International Journal of Advanced Research and Multidisciplinary Trends (IJARMT)
An International Open Access, Peer-Reviewed Refereed Journal
Impact Factor: 7.2 Website: https://ijarmt.com ISSN No.: 3048-9458

Exploring the Role of Nanomaterials in Improving Solar Cell Efficiency

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Abstract
Despite the fact that solar PV technology plays a key role in the global shift to renewable energy, the power conversion efficiency (PCE) of traditional silicon-based PV cells is limited by inherent optical and electronic losses, including the Shockley–Queisser limit. In the last ten years, the use of light trapping, light absorption, charge separation and charge transport nanomaterials, such as quantum dots, perovskite nanocrystals, carbon nanotubes, graphene, plasmonic nanoparticles and nanostructured metal oxides, have been identified as a promising way to address these challenges. In this paper, the potential of utilizing nanomaterials to enhance solar cell efficiency is investigated by critically reviewing and analyzing secondary information obtained from peer-reviewed journals and publications from 2018 to 2025. The paper compares efficiency data from three types of quantum-dot sensitised solar cell, perovskite solar cell, dye-sensitised solar cell, and carbon-nanomaterial based solar cell, and puts these in perspective with the efficiency data for conventional silicon solar cells. Results suggest that the incorporation of nanomaterials has led to measurable improvements in efficiency over the years, with perovskite solar cells increasing from less than four percent in power conversion efficiency to more than twenty-five percent in just about a decade, and has imposed novel challenges in long-term stability, environmental toxicity and scalable manufacturing. The paper notes that nanomaterials hold the promise of a truly promising but still developing route towards next-generation PV, though further research is needed in the areas of durability, encapsulation, and cost-effective fabrication that will make it viable to enter into more widespread commercialization.

Keywords: nanomaterials, solar cell efficiency, perovskite, quantum dots, carbon nanotubes, photovoltaics, renewable energy

