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Next-Generation Nanomaterials for Solar Cells: Physics, Fabrication, and Performance - A Mini Review

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Abstract: Through enhanced light harvesting, charge transfer, and spectrum management, the quick development of nanostructured materials has significantly improved photovoltaic performance. With a focus on perovskites, perovskite quantum dots, colloidal quantum dots, plasmonic nanostructures, and emerging 2D materials, this mini-review critically synthesizes recent literature (2013–2025) on next-generation nanomaterials for solar cells. It also assesses the physical mechanisms, fabrication processes, device performance, and translational barriers of these materials. A thorough search of IEEE Xplore, Web of Science, and Scopus was conducted to find important modeling and experimental studies influencing modern device architectures. Through band-gap engineering and sophisticated light-management techniques, we discover that perovskite-based devices and perovskite/silicon tandem architectures have the highest lab-scale power-conversion efficiency (claims approaching ~30% for monolithic tandems). Practical deployment is nevertheless constrained by enduring issues, such as long-term operational stability under heat, moisture, and photo-stress; scaling up low-cost, environmentally friendly manufacturing; a lack of standardized stability testing (such as ISOS-compliant protocols); and a lack of mechanistic studies of degradation pathways.Comparing investigation reveals trade-offs between higher cost and processing complexity and efficiency improvements from complicated nano-additives (such as plasmonic/gold nanostructures). To expedite the transition from laboratory demonstrations to commercially viable photovoltaic technologies, we suggest the following priority actions: adoption of standardized stability metrics, life-cycle and cost analyses, development of lead-free/low-toxicity chemistries, scalable deposition methods, and AI-driven nanostructure optimization.

Keywords: Perovskite solar cell, Quantum Dots, Stability, Photovoltaics, Plasmonic nanostructures, Tandem solar cell

1. Introduction

One of the most well-known contemporary technologies in the field of producing renewable energy is solar cells [1], which work by cleanly and sustainably converting solar radiation into electrical energy. Crystalline silicon-based conventional solar cells have become the most popular option in international markets due to their impressive advancements in efficiency and cost reduction over the past few decades. However, in addition to the difficulties brought on by intricate production procedures and high energy [2,3], this technology has theoretically hit its limitations in terms of conversion efficiency.

consumption in the process of production. These factors have led researchers to look for a new generation of solar cells that can overcome the technical and financial constraints facing conventional technologies, in addition to the requirement for raw materials with specific

specifications, which limits the potential for radical performance improvements [4]. Because of their special atomic and molecular characteristics, nanomaterials have become one of the most promising areas of study for creating the next generation of solar cells. These substances are distinguished by their capacity to precisely regulate the absorption of light [5], enhancing the kinetics of charge transport and decreasing loss brought on by electron and hole recombination. Their application also makes it possible to create sophisticated optical and electrical structures that might significantly boost solar cells' efficiency, possibly lowering production costs and enhancing operational stability [6]. Perovskites, quantum dots, and two-dimensional (2D) materials like graphene and its variants are notable examples of these nanomaterials [7].

Even though this subject has made great strides recently, there is still a glaring research deficit that prevents these technologies from being fully adopted at the industrial level. The inadequate long-term stability of these materials under practical operating conditions, the requirement to create industrially scalable and economical manufacturing techniques, and a lack of thorough knowledge of the processes underlying these materials' long-term chemical and physical deterioration are all contributors to this. In addition, a lot of research concentrates on attaining record efficiency in the lab without thoroughly assessing how well they function in operational settings that closely resemble actual circumstances [8,9].

In light of those mentioned above, this review attempts to present a thorough scientific analysis of the most recent advancements in the field of nanomaterials for next-generation solar cells [10], concentrating on three primary axes: manufacturing processes, their benefits and drawbacks, physical characteristics and their effect on performance [11], The results of the study are examined to spot potential trends. Additionally, the study aims to identify current scientific knowledge gaps and offer research suggestions that could hasten the shift from lab testing to extensive real-world applications.

2. Materials and Methods

To guarantee openness and reproducibility, this review adhered to the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) approach. Scopus, Web of Science, IEEE Xplore, and ScienceDirect were searched for structured literature.

2.1Search strategy

The following keyword and Boolean operator combinations were used in searches between January 1 and March 30, 2025: ("nanostructures" OR "quantum dots" OR "perovskite" OR "tandem") AND("solar cell*" OR "photovoltaic*"). Only peer-reviewed journal articles authored in English and published between 2013 and 2025 were included in the search.

2.2Inclusion criteria

research that specifically addresses how nanomaterials can be used to enhance solar cell performance. Simulation studies, hybrid analyses with performance measurements, or original experimental research articles that present quantitative results, including power-conversion efficiency (PCE), stability information (ideally via ISOS procedures), or improvements in fabrication.

2.3Exclusion criteria

- Theses, editorials, conference abstracts, and non-indexed journal articles.
- Research that does not focus on nanomaterials or solar cells.
- Reports that lack methodological details or quantitative results.

