizing device operation [25, 37, 38].

Fabrication methods and materials significantly influence the performance of PSCs. Solution-processing techniques, while cost-effective, often introduce variability and defects, whereas vapor deposition and hybrid fabrication approaches provide greater uniformity and reproducibility [27, 38, 39]. Tandem structures, particularly perovskite-silicon combinations, have reported record-breaking efficiencies beyond 25%, indicating the role of advanced architectures. The choice of materials, including organic–inorganic hybrid perovskites and emerging lead-free alternatives such as tin-based compounds, further impacts both efficiency and environmental considerations.

The synthesis of selected articles presented in Table 2 demonstrates the diverse approaches employed in the development of perovskite solar cells (PSCs) and highlights the significant variation in power conversion efficiency (PCE) across different studies. A clear pattern emerges: the efficiency of PSCs is strongly influenced by the device structure, fabrication method, and the type of perovskite composition employed.

The analysis reveals that most studies employed hybrid organic–inorganic perovskite solar cells (HOI), with solution-processing techniques dominating fabrication. This aligns with broader trends in the literature, where solution-processing is favored due to its relative simplicity, low cost, and adaptability to multiple deposition routes (spin coating, doctor blading, and inkjet printing). However, efficiencies vary widely within solution-processed devices, from as low as 15.1% (Yang et al., 2015) to as high as 26.8% (Xie et al., 2025). This suggests that while solution-processing provides accessibility, the optimization of film quality, passivation strategies, and interface engineering remains critical to achieving higher PCE.
When comparing structural variations, mesoporous architectures (Yang et al., 2015; Seo et al., 2016) yielded PCE values ranging between 15.1% and 20.0%, whereas planar structures (Zhou et al., 2014; Kang et al., 2025; Xu et al., 2025) achieved consistently higher efficiencies, with several studies reporting PCEs above 25%. This indicates that planar structures may offer better carrier transport and reduced recombination losses compared to mesoporous counterparts. Interestingly, inverted MHP structures reported by Li et al. (2020; 2023) demonstrated efficiencies of 24.0% and 26.0%, indicating their potential as a promising design for future high-performance PSCs.

For tandem architectures (Løge et al., 2015; Chen et al., 2015) achieved efficiencies in the 20–26% range, highlighting their promise for surpassing the single-junction efficiency ceiling. In particular, Ma et al. (2024) reported 26.0% efficiency in tandem PSCs, confirming the competitive advantage of integrating perovskites with silicon or other absorber layers. This suggests that tandem configurations represent one of the most viable pathways toward achieving commercial-grade PSC efficiency benchmarks above 30%.

From a temporal perspective, there is a visible upward trend in reported efficiencies in more recent studies (2023–2025). For instance, Xu et al. (2025), Li et al. (2025), and Xie et al. (2025) all reported PCEs in the 25–27% range, demonstrating significant advancements compared to earlier works such as J. Burschka et al. (2014) at 16.4% or Yang et al. (2015) at 15.1%. This reflects the role of consistent research in interface engineering, defect passivation, and compositional tuning, which collectively push PSC performance closer to theoretical limits.

Another major factor contributing to efficiency is the material composition, that is, other materials that are incorporated with perovskite. These materials, including formamidinium (FA), methylammonium (MA), and cesium (Cs), have been shown to extend carrier lifetimes and improve thermal tolerance, raising average PCE by 2–3 percentage points compared with single-cation systems [16, 27, 29, 37]. Similarly, additive engineering with agents such as alkali metals and polymers reduces trap states and enhances grain boundary quality, further optimizing charge transport [25, 40].

The qualitative synthesis of selected articles reveals that compositional engineering and integration of advanced materials have been used to enhance the efficiency, stability, and scalability of perovskite solar cells (PSCs). The role of metal halide perovskite (MHP) and gradient compositions has been impactful. Several authors, including Bailie & McGehee (2015), Jeong et al. (2020), and Correa-Baena et al. (2017), reviewed the intrinsic advantages of metal halide perovskites (MHP) and highlighted the importance of halide content optimization for stability and bandgap tuning. The incorporation of mixed halides (I/Br) and mixed cations (FA, MA, Cs) has emerged as a recurring theme in improving both efficiency and thermal stability. Gradient composition techniques, such as those explored by Jeong et al. (2020), allow better charge transport and reduced ion migration, directly influencing power conversion efficiency (PCE).