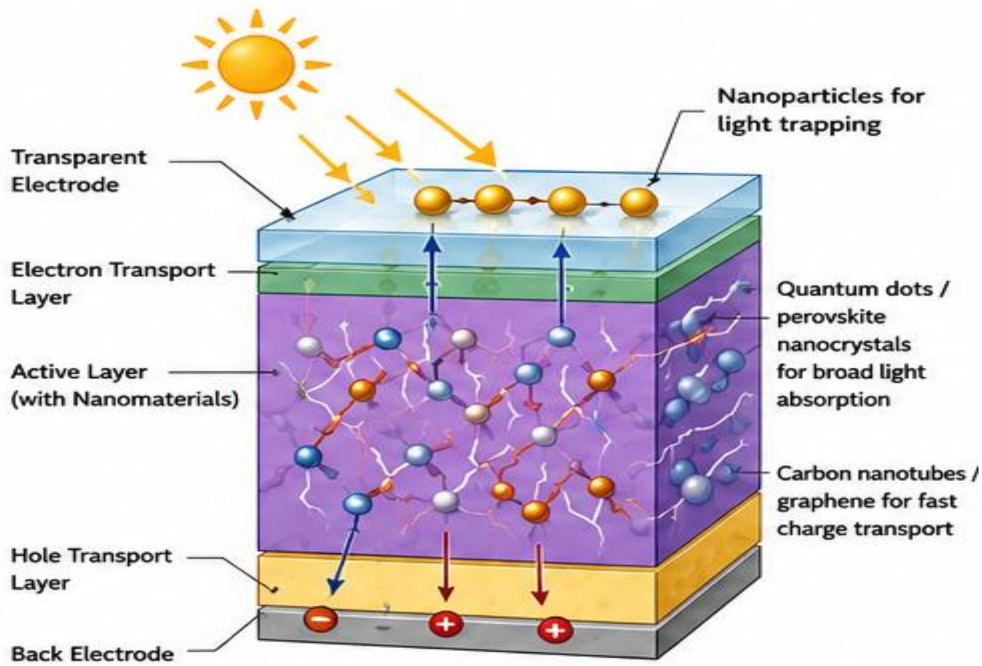
1. Introduction

1.1 Background of Solar Energy and Photovoltaic Technology

The direct conversion of solar energy into electricity using PV technology is one of the most rapidly expanding electricity generation technologies in the world, and solar is the most plentiful renewable resource at the disposal of humans. Commercial PV industry is dominated by crystalline silicon due to its availability, industrialization and long term reliability. Silicon based single-junction cells, however, have a fundamental efficiency limit of around thirty-three per cent under standard illumination, and in practice, commercial modules will not perform above about twenty-three per cent once optical reflection, thermalisation and recombination losses are considered (Green, 2016). With the rise of electricity demand and the need for decarbonisation globally, incremental improvements of conventional silicon technology are becoming increasingly seen as inadequate and there has been continued interest in materials and device architectures that can deliver efficiency and cost performance beyond that of first generation PV (Green et al., 2021).

The image illustrates how nanomaterials improve the performance of a multilayer solar cell. Incident sunlight enters through the transparent electrode, while nanoparticles placed near the upper surface enhance light trapping and reduce reflection losses. Quantum dots and perovskite nanocrystals in the active layer broaden the absorption range, allowing the device to capture a larger portion of the solar spectrum.

Image 1: *Role of Nanomaterial in Enhancing Solar Cell Efficiency*



The electron transport layer transfers generated electrons toward the transparent electrode, whereas the hole transport layer carries positive charges toward the back electrode. Carbon nanotubes and graphene further improve charge mobility and reduce recombination losses. Thus, the combined use of nanomaterials enhances light absorption, charge separation, and charge transport, ultimately increasing the power conversion efficiency of solar cells.

1.2 The Emergence of Nanotechnology in Photovoltaics

Nanotechnology, which involves controlling matter at scales usually less than 100 nanometres, has given rise to new opportunities for PV design in exploiting phenomena which are not seen in bulk materials, like quantum confinement, surface plasmon resonance, and extremely high surface-area-to-volume ratios. Nanotechnology can be used to tune engineered nanomaterials to absorb specific wavelengths of light, to carry charge carriers without recombination losses and to deposit them by low-cost solution-based processing methods instead of energy-intensive methods of vacuum deposition (Tanabe, 2022). This has created third and fourth generation PV based on quantum dot PV cells, perovskite PV cells, dye-sensitised PV cells and hybrid PV cells that incorporate carbon-based nanostructures like graphene and carbon nanotubes as functional PV layers in the cell stack.

1.3 Problem Statement

Although conventional silicon-based photovoltaics have been refined over decades, the improvements in efficiency that can be achieved with these technologies have now reached a plateau, and the latest confirmed efficiency tables for the most common silicon single-junction technologies indicate only minor increases in efficiency relative to the previous year (Green et al., 2021). Meanwhile, other materials that have the potential to outperform such limits, such as perovskites and quantum dots, still have a number of unsolved problems of operational stability, degradation in the presence of heat and moisture, and the use of toxic or rare elements. The research therefore requires a systematic study of the use of nanomaterials in various architectures of solar cells, the efficiency that they have shown in the literature, and the obstacles that must be overcome in order to be able to transfer the improvements to viable products.

1.4 Objectives of the Study

This research has four major objectives. First, it targets the main classes of nanomaterials being explored for solar cell applications such as quantum dots, perovskite nanocrystals, plasmonic metal nanoparticles, metal-oxide nanostructures, and carbon-based nanomaterials. Second, it aims to gather and compare secondary efficiency data from peer-reviewed literature from 2018 to 2025 for nano-enabled solar cells compared to the benchmark cells. Third, it explores the particular physical and chemical processes by which nanomaterials are contributing to the improvement of efficiency, including light trapping, spectral broadening and enhanced charge transport. Fourth, it highlights the major issues that remain to be addressed before the commercialization of PV technologies based on nanomaterials can be achieved, such as stability, toxicity and manufacturing scalability.