2.4Study selection

Sixty-two records were found in the first search. Following the elimination of duplicates (n = 115), 527 distinct articles were filtered based on their abstract and title. Of these, 135 articles were selected for full-text review after 392 were deemed irrelevant. 122 articles were selected for qualitative synthesis after their eligibility was evaluated in accordance with the aforementioned criteria. Twenty sample studies were selected from among them and

tabulated (Table 1) to offer in-depth comparative views; the remaining research supported a more general discussion and context.

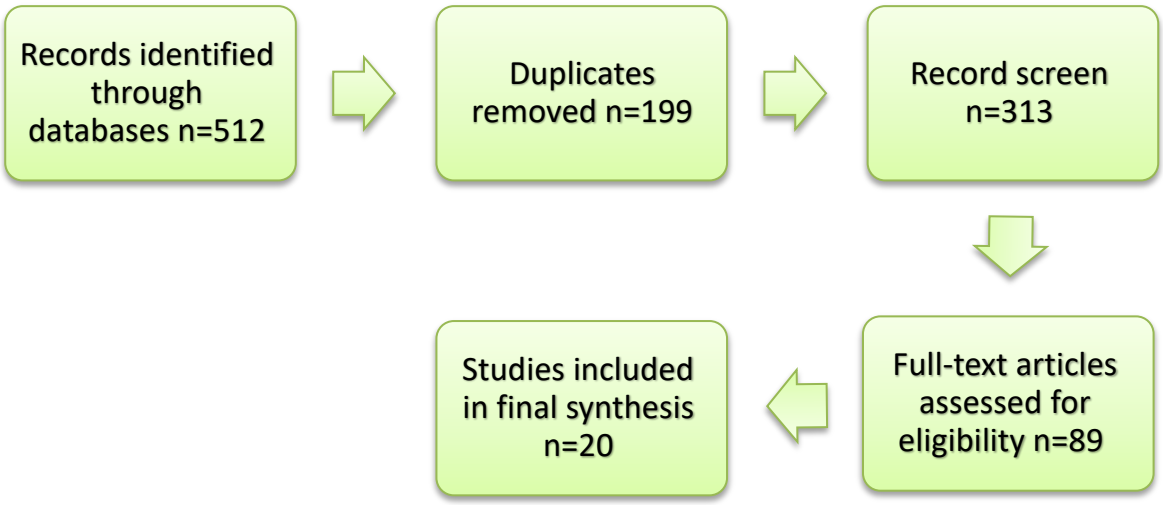
2.5Quality appraisal and risk of bias

- The quality of the study was evaluated separately by two reviewers using the following criteria:
- Journal indexing/impact factor (to establish credibility).
- Reporting clarity (methodology and performance measures).
- Pertinence to PV technologies of the future. Consensus was used to settle disagreements.
- Excluded were studies with unrealistic outcomes or inadequate methodological detail.

2.6PRISMA flow description

The screening process followed the PRISMA model:

- Records identified (n = 512).
- Records after duplicates removed (n = 313).
- Records screened (n = 313).
- Full-text articles assessed for eligibility (n = 89).
- Studies included in final synthesis (n = 20).



Fig(1):PRISMA flow chart description.

313 of the 512 records that were initially found remained after duplicates were eliminated. 89 studies were found to be pertinent to this study following screening and eligibility evaluation. The remaining research were used to support the larger discussion, but only 20 sample papers were tabulated and thoroughly critically examined (Table 1).

Table (1): Summary of selected studies

Sr. N0.	Material type	Study Method	Parameters	Main results	References	DOI
1	Polymer and gold nanorods	Experiment	Thickness: 350 nm, T=25℃	Cell efficiency: 18.7%	12	10.1016/j.solmat.2013.04.015
2	Non-fullerene organic materials	Experiment	λ = 400–800 nm, Intensity = 100	PCE=21.2 %	13	10.1038/s41566-018-0065-7

Sr. N0.	Material type	Study Method	Parameters	Main results	References	DOI
			mW/cm²			
3	Perovskite quantum dots	Experiment/ simulation	Jsc = 22.4 mA/cm², Voc = 1.05 V, Thickness = 200 nm	Band – Gap engineering	14	10.1002/adma.202404495
4	Perovskite/silicon	Experiment	NP size = 15 nm, Abs. coeff. = 1.2×10^5 cm^{-1}	PCE =17.9%	15	10.1038/s41467-025-05733
5	Perovskite/silicon	Experiment	Thickness = 250 nm, T = 300 K	PCE=19.8 %	16	10.1039/d5se00419
6	Perovskite/silicon	Simulation\ Analysis	Voc = 0.98 V, Jsc = 20.7 mA/cm²	FF = 75%	17	10.1007/s40243-025-0018
7	Perovskite/Colloidal Quantum Dots	simulation	Thickness = 500 nm, Reflection = 5%	PCE=22.5 %	18	10.1016/j.matpr.2021.06.003
8	Perovskite/Silicon and Plasmonic Nanorods	simulation	Jsc = 23.1 mA/cm², Voc = 1.08 V	beyond the Shockley-Queisser limit	19	arXiv preprint arXiv:2507.22803
9	Thin silicon cells and plasmonic nanostructures	Experiment/ simulation	Intensity = 1 sun, Layer = 40 nm	PCE=16.3 %	20	10.1364/OE.472911
10	rod-shaped nanomaterials	Hardware Experience/ Design	Voc = 0.92 V, Jsc = 18.9 mA/cm²	FF = 70%	21	10.3390/en8065440
11	Flexible perovskite	Experiment	Thickness = 300 nm, Abs. coeff. = 1.5×10^5 cm^{-1}	PCE=20.1 %	22	10.1002/anie.202307225
12	Thin-film cells processe	Experiment	Voc = 1.02 V, Jsc = 24.2	FF = 76%	23	10.1039/D2YA01161G