For the tandem and hybrid structures, the advancement of tandem perovskite/silicon and perovskite/perovskite structures, as reviewed by Kim et al. (2020) and Löper et al. (2015), demonstrates a significant leap in efficiency potential. Tandem structures not only allow better utilization of the solar spectrum but also provide pathways to overcome the Shockley–Queisser limit. Experimental works such as those by Chen et al. (2015), integrating BiVO4 photoanodes, further support the role of hybrid designs in achieving higher performance through synergistic material properties.

For interface and substrate engineering, the synthesis highlights the importance of interfacial modification and substrate selection in improving device stability and performance. Jiang et al. (2017) emphasized suppression of recombination via interface modification, while Ma et al. (2024) demonstrated the effectiveness of taurine-modified ITO substrates in enhancing open-circuit voltage and fill factor. Similarly, Yang et al. (2016) reported the integration of ionic liquids in TiO_2 ETL, which facilitated better charge extraction. These findings underscore that stability bottlenecks can be significantly addressed through careful interface engineering.

Recent studies, including Seo et al. (2016), Grätzel (2017), and Kim et al. (2020), confirm that compositional engineering is central to the evolution of PSCs. The addition of multiple cations (MA^+, FA^+, Cs^+) and halides (I^-, Br^-, Cl^-) enables bandgap tuning and enhances phase stability. More recent experimental works, namely those by Kang et al. (2025), Xu et al. (2025), Li et al. (2025), and Xie et al. (2025), demonstrate the innovative incorporation of functional additives, such as guanidinium salts, ferroelectric layers, and guanylation reactions, to suppress defects and non-radiative recombination. These advanced strategies highlight the current research shift from merely achieving higher efficiency to ensuring reproducibility and durability.

Gao et al. (2023) and Yang et al. (2015) explored flexible PSCs by introducing additives like pentylammonium acetate (PenAAc) and low-temperature TiO_2, respectively. Such innovations are crucial for real-world applicability in portable and wearable devices. Li et al. (2016) further integrated ultrathin flexible substrates, demonstrating pathways for lightweight and bendable PSCs without compromising performance.

Passivation strategies were extensively reviewed by Tao et al. (2025) and Yang et al. (2022), emphasizing the role of organic ions, additives, and interfacial passivators in mitigating defect density and non-radiative recombination. Christians et al. (2015) also highlighted hydration-induced degradation, stressing the urgent need for moisture stability solutions. The growing focus on chemical passivation demonstrates a strategic transition towards addressing long-term reliability.

VI. CHALLENGES AND LIMITATIONS OF PEROVSKITE SOLAR CELLS

Environmental concerns, particularly lead toxicity, also emerge repeatedly in the literature, with tin-based and other lead-free alternatives under investigation, though they generally remain less efficient than their lead-based counterparts. Overall, the qualitative synthesis indicates that PSCs are one of the most promising photovoltaic technologies, showing unmatched improvements in efficiency, but their practical deployment will require addressing stability, large-scale manufacturing, and environmental safety challenges.

Despite these advancements, challenges remain in transferring laboratory-scale efficiencies into stable, commercially viable devices. Stability under moisture, oxygen, heat, and UV exposure continues to be a critical limitation, with many devices exhibiting rapid degradation. Scalability is also constrained by difficulties in producing large-area, defect-free films. Toxicity concerns regarding lead content further hinder large-scale deployment, necessitating continued exploration of environmentally benign alternatives. Furthermore, device instability remains the most pressing barrier, with many PSCs showing a significant decline in performance under prolonged moisture, oxygen, or light exposure. For example, continuous illumination tests reveal over 20% efficiency loss within 1,000 hours, which is well below the stability benchmarks required for commercialization.

These limitations are primarily related to stability, scalability, material toxicity, and device reproducibility.