1.5 Significance and Scope of the Study

The results of this study will benefit renewable energy researchers looking for an up-to-date summary of efficiency gains and trends in recent years, industry participants who need to determine which nanomaterial technologies are likely to become commercial in the near future, and policy makers who wish to determine where the greatest potential return on investment may lie in the near future. The study will be limited to secondary data based literature review, no original laboratory synthesis and device fabrication. Data presented here are efficiency figures, comparative tables and analytical discussion that have been compiled and summarised from peer-reviewed papers and review papers in the journals and technical literature, mostly published between 2018 and 2025 and in a few cases from the years immediately before this period for historical context. The study is also restricted to secondary data, and therefore can benefit from a much broader sample of device architectures, laboratories, and research settings than can be considered by any single experimental programme, enhancing the generalisability of the comparative patterns identified in the results section. This breadth is not, however, treated as an analytical strength and all reported efficiency and stability numbers are given with reference to the specific conditions under which they were obtained, so that the reader can form his own opinion about the direct comparability of different studies; all reported percentages are not necessarily equal.

2. Literature Review

2.1 Nanomaterials for Light Absorption Enhancement

There is a large literature that explores the possibility of creating nanostructures that absorb a wider range of the sunlight. The bandgap of quantum dots is tunable by the size of the particles (typically 2 to 10 nanometres across) and can be changed by controlling the particle size in their synthesis process. Pan et al. (2018) have comprehensively reviewed quantum-dot-sensitised solar cells (QDSSCs) and described the utilization of various kinds of quantum dots (QDs), including CdS, CdSe, and lead sulfide (PbS), to enable the extension of the light absorption of the photoanode into the near-infrared part of the spectrum, which is otherwise largely unavailable to traditional dye sensitisers. This topic is expanded upon by Sahu, Garg and Dixit (2020), who review the phenomenon of carrier multiplication in quantum-dot systems in which a single absorbed photon can produce more than one electron–hole pair, which is theoretically capable of bringing the efficiencies in quantum-dot-based devices beyond the Shockley–Queisser limit of the single-junction devices. Perovskite nanomaterials, however, have been of great interest due to their extremely high absorption coefficients and defect tolerance. In the theoretical analysis of halide perovskite materials, provided by Yin et al. (2015), the electronic structure of those compounds, specifically the antibonding nature of the valence band, gives them a tolerance to the presence of point defects, atypical for photovoltaic absorbers, which is partly responsible for the swift efficiency improvements in perovskite devices since their inception.

Image 2: *Types of Nanomaterials Used in Solar Cells and their Functions*

Nanomaterial	Function in Solar Cells
Quantum Dots (QDs)	• Size-tunable bandgap • Broad-spectrum absorption • Multiple exciton generation
Perovskite Nanocrystals	• High absorption coefficient • Long carrier diffusion length • High power conversion efficiency
Graphene	• Excellent electrical conductivity • Transparent electrode material • Facilitates fast charge transport
Carbon Nanotubes (CNTs)	• High carrier mobility • Improves charge extraction • Enhances mechanical stability
Metal Oxide Nanostructures (TiO_2, ZnO, SnO_2)	• High electron mobility • Large surface area • Improves dye/perovskite loading and separation
Plasmonic Metal Nanoparticles (Au, Ag, Al)	• Surface plasmon resonance • Strong light scattering • Improves light harvesting

Aside from the absorber materials, plasmonic nanostructures made of noble metals like gold and silver are also added to the solar cell architecture to amplify the absorption of incident light and scatter it in the absorbing film, thereby increasing the optical path length without adding more material to the absorber film. This strategy is especially relevant for thin film technologies where the aim is to deliberately reduce the thickness of the materials in order to decrease the costs of the technology, and nanostructured antireflective and light trapping layers, such as moth-eye-inspired surface textures, have been demonstrated to be effective in significantly minimizing reflective losses at the cell surface (Kim, Jang, Choi, Kang, & Choi, 2019).