Sr. N0.	Material type	Study Method	Parameters	Main results	References	DOI
	d by solution		mA/cm²			
13	TiO2 nanoparticles	Experiment	Thickness = 180 nm, T = 27 °C	PCE=15.7 %	24	10.1016/j.ceramint.2021.05.098
14	plasmonic nanostructures	simulation	Voc: 0.88 V, Jsc: 17.3 mA/cm²	FF: 68%.	25	10.1080/23746149.2021.1908848
15	Closed metallofullerenes	Experiment/ simulation	Thickness = 600 nm, Reflection = 3%	PCE= 23.4%	26	10.1021/acs.chemmater.3c01642
16	Self-assembled monolayers	Experiment	Voc = 1.10 V, Jsc = 25.0 mA/cm²	FF = 78%	27	10.1002/aenm.202002606
17	phosphorene strips	Experiment	λ = 350–750 nm ,light intensity: 100 mW/cm².	PCE=14.8 %	28	10.1016/j.joule.2022.08.017
18	Perovskite/silicon	Experiment	Voc = 0.95 V, Jsc = 19.5 mA/cm², FF = 72%	PCE >22%	29	10.1016/j.nanoen.2018.09.021
19	Perovskite/silicon	Experiment	Thickness = 280 nm, T = 295 K	PCE=28.3 %	30	10.1016/j.nanoen.2021.105934
20	Perovskite/silicon	Experiment	Voc = 1.07 V, Jsc = 24.0 mA/cm²	FF = 78% Stable 1-year outdoor pref	31	10.1016/j.xcrp.2022.101234

3. Results

Physics and Performance of Nanomaterials

Properties of Nanomaterials

Compared to their bulk counterparts, nanoparticles have special qualities that give them advantages; however, these qualities may also give them special toxicity mechanisms [12]. The size, surface area, composition, and forms of nanomaterials have been assumed to be the source of toxicity, the particles' size and surface area. Surface area and particle size have a significant impact on how materials interact with biological systems [13]. The surface area of the materials appears to rise exponentially with decreasing size about volume [14], increasing the surface reactivity of the nanomaterial both to itself and to its surrounding

environment. Notably, the way the system reacts to, disperses, and gets rid of the materials depends on particle size and surface area [15]. The size of the material has been shown to affect several biological processes, such as endocytosis, cellular uptake, and the effectiveness of particle processing in the endocytic pathway [16]. Numerous researchers have used a range of cell types, culture conditions, and exposure durations to assess the in vitro cytotoxicity of NPs of varying sizes [17,18],

Although several authors have assessed their toxicity issues in biological systems using a variety of in vivo models, their in vivo evaluation is challenging due to their more complicated nature in biological systems and the need for a more thorough understanding of the particles [19]. The ability of nanoparticles to infiltrate biological systems [20] and alter the structure of different macromolecules [21] is generally responsible for their size-dependent toxicity, which interferes with vital biological processes. The production of oxidative reactions through the formation of free radicals is one of the primary mechanisms for the toxicity of ENMs in vivo [22]. Size plays a crucial part in this process, as numerous authors have noted that the smaller the size, the more capable it is of forming ROS [23]. The pharmacological behaviors of nanoparticles are also determined by their size. While NPs larger than 50 nm (especially 100–200 nm positively charged particles) are easily absorbed by RES and do not spread to other tissues, NPs smaller than 50 nm (administered by intravenous injection) have been found to transverse rapidly to almost all tissues and impart potentially toxic manifestations in various tissues [24,25].

3.1 Effect of Particle Shape and Aspect Ratio.

Significant progress has been made in understanding how particle size and shape interact to create more effective targeted delivery systems based on nanomaterials [26]; however, this also underscores the need to consider their harmful effects. Nanomaterials can take many different shapes, such as fibers, rings, tubes, spheres, and planes. Many nanoparticles, such as carbon nanotubes, silica nanoparticles, allotropes, nickel, gold, and titanium nanomaterials, have been shown to exhibit shape-dependent toxicity [27]. In essence, shape-dependent nanotoxicity affects how membranes are rolled up during phagocytosis or endocytosis in vivo [28]. In contrast to rod-shaped or fiber-like nanoparticles, spherical nanoparticles are easier and faster to phagocytize [29]. Importantly, spherical nanoparticles, whether homogeneous or heterogeneous, are relatively less hazardous [30]. Figure 1 illustrates the different nanoshapes.

Other biological effects can result from nonspherical nanoparticles' propensity to pass through capillaries [31]. Because longer asbestos fibers cannot be efficiently removed from the respiratory tract by macrophages because they cannot be phagocytized, it was found that asbestos fibers longer than 10 microns caused lung carcinoma, fibers longer than 5 microns caused mesothelioma, and fibers longer than 2 microns caused asbestosis [32]. Therefore, as the complexities of these phenomena become clearer, they will undoubtedly aid in the deployment of safer systems based on nanotechnology [33].