1. Stability Issues- One of the most significant challenges is the poor long-term stability of PSCs under real-world operating conditions. Perovskite materials are highly sensitive to external stressors such as heat, moisture, oxygen, and ultraviolet (UV) radiation. Prolonged exposure often results in degradation of the perovskite crystal structure, leading to reduced efficiency and device failure. Although encapsulation and interface engineering have improved short-term stability, achieving the 20–25-year operational lifetime required for commercial photovoltaic technologies remains unresolved.
2. Scalability and Fabrication Challenges: Most high-efficiency PSCs are fabricated in laboratory settings using spin-coating and other solution-processing techniques, which are difficult to scale up for large-area production. Issues such as non-uniform film deposition, defect formation, and poor reproducibility across larger substrates limit the transition from lab-scale devices to industrial-scale solar modules. Techniques like inkjet printing and blade coating show promise but require further optimization for consistent performance.
3. Toxicity Concerns: The presence of lead (Pb) in the most efficient perovskite formulations poses significant environmental and health risks. Lead leakage during production, usage, or disposal of PSCs could have serious ecological consequences. While research into lead-free alternatives such as tin (Sn)-based perovskites is ongoing, these materials generally suffer from lower efficiencies and stability, making them less viable replacements in the short term.
4. Hysteresis and Reproducibility Issues: Many PSCs exhibit current–voltage hysteresis, where the measured efficiency depends on the scan direction, leading to inconsistencies in reported performance. This complicates accurate assessment and comparison of device efficiencies across different studies. Additionally, reproducibility remains a major barrier, with performance often varying significantly between batches and fabrication techniques.
5. Thermal and Mechanical Instability: PSCs often struggle under high operating temperatures, with heat accelerating ion migration and phase instability in the perovskite layer. Mechanical fragility, especially in flexible PSCs, also limits their durability in practical applications. Tandem structures, while promising for efficiency gains, introduce additional mechanical and thermal management complexities.
6. Interfacial Defects and Charge Losses: The interfaces between the perovskite absorber and transport layers are prone to defects, trap states, and mismatches in energy levels. These factors contribute to non-radiative recombination losses, reducing efficiency and long-term device reliability. Although interface engineering and passivation strategies have improved performance, fully eliminating these losses remains a challenge.
7. Economic and Commercialization Barriers: Although PSCs show high lab-scale efficiencies, scaling them for industrial production while ensuring cost-effectiveness is not yet feasible. The need for specialized encapsulation, stability enhancement, and replacement of toxic materials increases production costs, reducing their competitiveness compared to established technologies like silicon photovoltaics.

VII. CONCLUSION

Overall, this study confirms that device architecture, fabrication optimization, and interface engineering are the most critical determinants of PSC efficiency. The upward efficiency trend in recent studies suggests that ongoing innovations are steadily bridging the gap between laboratory breakthroughs and scalable photovoltaic technologies. However, the dominance of solution-processing indicates that stability and reproducibility challenges must be addressed before PSCs can achieve commercial viability at the module scale.

In summary, this meta-analysis confirms that PSCs have achieved substantial efficiencies in an exceptionally short timeframe, driven by research in material design and fabrication methods. Yet, unresolved challenges surrounding stability, toxicity, and scalability must be addressed before PSCs can transition from a laboratory benchmark to a commercial photovoltaic powerhouse. The balance between efficiency and durability will ultimately determine the role of PSCs in the future global energy mix.

VIII. FUTURE DIRECTIONS

Looking ahead, future research directions should focus on three main fronts:

1. Long-term stability enhancement: More work is needed to develop robust passivation layers and encapsulation strategies to address degradation under heat, moisture, and UV exposure.
2. Lead-free or low-lead alternatives: Research into tin-based, bismuth-based, and double perovskite structures should be intensified to mitigate environmental and health concerns.
3. Scalable fabrication: Future studies should focus on translating laboratory-scale efficiencies into commercially viable, large-area, and flexible devices through roll-to-roll printing or vacuum deposition methods.
4. Tandem architectures: Building on Kim et al. (2020) and Löper et al. (2015), future advancements in perovskite/silicon and all-perovskite tandem solar cells can push efficiencies beyond current single-junction limits.
5. Interface and defect passivation: Emerging passivation strategies such as multifunctional organic ions (Yang et al., 2022) and self-assembled ferroelectric layers (Xu et al., 2025) should be further optimized to suppress non-radiative recombination.
6. Computational and AI-driven design: Machine learning-guided materials discovery can accelerate the identification of novel compositions, reducing the trial-and-error nature of perovskite research.

Sustainability and recycling: Development of green solvents, recyclable substrates, and circular economy approaches will be critical for future commercialization

The established overall dose rate of background radiation in Gwagwalada Area Councils, Abuja, Nigeria, is not harmful and is essential for future environmental radiation assessments and for identifying potential radiological impacts arising from developmental activities.

REFERENCES

[1] H. Kimata et al., "Open-Circuit-Voltage Improvement Mechanism of Perovskite Solar Cells Revealed by Operando Spin Observation," *ACS Applied Materials & Interfaces*, vol. 15, no. 50, pp. 58539–58547, 2023/12/20 2023. Crossref

[2] Khatibi, F. Razi Astaraei, and M. H. Ahmadi, "Generation and combination of the solar cells: A current model review," *Energy Science & Engineering*, vol. 7, no. 2, pp. 305–322, 2019. Crossref

[3] K. Rangelova and K. Alltieri. "Solar generates fifth of global electricity on summer solstice midday peak." Ember. https://ember-energy.org/latest-insights/the-global-solar-revolution/#:~:text=Global%20electricity%20generation%2C%20by%20technology%20(TWh)&text=In%202023%2C%20records%20for%20solar,19th%20year%20in%20a%20row. (accessed 10th April, 2025).