2.2 Nanostructured Electron and Hole Transport Layers

Another large body of literature is not concerned with the absorption of light, but rather with the materials used to harvest and deliver the electrons and holes to the external contact. Due to their high surface area and the possibility of efficient charge injection, whereas their wide bandgap prevents unwanted recombination at the interface, metal-oxide nanostructures such as titanium dioxide (TiO2) and zinc oxide nanorods, nanowires and mesoporous scaffolds have all been used in dye-sensitised solar cells (DSSCs) and perovskite solar cells (PSCs) as electron transport layers (ETLs). Compositional engineering of the perovskite layer itself has also been found to be essential: Yang et al. (2017) showed that by carefully controlling the amount of iodide present in the film of formamidinium-lead-halide perovskite, it was possible to substantially reduce the formation of trap states, with certified results topping twenty percent in devices where non-radiative recombination losses have previously limited performance. It has been often referred to as a milestone in the research journey from lab curios to making perovskite solar cells competitive with already proven thin film devices.

These developments come at a time when perovskites and related nanostructured devices are steadily improving in efficiency, thanks to iterative improvements in transport-layer optimisation, defect passivation, and interfacial engineering by numerous research groups, as Nayak, Mahesh, Snaith and Cahen (2019) explain. They point out that high absorption coefficients have been key to achieving high measured device efficiencies, but that the nanostructuring has been needed in the transport layers, as well as in the absorber, to overcome the effects of non-radiative recombination losses caused by poorly matched energy levels or high trap densities at the interfaces.

2.3 Carbon-Based Nanomaterials in Solar Cells

Carbon nanomaterials, especially graphene and carbon nanotubes (CNTs), have been widely studied replacing the noble-metal electrodes and organic charge-transport materials typically employed in solar cells with chemically stable materials and at low cost. While the power conversion efficiencies in the graphene thin-film solar cells were modest at the time they were reviewed in 2018, as compared to those of their metal-electrode based counterparts, Shi and Jayatissa (2018) review the use of graphene as front and back contacts and as an active interfacial layer in thin-film solar cells, citing its optical transparency, tunable work function, and mechanical flexibility as factors that make it a promising candidate for both hole-transport and electrode applications. Similarly, Wu et al. (2015)

review the carbon and other alternative electrolyte and electrode materials in dye-sensitised solar cells, emphasizing that other materials, such as carbon-based counter electrodes, can be catalytic with comparable performance to platinum, but at a much lower cost, which is particularly important since the scarcity of platinum has historically been cited as a hindrance to large-scale deployment of dye-sensitised solar cells. Perovskite solar cell research has been focused in particular on carbon nanotubes as a way to enhance the efficiency and operational longevity of the devices. Bati, Yu, Batmunkh, and Shapter (2019) review the applications of sorted single-walled carbon nanotubes in various optoelectronic applications, such as their use as transparent conductive electrodes and as charge-selective layers in perovskite devices, which would face degradation due to moisture and oxygen. Building on this analysis, Habisreutiner and Blackburn (2021) focus their consideration specifically on the use of CNTs in high performance perovskite PV devices, where they have been shown to not only allow for competitive efficiency, but to also significantly enhance thermal and environmental stability of the devices, making carbon nanotubes one of the more commercial viable classes of nanomaterials for stabilising next generation PV devices beyond their maximum efficiency.

2.4 Challenges and Research Gaps

Despite these efficiencies, the literature consistently points to “stability”, “toxicity” and “scalability” as challenges that remain to be addressed for commercialisation. The promises and challenges faced by perovskite solar cells are described in detail by Correa-Baena et al. (2017) who note that the highest efficiency cells of the literature have been produced in small laboratory-scale devices in controlled atmospheric conditions, and that the typical scaling problem of reduced efficiency with increased device area is observed for perovskite cells, as reported by Khatoon et al. (2023) who state that most high-efficiency perovskite devices in the literature have been fabricated on areas of only 0.01 square centimetres and that maximum demonstrated operational stability at 10,000 hours is significantly lower than the multi-decade lifetimes demanded for crystalline silicon modules. While the most efficient perovskite formulations contain lead, the inclusion of lead adds to the set of concerns regarding the environment and regulation of which a lead-free approach is not a complete solution, as the lead-free perovskites are less efficient and less stable. Scalability issues are more widespread than just for perovskites—nanomaterials in general face these problems. In addition to these challenges, Li (2021) considers the challenges of scaling up laboratory-scale synthesis of nanomaterials to industrially viable, defect-free films at a commercial scale that are required for commercial module production, while Sharma (2021) reviews the larger array of technical and economic hurdles to be overcome that remain between promising laboratory work and bankable commercial thin film products, such as the need to control nanoparticle size distribution, batch-to-batch reproducibility and the costs of specialised thin film deposition equipment. Collectively, this literature indicates that although nanomaterials have clearly shown the ability to improve the efficiency of solar cells, the emphasis in the research has shifted to achieving high efficiency with durability, environmental safety and manufacturability.