3.2 Effect of Surface Charge

Because surface charge significantly determines how nanoparticles interact with biological systems, it also has a significant impact on toxicity. Numerous features of nanomaterials [34], including plasma protein binding, colloidal behavior, and selective adsorption of nanoparticles. The surface charge of nanoparticles largely controls transmembrane permeability and blood-brain barrier integrity [35]. Because of their improved opsonization by the plasma proteins, positively charged nanoparticles exhibit notable cellular absorption in contrast to negatively charged and neutral nanoparticles. Additionally, it has been demonstrated that they cause platelet aggregation and hemolysis [36,37], which results in the system becoming extremely poisonous. Because surface charge is a key factor in determining colloidal behavior, it particularly affects how an organism reacts to nanoparticle exposure by altering the size and shape of the particles through the formation of aggregates

or agglomerates [38].

3.3 Effect of Composition and Crystalline Structure

We cannot disregard studies that demonstrate similar toxicities for different nanoparticle chemistries with the exact dimensions, even if it has been underlined that particle size plays a crucial role in determining the toxicity of nanoparticles [39].

These investigations demonstrate that the crystalline structure and composition of nanoparticles also affect their toxicity. Using zebrafish, daphnids, and algae as models of different trophic levels, Griffitt et al. [40] found that while TiO2 of the exact dimensions did not cause any toxicity issues, nanosilver and nanocopper in their soluble forms were harmful to all examined organisms [41].

3.4Effect of Aggregation and Concentration

The toxicities of nanoparticles are also influenced by their aggregation states. In general, NPs' aggregation states are influenced by several factors, including size, composition, and surface charge [42]. According to observations, carbon nanotubes primarily collect in the liver, spleen, and lungs. They do not exhibit immediate toxicity, but they do have cytotoxic consequences, primarily due to the formation of aggregates over extended periods. Agglomerated particles of carbon nanotubes have more negative effects than well-dispersed carbon nanotubes and promote lung interstitial fibrosis [43,44]. Furthermore, it has been discovered that when the concentration of nanoparticles increases, their toxicity decreases [45].

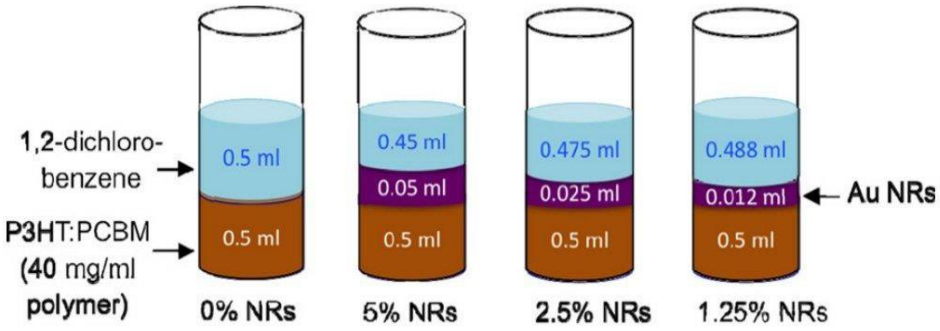
3.5Effect of Surface Coating and Surface Roughness

Since the surface characteristics of particles are crucial in determining how they interact with cells and other biological entities, they have a substantial impact on the toxicity of nanoparticles [46]. By altering the physicochemical characteristics of nanoparticles, including their magnetic, electric, optical, and chemical reactivity, surface coating might influence their lethal qualities. It can change a nanoparticle's toxicity, dispersion, pharmacokinetics, and accumulation [47]. It is well known that the presence of oxygen, ozone, oxygen radicals, and transition metals on the surface of nanoparticles causes ROS to be produced and inflammation to be induced by these systems [48]. These factors undoubtedly affect the toxicities that are linked to them. More precisely, in light of this, Fubini et al. [49] have demonstrated a considerable correlation between the presence of reactive oxygen species and surface radicals on silica and their particular cytotoxicity.

3.6 Performance in Solar Cell

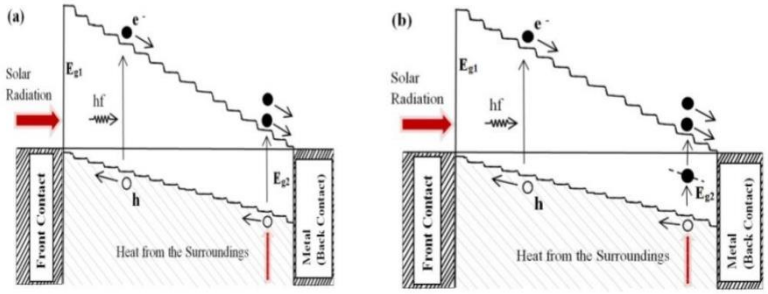
One of the most important metrics for assessing the performance of photovoltaic devices is solar cell efficiency, which is primarily determined by the characteristics of the active layers and nanostructures that are integrated into the cell [50]. According to recent research, adding other nanomaterials—like plasmonic structures and gold nanorods—as well as enhancing the crystal structure of perovskites boosts light absorption and charge transport, which raises the device's overall efficiency [51].