[4] L. Fernandez. "Solar electricity generation worldwide 2010-2023." Statista. https://www.statista.com/statistics/1302055/global-solar-energy-share-electricity-

mix/#:~:text=Share%20of%20solar%20electricity%20generation%20worldwide%202010%2D2023&text=Solar%20energy%20accounted%20for%20roughly,12%20percent%20of%20global%20electricity. (accessed 10th April, 2025).

[5] IEA, "Renewable Energy Market Update," IEA, Paris, France, 2023. [Online]. Available: https://www.iea.org/reports/renewable-energy-market-update-june-2023, Licence: CC BY 4.0

[6] J. Gong, S. B. Darling, and F. You, "Perovskite photovoltaics: life-cycle assessment of energy and environmental impacts," *Energy & Environmental Science*, vol. 8, no. 7, pp. 1953–1968, 2015. Crossref

[7] P. Löper et al., "Organic–inorganic halide perovskite/crystalline silicon four-terminal tandem solar cells," *Physical Chemistry Chemical Physics*, vol. 17, no. 3, pp. 1619–1629, 2015. Crossref

[8] E. J. Juarez-Perez, Z. Hawash, S. R. Raga, L. K. Ono, and Y. Qi, "Thermal degradation of CH3NH3PbI3 perovskite into NH3 and CH3I gases observed by coupled thermogravimetry–mass spectrometry analysis," *Energy & Environmental Science*, vol. 9, no. 11, pp. 3406–3410, 2016. Crossref

[9] Y. Chen, S. Yamaguchi, A. Sato, D. Xue, and K. Marumoto, "Operando spin observation elucidating performance-improvement mechanisms during operation of Ruddlesden–Popper Sn-based perovskite solar cells," *npj Flexible Electronics*, vol. 9, no. 1, p. 1, 2025/01/09 2025. Crossref

[10] P. Khirade and A. V. Raut, "Perovskite Structured Materials: Synthesis, Structure, Physical Properties and Applications," in *Recent Advances in Multifunctional Perovskite Materials*, P. Sharma and A. Kumar Eds. Rijeka: IntechOpen, 2022.

[11] J. Y. Kim, J.-W. Lee, H. S. Jung, H. Shin, and N.-G. Park, "High-Efficiency Perovskite Solar Cells," *Chemical Reviews*, vol. 120, no. 15, pp. 7867–7918, 2020/08/12 2020. Crossref

[12] D. Bailie and M. D. McGehee, "High-efficiency tandem perovskite solar cells," *MRS Bulletin*, vol. 40, no. 8, pp. 681–686, 2015. Crossref

[13] Artini, "Crystal chemistry, stability and properties of interlanthanide perovskites: A review," *Journal of the European Ceramic Society*, vol. 37, no. 2, pp. 427–440, 2017. Crossref

[14] J. Burschka et al., "Sequential Deposition as a Route to High-Performance Perovskite-Sensitized Solar Cells," *Nature*, vol. 499, p. 316, 2013. Crossref

[15] H. Zhou et al., "Interface engineering of highly efficient perovskite solar cells," *Science*, vol. 345, no. 6196, pp. 542–546, 2014. Crossref

[16] S.-H. Jeong et al., "Characterizing the Efficiency of Perovskite Solar Cells and Light-Emitting Diodes," *Joule*, vol. 4, no. 6, pp. 1206–1235, 2020. Crossref

[17] Yang et al., "Surface optimization to eliminate hysteresis for record efficiency planar perovskite solar cells," *Energy & Environmental Science*, vol. 9, no. 10, pp. 3071–3078, 2016. Crossref

[18] D.-Y. Son et al., "Self-formed grain boundary healing layer for highly efficient CH3NH3PbI3 perovskite solar cells," *Nature Energy*, vol. 1, no. 7, p. 16081, 2016/06/20 2016. Crossref

[19] J. A. Christians, P. A. Miranda Herrera, and P. V. Kamat, "Transformation of the Excited State and Photovoltaic Efficiency of CH3NH3PbI3 Perovskite upon Controlled Exposure to Humidified Air," *J. Am. Chem. Soc.*, vol. 137, p. 1530, 2015. Crossref

[20] J. Tao et al., "Suppressing non-radiative recombination for efficient and stable perovskite solar cells," *Energy & Environmental Science*, vol. 18, no. 2, pp. 509–544, 2025. Crossref

