Research Article

Open Access

A review of nanomaterials for enhancing solar energy conversion efficiency

Abstract

The escalating global energy demand and the pressing concerns over climate change have catalyzed intensive research into renewable energy technologies, with solar energy emerging as a leading contender. The efficiency of solar energy conversion, however, remains a critical bottleneck for its widespread adoption. Nanotechnology has surfaced as a transformative field, offering unprecedented opportunities to surmount the limitations of conventional solar cell technologies. This comprehensive review elucidates the pivotal role of various nanomaterials in enhancing the efficiency of solar energy conversion. We delve into the fundamental principles and mechanisms by which nanomaterials, including plasmonic nanoparticles, quantum dots, nanowires, carbon nanotubes, and graphene, enhance light absorption, charge generation, separation, and transport in photovoltaic devices. The review explores the application of these nanomaterials across a spectrum of solar cell architectures, from established silicon-based cells to next-generation perovskite, organic, and dye-sensitized solar cells. Furthermore, we critically analyze the current challenges —material stability, large-scale manufacturing, and potential environmental implications —that impede the commercialization of nanomaterial-enhanced solar cells. Finally, we provide a forward-looking perspective on the future research directions and prospects of nanotechnology in paving the way for a more efficient and sustainable solar-powered future.

Keywords: nanomaterials, solar energy, conversion efficiency, photovoltaics, nanotechnology, quantum dots, plasmonic nanoparticles, nanowires, carbon nanotubes, graphene

Volume 10 Issue 1 - 2026

Al-Mahmud Al-Mamun
Department of Computer Science and Engineering, Islamic University, Bangladesh

Correspondence: Al-Mahmud Al-Mamun, Department of Computer Science and Engineering, Islamic University, Bangladesh, Tel +880 1813-819133

Received: January 06, 2025 | **Published:** January 15, 2026

Abbreviations: PV, photovoltaic; LSPR, plasmon resonance; QDs, quantum dots; excitons, electron-hole pairs; MEG, multiple exciton generation; DSSCs, dye-sensitized solar cells; CNTs, carbon nanotubes; TCEs, transparent conductive electrodes; ITO, indium tin oxide; PSCs, perovskite solar cells; OSCs, organic solar cells; TiO_2, titanium dioxide; ZnO, zinc oxide; Al_2O_3, aluminum oxide

Introduction

The sun provides the Earth with an abundant and inexhaustible source of clean energy. Harnessing this energy effectively is paramount to mitigating the adverse effects of climate change and ensuring a sustainable energy future. Photovoltaic (PV) technology, which directly converts sunlight into electricity, stands at the forefront of this endeavor. However, the efficiency and cost of conventional silicon-based solar cells face inherent limitations. Nanotechnology, the manipulation of matter at the atomic and molecular scale, has emerged as a revolutionary approach to overcoming these limitations and unlocking the full potential of solar energy.

Nanomaterials, materials with at least one dimension in the nanoscale (1-100 nanometers), exhibit unique optical, electrical, and mechanical properties that differ significantly from their bulk counterparts. These novel properties can be harnessed to enhance various aspects of solar cell performance. For instance, the quantum confinement effect in semiconductor nanocrystals, known as quantum dots, allows their bandgap to be tuned to absorb a broader range of the solar spectrum. The localized surface plasmon resonance (LSPR) of metallic nanoparticles can be exploited to enhance light trapping in the active layer of a solar cell, thereby increasing the probability of photon absorption.[1] One-dimensional nanostructures, such as nanowires, can decouple the directions of light absorption and charge-carrier collection, leading to improved efficiency in thin-film solar cells.[2] Furthermore, carbon-based nanomaterials, such as carbon nanotubes and graphene, exhibit exceptional charge-transport properties, facilitating the efficient collection of photogenerated carriers.[3]

This review paper provides a comprehensive overview of recent advancements in applying nanomaterials to enhance solar energy conversion efficiency. We will first discuss the fundamental mechanisms by which nanomaterials improve the performance of solar cells. Subsequently, we will explore the integration of various types of nanomaterials into different solar cell architectures, including silicon-based, thin-film, perovskite, organic, and dye-sensitized solar cells. The challenges associated with the synthesis, large-scale production, long-term stability, and potential environmental impact of these nanomaterials will also be critically examined. Finally, we will conclude with a perspective on the future directions and prospects of nanotechnology in solar energy conversion.

While previous reviews have focused on individual material classes, this article provides a comprehensive comparative analysis of nanomaterial integration across five distinct solar technologies, with a particular emphasis on recent efficiency benchmarks and a critical assessment of environmental safety and manufacturing scalability.