According to the findings of a 2013 study by Mahmoud et al [52], adding gold nanorods to the polymer's active layer significantly increased efficiency at particular thicknesses. The study's Figure 2 shows how layer thickness and photoresistance efficiency are related. It illustrates the relationship between active layer thickness and light absorption efficiency. If the layer is too thin, it doesn't absorb all photons, and if it is too thick, charge loss occurs due to recombination. Therefore, there is an optimal thickness that gives the highest energy conversion efficiency. Performance was assessed using current-voltage (J-V) measurements in a standard solar irradiation of 1000 W/m². According to the study, the nanostructures improve electron and hole collection and photoconversion efficiency by strengthening the local electric field inside the active layer.



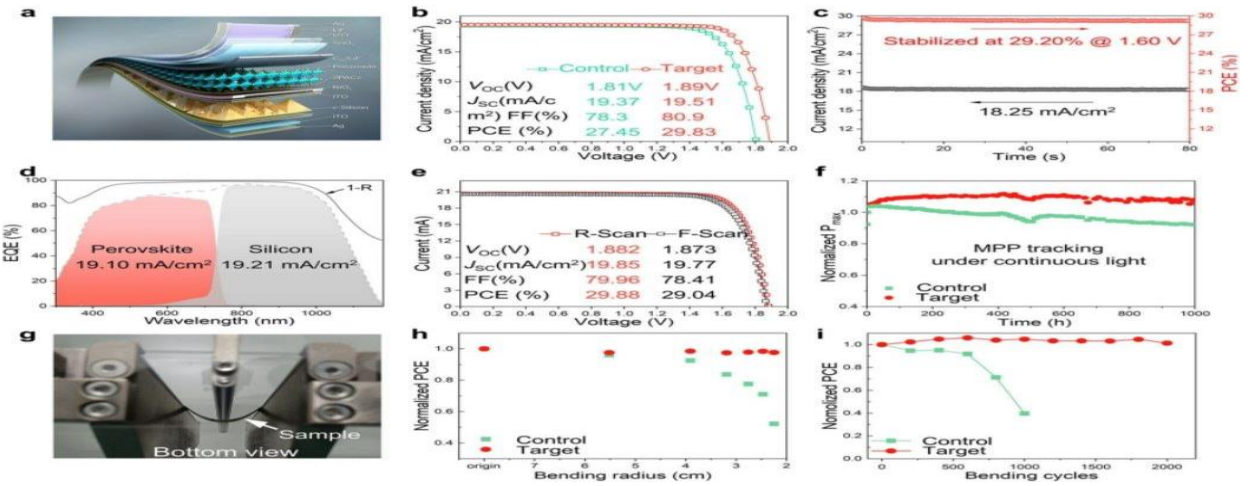
Fig(2): The relationship between layer thickness and light absorption efficiency.

Dharmadasa et al. [53] concentrated on the application of rod-type nanostructures in wide-band solar cells. These nanostructures were shown to reduce internal losses and broaden the absorption spectrum, thereby enhancing device efficiency. Figure 3a illustrates the process of carrier generation under solar illumination, where electrons are excited from the valence band to the conduction band, while heat from the surroundings contributes to additional carrier activity. Figure 3b shows the subsequent electron–hole separation and transport across the junction, demonstrating how the nanostructured architecture facilitates effective charge collection. When light falls on the material, photons impart energy to electrons, which then ascend from the valence band to the conduction band. The electrons and holes then move in opposite directions across the junction, generating an electric current. The presence of nanostructures helps absorb more light and facilitates the movement of charges. This observation is in agreement with the present findings, as summarized in Table 2.



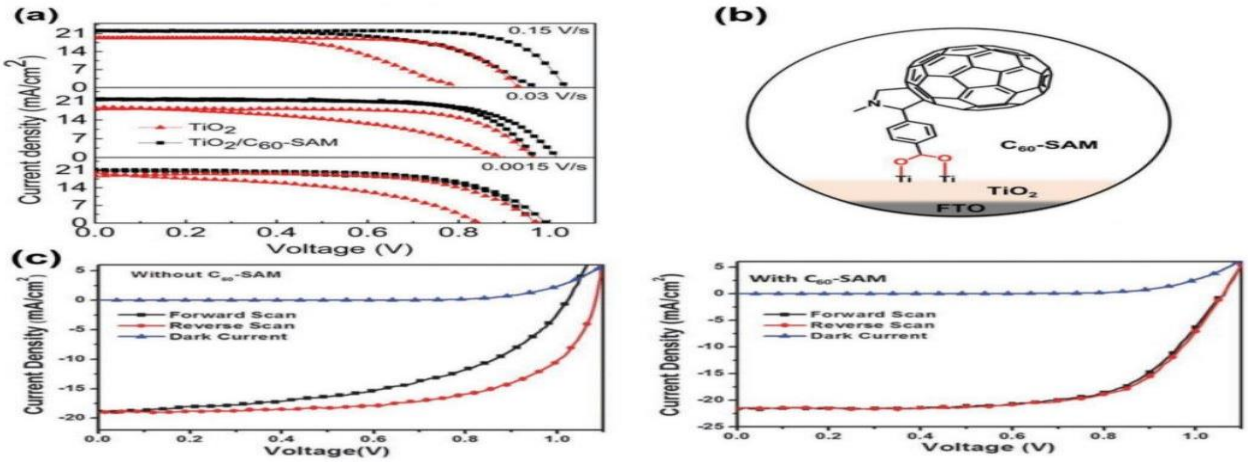
Fig(3): Distribution of light absorption across cell layers.[21]