Another gap was found in the reviewed sources, which had inconsistent reporting standards between studies. The efficiencies of individual cells are often quoted for active areas that are significantly different, under differing light and humidity conditions, in a single test only, or for conditions where the cell is operated only once. As a result, it is not possible to directly, like-for-like compare data across studies, and several authors, such as Nayak et al. (2019), explicitly have called for increased consistency in reporting efficiency and degradation data, in order to more reliably be able to discern genuine technological advances from favourable but unrepresentative testing conditions. This methodological issue directly affected the methodological orientation adopted in the present study, where the numbers reported are viewed as representative values, but not strictly equal across sources.

3. Research Methodology

This study is not experimental; it is not based on primary data, but on secondary data. The aim was not to synthesize or test new nanomaterials but to systematically collect, compare and analyze already published and peer-reviewed data on the power conversion efficiency and other performance metrics of nanomaterials. This design was felt to be appropriate because of the diversity of classes and types of devices that were being considered, and because the field of nanomaterials has a large and growing number of published data studies from which meaningful comparative patterns could be drawn, and which would not be possible to replicate experimentally within the scope of a single study.

Peer-reviewed journal articles, review papers and editorial overviews retrieved from the major academic databases such as ScienceDirect, Springer Nature, MDPI journals, American Chemical Society publication suite and the American Chemical Society Frontiers journals were used for the data acquisition, along with efficiency benchmarks published by the National Renewable Energy Laboratory (NREL, 2024). The search strategy included the following keywords: nanomaterials, solar cell efficiency, perovskite, quantum dot, carbon nanotube and photovoltaic in the title, abstract, and keywords. The review focused on works from the last seven years (published between 2018 and 2025) to prioritise currency of efficiency data, and in a few cases, older foundational studies (after 2015) were included where they had provided theoretical background for more recent empirical findings – for example, early theoretical research on perovskite defect tolerance. The following three criteria were used for selecting the sources: First, study reported quantitative power conversion efficiency, stability or similar performance data for a solar cell that uses a nanomaterial, or enhanced with such a material; Second, study was published in peer-reviewed journal or recognised technical database; Third, sufficient details were provided in the study to place the reported figures within a specific device architecture and nanomaterial family. The data collected from the sources that met the criteria comprised nominal or certified power conversion efficiency data, the nanomaterial and device architecture reported, the year of publication, and, if reported or certified, a qualitative or quantitative measure of the device's operational stability, e.g., hours of continuous operation before observed efficiency loss.

Extracted data were later organized thematically, into five comparative tables, corresponding to the first, the second, the third, the fourth, and the fifth sets of data, respectively, concerning the historical

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timeline of efficiency milestones related to nanomaterials, the classification of nanomaterials by functional role within the device stack, the reported range of efficiencies by category of solar cell, a comparative evaluation of advantages and limitations across nanomaterial types, and reported indicators of stability and durability. The aim of this thematic organisation was to enable patterns to be identified in studies which may not have been able to be directly compared in other ways, due to the different experimental set-ups and reporting conventions. As with any secondary data-based study, a major drawback of this approach is that the efficiency values reported in this study have not been independently verified and are likely to represent idealised laboratory conditions, small device areas, or non-standardised tests, which is discussed in detail when considering the values obtained and is treated as a finding rather than a caveat.

4. Results

The following section presents the secondary data compiled for this study across five thematic tables, drawing on efficiency figures and comparative performance data reported in the literature reviewed above, spanning approximately 2018 to 2025.