Fundamental mechanisms of nanomaterial-enhanced solar energy conversion

The enhancement of solar cell efficiency through the incorporation of nanomaterials stems from a variety of physical and chemical phenomena that influence light absorption, charge generation, and charge transport. The distinct properties of the most prominent nanomaterials used in photovoltaics are summarized in Table 1. These mechanisms can be broadly categorized into improvements in light harvesting, charge generation and separation, and charge transport and collection. (Table 1)

Table 1 Key nanomaterial types and their intrinsic properties for photovoltaic applications

Nanomaterial type	Representative materials	Key intrinsic property	Primary photovoltaic function
Plasmonic nanoparticles	Gold (Au), Silver (Ag), Aluminum (Al)	Localized Surface Plasmon Resonance (LSPR)	Light Trapping / Absorption Enhancement
Quantum Dots (QDs)	CdSe, CdTe, PbS, InP	Size-tunable bandgap due to quantum confinement	Broadened spectral absorption; Multiple Exciton Generation (MEG)
Semiconductor nanowires	Silicon (Si), Zinc Oxide (ZnO), Gallium Arsenide (GaAs)	High aspect ratio; large surface area	Antireflection; Decoupling light absorption and charge collection
Carbon nanotubes (CNTs)	Single-Walled (SWCNTs), Multi-Walled (MWCNTs)	Exceptional charge carrier mobility; high conductivity	Charge transport pathways; Hole/ Electron extraction layers
Graphene	Single-layer, Multi-layer, Graphene Oxide (GO)	High optical transparency (~97.7%); extremely high carrier mobility	Transparent conducting electrodes; Interfacial layers

Enhanced light absorption

A primary strategy for improving solar cell efficiency is to maximize the absorption of incident sunlight. Nanomaterials offer several unique approaches to achieve this:

Metallic nanoparticles, such as those made of gold (Au) and silver (Ag), exhibit a phenomenon known as localized surface plasmon resonance (LSPR). When light of a specific frequency interacts with these nanoparticles, the collective oscillation of their conduction electrons creates a strong electromagnetic field in their vicinity. This enhanced near-field can significantly increase the absorption of light by a nearby semiconductor material.[4] Furthermore, the scattered light from these nanoparticles can be coupled into the waveguide modes of the solar cell's active layer, effectively increasing the optical path length and the probability of photon absorption.[5] The spectral position of the LSPR can be tuned by controlling the size, shape, and surrounding dielectric environment of the nanoparticles, allowing for the optimization of light trapping across the solar spectrum.[6] This plasmonic enhancement is particularly beneficial for thin-film solar cells, where the active layer is too thin to absorb a significant portion of the incident light. The excitation of higher-order plasmon modes in larger nanoparticles can further enhance the energy transmitted into the active layer.[7]

Dielectric nanoparticles and nanostructures can also be employed to enhance light absorption through scattering. By creating a textured surface with features smaller than the wavelength of light, the reflection of incident sunlight can be significantly reduced. This is a well-established technique in conventional silicon solar cells, in which pyramidal structures are etched into the surface. Nanowire arrays, for instance, have demonstrated exceptionally low reflective losses and can increase the optical path length of incident solar radiation by up to 73 times greater, which is significantly higher than the Lambertian scattering limit.[8] This remarkable light-trapping capability enables the use of thinner absorber layers, which can reduce material costs and improve charge-collection efficiency.[9,10]

Quantum dots (QDs) are semiconductor nanocrystals whose electronic and optical properties are governed by quantum mechanical effects. The bandgap of a quantum dot is dependent on its size; smaller dots have larger band gaps and absorb higher-energy (bluer) light, while larger dots have smaller band gaps and absorb lower-energy (redder) light. This size-tunable bandgap allows for the creation of solar cells that can absorb a broader portion of the solar spectrum. Multi-junction solar cells, which utilize different materials to absorb different parts of the solar spectrum, can be conceptually realized using layers of quantum dots with varying sizes. This approach has the potential to significantly increase the theoretical thermodynamic conversion efficiency of solar photon conversion. Recent advances have seen quantum dot solar cells achieve record efficiencies, positioning them as serious competitors to traditional silicon technologies.[11] (Figure 1)

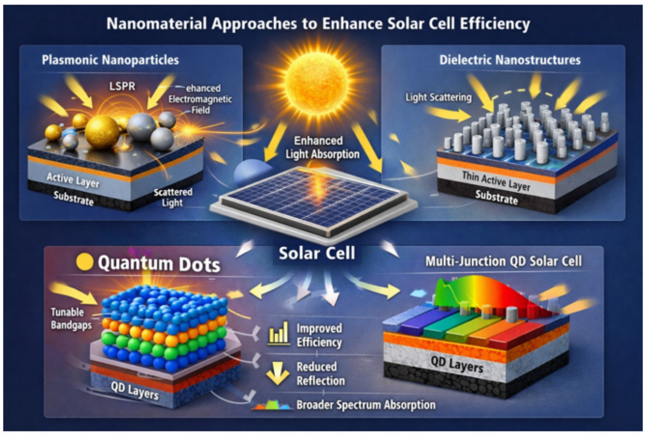

Figure 1 Nanomaterials improving solar cell efficiency.