The development of dual-layer perovskite/silicon cells has been the subject of recent research. According to a 2025 study by Sun et al. [15], flexible monocrystalline cells can achieve efficiencies of up to 30%. Figure 4 of the study shows the light absorption pattern across different layers. J-V curves and total absorption spectra were used to measure performance, focusing on improving light transmittance and electrical conductivity within the cell and shows how light is absorbed in bilayer cells such as perovskite/silicon. Perovskite absorbs high-energy photons, while silicon absorbs lower-energy photons. This broadens the spectral absorption range and increases efficiency.In contrast, the 2025 study by Kumar et al. used sophisticated simulations to overcome manufacturing issues, while the study by Ir-Raji et al. [54] focused on the coating dynamics in dual-layer cells to remove minor defects. Figure 4 shows the distribution of light absorption across different layers.

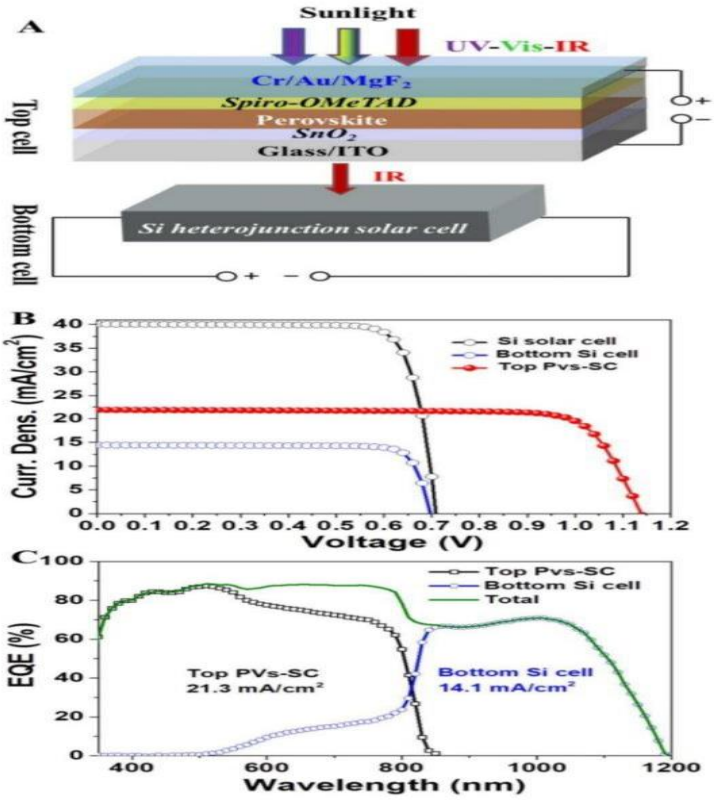


Fig(4): Distribution of light absorption in different layers.

While Yang and colleagues' 2021[55] work used modifications to the transparent layers and electrodes to achieve 28.3% efficiency, Qiu and colleagues' 2018 study demonstrated that strengthening the top absorber layer in perovskite/silicon cells raised efficiency to more than 22%. Both investigations' absorption curves for varying thicknesses are displayed in Figures 5 and 6, which highlight how essential layer characteristics and material choice are to the result.



Fig(5): Absorption curves for each different thickness.[27]



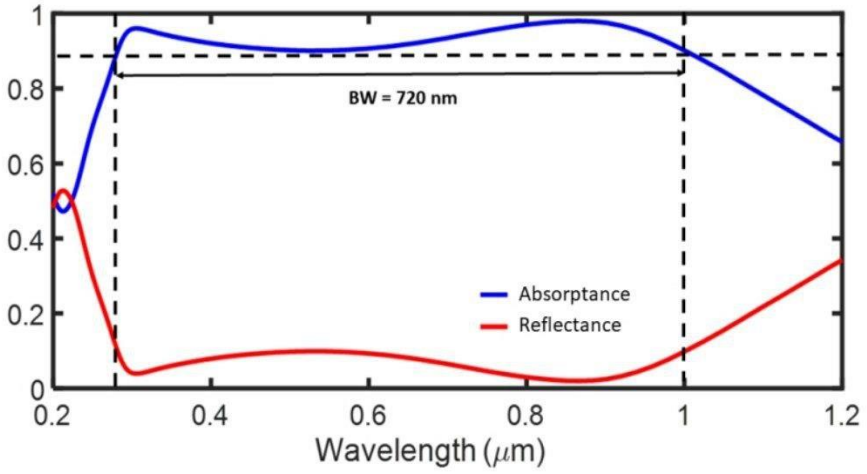
Fig(6): Absorption curves for each different thickness.[56]

Sami and colleagues' 2025 study [57] in the field of lead-free cells demonstrated that the conventional Shaughley-Queisser limit was overcome by using plasmonic nanostructures in hybrid perovskite/silicon cells. Spectral simulation and photometric analysis were used to assess the performance, which showed the possibility of increasing efficiency through better material qualities. Acchutharaman and associates' 2021 study [58] likewise concentrated on using hydrolyzed TiO_2 nanoparticles to enhance electron collecting.