4.1 Timeline of Nanomaterial-Related Efficiency Milestones

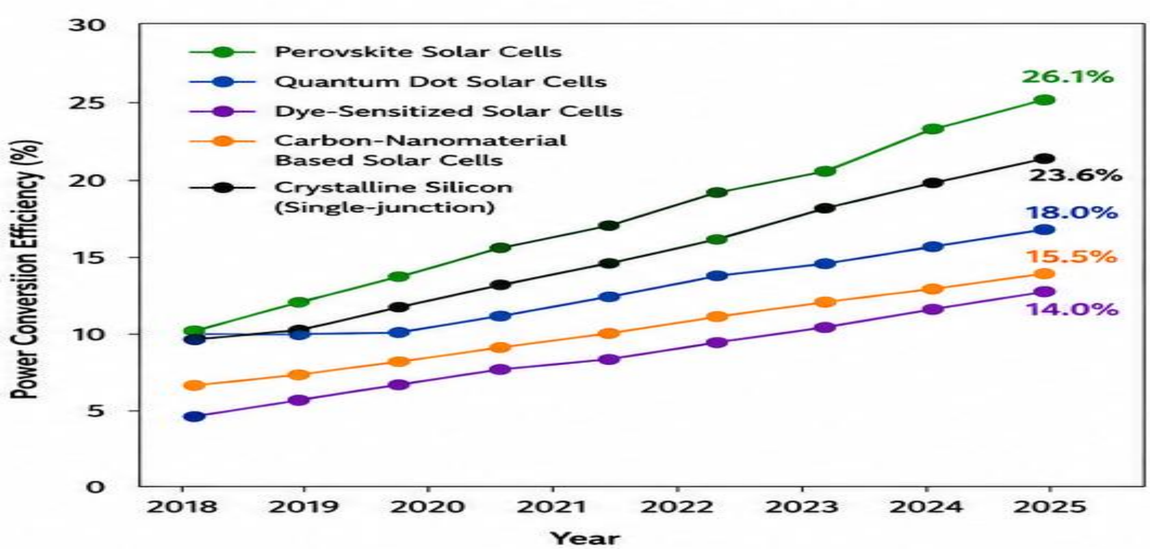
Table 1 lists the important efficiency achievements for the nanomaterial-based solar cell technologies for the time period of this study. The data show that perovskite-based devices have exhibited the most dramatic efficiency trajectory of any nanomaterial-enhanced technology, whereas carbon-nanomaterial-based devices have recorded comparatively steady and incremental efficiencies, with as much emphasis as possible on stability.

Year	Technology	Reported Efficiency	Source
2018	Quantum-dot-sensitised solar cell (Pb-based colloidal QDs)	~13% (up from ~3% eight years earlier)	Sahu, Garg, & Dixit (2020)
2018	Graphene-incorporated bulk-heterojunction thin-film cells	0.5%–3% (device dependent)	Shi & Jayatissa (2018)
2019	CdTe solar cell with nanostructured back layer	22.62% (up from 16.04% baseline)	State-of-the-Art Nanomaterials review (2024)

Year	Technology	Reported Efficiency	Source
2019	Moth-eye nanostructured antireflective perovskite cell	Improved light absorption vs. planar control	Kim, Jang, Choi, Kang, & Choi (2019)
2017–2019	CNT- and graphene-electrode inverted perovskite cells	12.8% (CNT) and 14.2% (graphene) vs. 17.8% (ITO control)	Habisreutinger & Blackburn (2021)
2021	MWCNT-doped TiO_2 electron transport layer perovskite cell	21.4%	Recent CNT-in-perovskite reviews (2021–2024)
2023	Perovskite solar cell (laboratory record, small area)	25.7% (up from 3.8% in 2009)	Khatoon et al. (2023)
2024–2025	Silicon single-junction commercial modules (benchmark)	~22–23% (mature, near-plateau)	NREL (2024); Green et al. (2021)

Table 1. Timeline of reported efficiency milestones for nanomaterial-based solar cells, 2018–2025 (secondary data compiled from cited sources).

Image 3: *Efficiency Progress of Nano-Enabled Solar Cells (2018-2025) vs. Silicon Cells*



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4.2 Classification of Nanomaterials by Functional Role

Table 2 classifies the major types of nanomaterials reviewed in this work based on their main function in the PV device stack as light absorption materials, charge transport materials, and electrode or interfacial materials.