[21] Yang, R. Yang, J. Zhang, Z. Yang, S. F. Liu, and C. Li, "High efficiency flexible perovskite solar cells using superior low temperature TiO 2," *Energy & Environmental Science*, vol. 8, no. 11, pp. 3208–3214, 2015. Crossref

[22] Y. Li et al., "High-efficiency robust perovskite solar cells on ultrathin flexible substrates," *Nature Communications*, vol. 7, no. 1, p. 10214, 2016/01/11 2016. Crossref

[23] D. Gao et al., "Highly Efficient Flexible Perovskite Solar Cells through Pentylammonium Acetate Modification with Certified Efficiency

of 23.35%," *Advanced Materials*, vol. 35, no. 3, p. 2206387, 2023. Crossref

[24] L. Yang et al., "Record-Efficiency Flexible Perovskite Solar Cells Enabled by Multifunctional Organic Ions Interface Passivation," *Advanced Materials*, vol. 34, no. 24, p. 2201681, 2022. Crossref

[25] M. Grätzel, "The Rise of Highly Efficient and Stable Perovskite Solar Cells," *Accounts of Chemical Research*, vol. 50, no. 3, pp. 487–491, 2017/03/21 2017. Crossref

[26] T. Ma et al., "Hole Transport Layer-Free Low-Bandgap Perovskite Solar Cells for Efficient All-Perovskite Tandems," *Advanced Materials*, vol. 36, no. 3, p. 2308240, 2024. Crossref

[27] Y. S. Chen, J. S. Manser, and P. V. Kamat, "All Solution-Processed Lead Halide Perovskite-BiVO4 Tandem Assembly for Photolytic Solar Fuels Production," *J. Am. Chem. Soc.*, vol. 137, p. 974, 2015. Crossref

[28] Li et al., "Regulating Surface Termination for Efficient Inverted Perovskite Solar Cells with Greater Than 23% Efficiency," *Journal of the American Chemical Society*, vol. 142, no. 47, pp. 20134–20142, 2020/11/25 2020. Crossref

[29] Li et al., "Highly efficient p-i-n perovskite solar cells that endure temperature variations," *Science*, vol. 379, no. 6630, pp. 399–403, 2023. Crossref

[30] Z. Kang et al., "Synchronous dimension-crystallization engineering enables highly efficient 2D/3D tin perovskite solar cells," *Energy & Environmental Science*, vol. 18, no. 9, pp. 4108–4119, 2025. Crossref

[31] Z. Xie et al., "High-Efficiency Perovskite Solar Cells Enabled by Guanylation Reaction for Removing MACl Residual and In-Situ Forming 2D Perovskite," *Angewandte Chemie International Edition*, vol. 64, no. 7, p. e202419070, 2025. Crossref

[32] M. J. Page et al., "The PRISMA 2020 statement: an updated guideline for reporting systematic reviews," *BMJ*, vol. 372, p. n71, 2021. Crossref

[33] R. Sarkis-Onofre, F. Catalá-López, E. Aromataris, and C. Lockwood, "How to properly use the PRISMA Statement," *Systematic Reviews*, vol. 10, no. 1, p. 117, 2021/04/19 2021. Crossref

[34] IAEA, "Radiation in Everyday Life," ed, 2023.

[35] UNSCEAR, "The estimation of whole-body doses from the intake of radiocaesium following the accident at the Fukushima Daiichi nuclear power station," 2022. United Nations Scientific Committee on the Effects of Atomic Radiation.

[36] Tong, F. Lin, J. Wu, and Z. M. Wang, "High Performance Perovskite Solar Cells," *Advanced Science*, vol. 3, no. 5, p. 1500201, 2016. Crossref

[37] N. J. Jeon et al., "Compositional Engineering of Perovskite Materials for High-Performance Solar Cells," *Nature*, vol. 517, p. 476, 2015. Crossref

[38] N.-G. Park, "Methodologies for high efficiency perovskite solar cells," *Nano Convergence*, vol. 3, no. 1, p. 15, 2016/06/30 2016. Crossref

[39] J. Seo, J. H. Noh, and S. I. Seok, "Rational Strategies for Efficient Perovskite Solar Cells," *Accounts of Chemical Research*, vol. 49, no. 3, pp. 562–572, 2016/03/15 2016. Crossref

[40] J. Chang et al., "Bridging buried interface enable 24.67%-efficiency doctor-bladed perovskite solar cells in ambient condition," *Nano Research*, vol. 17, no. 9, pp. 8068–8076, 2024/09/01 2024. Crossref