However, a 2021 study by Manzhos and associates [59] showed that by mimicking the plasmonic characteristics of nanoparticles, enhanced spectrum performance might be achieved. Cheng and colleagues' 2018 study [60] demonstrated that improving the materials' molecular structure resulted in higher stability and efficiency for non-fluorescent receptor-based organic cells. While Chen and colleagues' 2024 study [61] focused on electron beam engineering in perovskite quantum crystals to improve performance, the study used J-V measurement and absorption spectroscopy to assess performance; the 2023 study [62] by Liu and associates concentrated on cells that are recoverable and bendable. The study's Figure 4 demonstrated how the layers might be adjusted to provide considerable flexibility without sacrificing effectiveness. Absorption spectroscopy and J-V measurements were employed in the study to assess performance under different circumstances. The 2022 study by Mishra and associates [63] looked at solution-treated thin-film cells for usage indoors in low light.

However, a 2022 study by Macdonald and colleagues [64] showed how phosphorene nanosheets might be employed in future energy devices, while a 2023 study by Nam and colleagues [65] concentrated on using new fluorinyl in thin layers to improve charge and conductivity. The 2020 study by Kim and colleagues [66] also showed that enhanced stability and efficiency were achieved at the cell interface by the use of self-assembled monolayers as tailored materials. However, a study conducted in 2025 by Mondal and associates [67] showed that large-scale plasmonic structures improved absorption in thin-film solar cells. The 2021 study by Singh and associates [68] included a thorough analysis of contemporary materials and technologies in PV cells, emphasizing the connection between the efficiency

attained and the kind of materials and technologies employed. Figures 7 illustrate how efficiency changes over time under typical settings and shows how cell efficiency changes over time under normal operating conditions. Efficiency gradually declines due to the effects of temperature and humidity, which illustrates the stability problem., despite Babics and colleagues' 2023 work showing that perovskite/silicon dual cells operated outside for a year with good efficiency stability.



Fig(7): Efficiency change under normal conditions.[20]

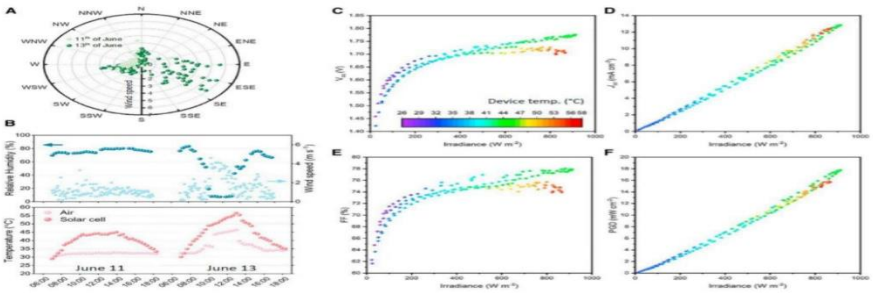


Fig (8): Perovskite/silicon cells after a year of operation outside the laboratory.

Figure (8) demonstrates the performance of the cells after one year of outdoor operation. Despite some decline, efficiency remained relatively stable, indicating improved materials and technologies for resisting environmental conditions.It is evident from comparing several studies that the primary causes of the variations in efficiency are the kinds of materials employed, layer thickness, nano-modifications, and electrical interface engineering techniques. While experiments that focused on minor layer thickness improvements or the use of restricted nanomaterials demonstrated lesser efficiency gains, studies that used flexible and dual-layer hybrid cells supplemented with plasmonic nanoparticles produced the best efficiencies. Accurate comparison between various technologies and designs was made possible by the evaluation of performance under different conditions using a variety of measurement techniques, including J-V, absorption spectroscopy, and spectral simulations.

3.7 Challenges and Innovations

Perovskite cells and perovskite/silicon hybrid cells are examples of next-generation solar cells that confront major obstacles in terms of industrial scalability, production costs, and long-

term stability. According to a study by Babics et al, which tracked the performance of outdoor cells for a whole year and noted some minor changes in efficiency despite overall stable performance, perovskite cells are sensitive to temperature and humidity, which causes the active layers to decompose over time.

However, a study by Liu et al. demonstrated that to maintain performance during repeated and continuous bending, bendable cells must enhance their mechanical stability. Cost-wise, the production of hybrid and dual cells frequently necessitates sophisticated materials and exacting technology. Research by Sun et al and Kumar et al has demonstrated that sophisticated procedures like double coating, layer thickness control, and enhanced homogeneity through simulation considerably raise production costs. Because of the materials themselves and the exact integration techniques needed, the employment of gold and plasmonic nanoparticles, as in the studies of Mahmoud & Z J and Sami et al [68], further raises the cost.