Nanomaterial Type	Primary Function	Representative Application
Quantum dots (CdS, CdSe, PbS)	Light absorption / spectral broadening	Quantum-dot-sensitised photoanodes; carrier multiplication (Pan et al., 2018)
Perovskite nanocrystals	Light absorption / defect-tolerant absorber	Thin-film perovskite absorber layers (Yin et al., 2015; Jena et al., 2019)
Metal-oxide nanostructures (TiO2, ZnO)	Electron transport layer	Mesoporous scaffolds in DSSCs and perovskite cells
Plasmonic metal nanoparticles (Au, Ag)	Light trapping / scattering	Thin-film absorption enhancement layers
Graphene	Transparent electrode / hole-transport layer	Front and back contacts in thin-film cells (Shi & Jayatissa, 2018)
Carbon nanotubes (SWCNTs, MWCNTs)	Electrode / charge-selective and stabilising layer	Perovskite top electrodes and ETL dopants (Bati et al., 2019; Habisreutinger & Blackburn, 2021)
Nanostructured antireflective coatings	Optical loss reduction	Moth-eye and textured surface layers (Kim et al., 2019)

Table 2. Classification of nanomaterials by primary functional role in solar cell devices (secondary data compiled from cited sources).

4.3 Reported Power Conversion Efficiency by Solar Cell Category

Table 3 shows the estimated range of the power conversion efficiencies reported for the various types of nanomaterial-based solar cells compared to the best value of crystalline silicon cells, as reported in the literature from 2018 to 2025.

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Solar Cell Category	Reported PCE Range	Key Comparative Notes
Crystalline silicon (benchmark)	~20–23%	Mature technology; near-plateau efficiency gains (Green et al., 2021)
Perovskite (lab-scale)	20–25.7%	Highest reported gains of any nanomaterial category; area- and stability-limited (Khatoon et al., 2023)
Quantum-dot-sensitised	~10–13%	Strong absorption tunability; efficiency still below silicon (Sahu et al., 2020)
Dye-sensitised (carbon-based counter electrodes)	~6.8–9.3%	Carbon nanomaterials approach platinum-level catalytic performance at lower cost (Wu et al., 2015)
Carbon-nanotube / graphene-electrode perovskite	12.8–21.4%	Efficiency trade-off offset by improved environmental stability (Habisreutinger & Blackburn, 2021)
Graphene thin-film heterojunction (early-stage)	0.5–3%	Still developmental; limited by interfacial binding challenges (Shi & Jayatissa, 2018)

Table 3. Reported power conversion efficiency (PCE) ranges by solar cell category, based on secondary data from cited literature, 2018–2025.

4.4 Comparative Advantages and Limitations of Nanomaterial Types

Table 4 summarises the benefits and drawbacks commonly reported in the literature for the major classes of nanomaterials, and indicates that no single class of nanomaterials is clearly superior on all of the performance measures at this time.

Nanomaterial Category	Key Advantages	Key Limitations
Quantum dots	Tunable bandgap; potential carrier multiplication above Shockley–Queisser limit	Toxic heavy-metal content (Cd, Pb); lower efficiency than perovskites (Sahu et al., 2020)
Perovskite nanocrystals	Very high absorption coefficient; rapid efficiency gains; low-cost solution processing	Poor moisture/thermal stability; lead toxicity; efficiency drops sharply with device area (Correa-Baena et al., 2017)

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Nanomaterial Category	Key Advantages	Key Limitations
Metal-oxide nanostructures	Chemically stable; high surface area for charge injection	Can introduce interfacial trap states if poorly engineered
Plasmonic nanoparticles	Enhances light trapping without added film thickness	Noble-metal cost; potential parasitic absorption
Graphene	Highly transparent, conductive, flexible	Difficult large-area synthesis; interfacial binding still limited (Shi & Jayatissa, 2018)
Carbon nanotubes	Chemically inert; improves stability under humidity/oxygen exposure; low cost vs. noble metals	Efficiency still generally trails gold-electrode devices; dispersion/uniformity control needed (Bati et al., 2019)

Table 4. Comparative advantages and limitations of major nanomaterial categories used in solar cells (secondary data synthesis).