Improved charge generation and separation

Once photons are absorbed, the next critical step is the efficient generation and separation of electron-hole pairs (excitons). Nanomaterials can play a crucial role in these processes:

In conventional semiconductors, the absorption of a high-energy photon typically results in the creation of a single electron-hole pair, with the excess energy being lost as heat. However, in some quantum dots, a phenomenon known as multiple exciton generation (MEG) can occur. Here, the absorption of a single high-energy photon can generate two or more electron-hole pairs, potentially leading to a significant increase in the photocurrent and overall efficiency of the solar cell. While still an active area of research, MEG offers a promising avenue for overcoming the Shockley-Queisser limit in single-junction solar cells.

The interfaces between layers in a solar cell are crucial for efficient charge separation and recombination prevention. Nanostructured interfaces, with their high surface area, can provide more pathways for charge separation. For instance, in dye-sensitized solar cells (DSSCs), a mesoporous layer of metal oxide nanoparticles provides a large surface area for adsorbing dye molecules, facilitating efficient electron injection from the excited dye into the semiconductor. The use of nanomaterials can also help create more intimate, well-defined interfaces, reducing defect states that can act as recombination centers.

Citation: Al-Mamun AM. A review of nanomaterials for enhancing solar energy conversion efficiency. *Material Sci & Eng.* 2026;10(1):1–6. DOI: 10.15406/mseij.2026.10.00261

Enhanced charge transport and collection

After generation and separation, the charge carriers must be efficiently transported to the respective electrodes for collection. Nanomaterials with excellent electrical conductivity can significantly improve this process:

Carbon nanotubes (CNTs) and graphene, with their exceptional electrical conductivity and high charge carrier mobility, are ideal candidates for enhancing charge transport in solar cells. When incorporated into the active layer or as interlayers, these materials can provide direct pathways for charge carriers to travel to the electrodes, reducing resistive losses and recombination. For instance, multi-walled carbon nanotubes embedded in the perovskite layer of a solar cell can act as "charge transport highways," facilitating the collection of photogenerated holes by the carbon electrode.[3] Similarly, single-walled carbon nanotubes can be incorporated into the hole transport material of perovskite solar cells to facilitate charge transport from the perovskite to the back contact.[12]

Transparent conductive electrodes (TCEs) are essential components of many solar cell designs, allowing light to enter the device while also collecting charge carriers. Indium tin oxide (ITO) is the most commonly used TCE, but it is brittle and expensive. Graphene, with its unique combination of high optical transparency and excellent electrical conductivity, has emerged as a promising alternative.[13] Solution-processed graphene thin films can serve as transparent anodes for organic photovoltaic cells, offering the potential for low-cost, flexible devices.[14] While the sheet resistance of graphene films currently limits the performance of these devices compared to their ITO-based counterparts, ongoing research is focused on improving their conductivity.[15]

Application of nanomaterials in different solar cell technologies

The versatility of nanomaterials allows for their integration into a wide range of solar cell architectures, each benefiting from their unique properties.

Silicon-based solar cells

While crystalline silicon solar cells are the dominant technology in the current market, their efficiency is approaching the theoretical limit. Nanomaterials offer avenues for further performance enhancements and cost reduction.

Nanostructured surfaces can act as highly effective antireflection coatings. For example, arrays of silicon nanowires can significantly suppress light reflection over a broad spectral range, increasing the amount of light that enters the solar cell.

As previously discussed, silicon nanowire arrays are excellent light trappers. By fabricating thin films from ordered arrays of vertical silicon nanowires, researchers have demonstrated a significant increase in the optical path length of incident light.[2] This allows the use of less silicon, which can substantially reduce the cost of solar panels.[9] The radial p-n junction geometry in these nanowire arrays also decouples the directions of light absorption and charge-carrier collection, which is beneficial for materials with short minority-carrier diffusion lengths.[8]

Plasmonic nanoparticles can be incorporated on the surface of silicon solar cells to enhance light absorption. By scattering light into the silicon substrate, these nanoparticles increase the optical path length, particularly for weakly absorbed long-wavelength light.[1] This can lead to a significant enhancement in the short-circuit current of the solar cell.