Regarding industrial growth, research has indicated that high-performance cells frequently have dimension and mass production limitations since they necessitate exact control over layer thickness, nanomaterial distribution, Coating techniques, such those demonstrated by Qiu et al. [69] and Er-Raji et al [70], present a challenge to manufacturing on an industrial scale. The integration of plasmonic nanoparticles with thin films necessitates specialized equipment, which restricts the rate of industrial expansion, as demonstrated by Mondal et al [71]

These studies demonstrate that increasing stability requires the creation of heat- and moisture-resistant materials, that increasing cost requires the use of affordable alternatives to complex nanomaterials, and that reaching industrial scale requires simplifying manufacturing processes and maintaining standardization and efficiency in large-scale production. Table 2 summarizes the solutions and challenges proposed in recent studies on solar cells.

Table (2): Summary of proposed solutions and challenges in recent studies on solar cells.

Sr.No.	Challenge	Proposed solutions
1	The high cost of nanomaterials and the difficulty of industrial expansion	Introducing gold nanorods to improve light absorption and increase efficiency.
2	High cost of materials and fine-layer manufacturing	Development of non-fluorescent receptors to improve performance and stability
3	Difficulty of controlling crystal quality on an industrial scale	Electron beam engineering in perovskite quantum crystals to improve performance
4	Difficulty of industrial expansion and maintaining efficiency under flex	Development of flexible monocrystalline cells with improved electronic conductivity
5	Precise layer control in large production	Use double coating and improve the homogeneity of the layers.
6	The high cost of complex technology and the difficulty of industrial production	Advanced simulation to address manufacturing

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Sr.No.	Challenge	Proposed solutions
		challenges
7	High cost and challenges in industrial expansion	Improving materials and manufacturing techniques to increase performance
8	High material costs and difficulty integrating into mass production	Design of plasmonic structures to enhance absorption and exceed the Shaughley-Queisser limit
9	The need for specialized equipment	Incorporating large-scale plasmonic structures to enhance absorption
10	Difficulty controlling the distribution of materials on an industrial scale	Using nanomaterials to improve charge collection
11	Maintain thermal and mechanical stability during use.	Flexible, bendable materials for better mechanical stability
12	Limited performance under outdoor lighting and high material cost	Treating thin cells with solutions to enhance internal performance
13	Cost of materials and difficulty of industrial expansion	Using TiO2 nanoparticles to improve performance
14	Difficulty of accurately applying simulation models to large-scale production	Simulating plasmonic properties to improve spectral performance
15	Challenges of industrial-scale manufacturing and high costs	Use of fluorinyl within thin layers to enhance conductivity
16	Layer quality control and high cost	Self-assembling monolayers to improve cell interface
17	Challenges of industrial production and long-term stability	Using phosphorene nanosheets to improve electron collection
18	Difficulty of industrial expansion and control of homogeneous absorption	Improve the thickness and properties of transparent layers
19	Difficulty of manufacturing electrodes on an industrial scale	Improving transparent electrodes for better efficiency
20	Maintain long-term efficiency under different environmental conditions	Study of outdoor operational stability and improvement of moisture-resistant materials

MXenes and Hybrid Materials

Because of their high conductivity and adjustable surface chemistry, MXenes (such as TiC_2Tx) allow for better charge extraction and interface engineering. PCE values of approximately 22–24% are reported in MXene-modified perovskite devices in recent studies (2023–2025). Similarly, although long-term degradation is still unknown, organic–inorganic hybrids have stability benefits. Risks (ROS generation, Pb poisoning) are highlighted by nanotoxicity studies; nonetheless, in photovoltaics, these worries result in regulatory and commercialization obstacles. For instance, a significant barrier to widespread use of perovskite devices is lead leakage, necessitating encapsulation or lead-free substitutes.

While some perovskite/silicon tandems degrade quickly outside, others exhibit >28% steady efficiency. The necessity for uniform benchmarks is highlighted by the variations that result from encapsulation techniques, electrode stability, and ISOS testing circumstances.

3.8 Nomenclature

For the purpose of uniformity and clarity, the following abbreviations are used throughout this work.

Table(3):List of Abbreviations and Acronyms.

Abbreviation	Full Term
PCE	Power Conversion Efficiency
Voc	Open Circuit Voltage
Jsc	Short Circuit Current Density
FF	Fill Factor
NP	Nanoparticle

4. Conclusion

With tandem perovskite/Si devices reaching around 30% PCE, this research shows that combining nanomaterials like perovskites, QDs, MXenes, and plasmonic structures allows for notable efficiency advances in solar cells. However, there are still issues with scalability, cost, and stability in real-world scenarios. This work emphasizes the pressing need for scalable lead-free chemistry and repeatable measures by mapping conflicting data across research and pointing out weaknesses in standardized stability testing (ISOS). Our synthesis helps close the gap between lab and market in solar technology by providing a roadmap of research goals, ranging from low-cost production to AI-driven materials design.

Even though a lot of papers emphasize record efficiencies of 25–30%, translation and repeatability are still uneven. Cross-comparison is made more difficult by the fact that different studies frequently use different encapsulation techniques, testing procedures, and light sources. Some perovskite/silicon tandems, for example, exhibit outstanding stability for a year (Babics et al., 2023), but others break down quickly in the presence of comparable humidity. These inconsistencies highlight the necessity of open-access databases and standardized ISOS methods to verify stability claims.

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