4.5 Reported Stability and Durability Indicators

The reported stability indicators, which are usually reported as the number of hours of continuous device operation before the efficiency drops significantly, are presented in Table 5 and are generally recognized as a key metric to balance the high efficiency values of the literature when assessing the potential for commercialization of these nanomaterial-based solar cells.

Solar Cell Category	Reported Stability Indicator	Source / Notes
Crystalline silicon	Multi-decade (20–30+ years) module lifetime	Industry benchmark; not directly comparable to lab-scale nanomaterial cells
Perovskite (unencapsulated, lab-scale)	Up to ~10,000 hours under best reported conditions	Khatoon et al. (2023); considered low relative to silicon
Carbon-nanotube-electrode perovskite	Improved resistance to humidity/oxygen relative to metal-electrode cells	Habisreutinger & Blackburn (2021)

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Solar Cell Category	Reported Stability Indicator	Source / Notes
Graphene-electrode perovskite	Improved chemical stability enabling ambient-air fabrication	Shi & Jayatissa (2018)
Quantum-dot-sensitised	Stability strongly dependent on surface passivation quality	Pan et al. (2018)

Table 5. Reported stability and durability indicators for nanomaterial-based solar cells, based on secondary data from cited literature.

Overall, there is a pattern of improvements in achievable power conversion efficiency of solar cells across the five tables presented that has been demonstrated for nanomaterials; in the case of perovskite technologies, the improvements are significant, but not proportionate gains in operational stability have been demonstrated. As efficiency is not the name of the game, but stability is, as the carbon-based nanomaterials are not really seen as a means to get more efficient, but as a way to make the devices more stable, it is likely that in the future, high-performance devices will have multiple types of nanomaterials: perovskite or quantum-dot absorbers for efficiency, carbon-nanomaterial electrodes and transport layers for stability.

5. Conclusion

This paper aimed to structure a secondary data-driven review of the peer-reviewed literature from the last decade—mainly from 2018 to 2025—and investigate the role of nanomaterials in the efficiency enhancement of solar cells. The evidence presented in the five comparative tables shows that the nanomaterials, ranging from quantum dots, perovskite nanocrystals, plasmonic metal nanoparticles, nanostructured metal oxides to carbon-based materials like graphene and carbon nanotubes, have collectively led to some of the biggest efficiency advances in PV research over the last decade. Perovskite solar cells, especially, have come a long way from efficiencies of a few percent to over 25% for lab-scale devices, with a lot of this being achieved by nanoscale engineering of the absorber layer and its surrounding transport and interfacial layers.

The results also highlight that efficiency as a measure of technological readiness is not sufficient. In almost all the nanomaterial types considered, researchers note that the quest for higher peak power conversion efficiencies is always accompanied by the need for high operational stability, as well as issues of toxicity of the absorber materials based on heavy metals, scaling up the synthesis of the nanomaterials to commercially viable device sizes, and the cost and reproducibility of precise nanostructure fabrication. However, coming out from this review is that carbon-based nanomaterials, particularly carbon nanotubes, are not necessarily a path to record efficiency, but instead they are a promising strategy for making other high efficiency, but environmentally not robust enough, absorber materials more environmentally robust; that is, the most likely path forward in the near term is toward hybrid architectures that incorporate complementary classes of nanomaterials as opposed to a single material system.

The results offer a guide to future research focusing on defect passivation, encapsulation technology, and absorber formulations consisting of lead-free or less-toxic materials that can maintain the efficiency benefits that are desirable in nanomaterials, but that present other challenges. The findings argue for selective application of nanomaterials in near-term commercial deployment (e.g., within other established silicon technologies, such as those of the electrod or the transport layer) rather than complete replacement of conventional silicon device technology. It would be useful to have a greater degree of consistency in measuring efficiency and stability across studies when using secondary data, as some of these data reviewed here undergo a variety of testing conditions and device areas, making direct comparisons difficult. In conclusion, whereas nanomaterials seem to be a cornerstone of PV innovation, they will need to be able to overcome the efficiency-stability-scalability challenge outlined throughout this review to truly become a major contributor to PV commercialization at scale.

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