Quantitative assessments reveal that surface-integrated silver or gold nanoparticles provide an 8–12% enhancement in short-circuit current by increasing the optical path length. In contrast, silicon nanowire arrays reduce surface reflection to less than 5% across a broad spectrum. (Table 2)

Table 2 Nanomaterial integration in silicon-based solar cells

Nanomaterial integration	Specific nanomaterial	Function / Role	Reported benefit
Surface structuring	Silicon Nanowires (SiNWs)	Antireflection and light trapping	Reduces surface reflection to <5% over a broad spectrum.
Surface deposition	Silver (Ag) or Gold (Au) Nanoparticles	Plasmonic scattering to increase optical path length	~8-12% enhancement in short-circuit current (Jsc).
Luminescent downshifting	Europium-doped QDs	Convert UV light into visible light usable by Si	Potential efficiency gain of 1-2% absolute.
Black silicon	Nanotextured Silicon Surface (via etching)	Graded refractive index for ultra-low reflectivity	>99.5% absorption of visible light.

Thin-film solar cells

Thin-film solar cells, which use significantly less active material than conventional silicon cells, are a promising low-cost alternative. However, their efficiency is often limited by incomplete light absorption. Nanomaterials are particularly well-suited to address this challenge.

The incorporation of plasmonic metal nanoparticles is a highly effective strategy to enhance light absorption in thin-film solar cells.[5] By embedding these nanoparticles within or on the surface of the active layer, both near-field enhancement and far-field scattering can be used to increase the optical path length of light within the thin absorber layer.[6] The excitation of higher-order plasmon modes in larger nanoparticles can further enhance the energy transmitted into the active layer.[7]

Thin-film solar cells based on nanowire arrays can overcome the trade-off between light absorption and charge collection. The nanowires' long axis enables efficient light absorption. At the same time, the small radial dimension ensures that photo generated carriers

Citation: Al-Mamun AM. A review of nanomaterials for enhancing solar energy conversion efficiency. *Material Sci & Eng.* 2026;10(1):1–6. DOI: 10.15406/mseij.2026.10.00261

are quickly collected at the p-n junction, reducing recombination losses.

Perovskite solar cells

Perovskite solar cells (PSCs) have emerged as a revolutionary photovoltaic technology, with power conversion efficiencies rapidly approaching those of conventional silicon solar cells.[16] Nanomaterials are playing a crucial role in further improving the efficiency and stability of PSCs.

Carbon nanotubes (CNTs) are being extensively investigated for their potential to enhance charge transport in PSCs. Incorporating single-walled or multi-walled CNTs into the perovskite layer or the charge transport layers can provide efficient pathways for charge extraction and transport, leading to improvements in short-circuit current and overall efficiency.[3,12] CNTs can also help to form a better interface between the perovskite and the electrode, reducing charge recombination.

Graphene is a promising candidate to replace ITO as a transparent electrode in PSCs, offering the potential for flexible, low-cost devices.

Replacing the electron transport layers in PSCs with a thin layer of quantum dots has led to record efficiencies of over 25.6%. The quantum dot layer can also improve the device's operational stability.[11]

Organic solar cells (OSCs)

Organic solar cells, made from carbon-based polymers and small molecules, offer the advantages of being lightweight, flexible, and potentially low-cost. However, their efficiency and stability are still major challenges. Nanomaterials are being explored to address these issues.

Graphene is a particularly attractive transparent electrode for OSCs due to its flexibility, which is compatible with the organic active materials. Researchers have demonstrated that solution-processed graphene films can be used as transparent anodes in OSCs.[14,15] The sheet resistance of the graphene currently limits the performance of these devices, but ongoing research aims to improve this.[13]

Incorporating carbon nanotubes into the active layer or as interlayers in OSCs can enhance charge transport and collection, as in PSCs.

Plasmonic nanoparticles can be used to enhance light absorption in the thin active layers of OSCs, thereby improving photocurrent and efficiency.[4]

Dye-sensitized solar cells (DSSCs)

Dye-sensitized solar cells are a type of photo electrochemical cell that uses a photosensitive dye to absorb light. Nanomaterials are fundamental to the operation and performance of DSSCs.

The photoanode in a DSSC is typically made of a mesoporous film of wide-bandgap semiconductor nanoparticles, most commonly titanium dioxide (TiO_2).[17] This nanostructured film provides a large surface area for the adsorption of dye molecules, which is essential for efficient light harvesting and electron injection. The synthesis method, shape, and size of these nanoparticles are crucial in determining the overall efficiency of the DSSC. Other metal oxides, such as zinc oxide (ZnO) and aluminum oxide (Al_2O_3), are also being investigated as photoanode materials.

There is a growing interest in the green synthesis of metal and metal oxide nanoparticles for DSSC applications. Using biological agents for nanoparticle synthesis is a cost-effective, non-toxic, and environmentally friendly approach compared to conventional chemical methods. (Figure 2)

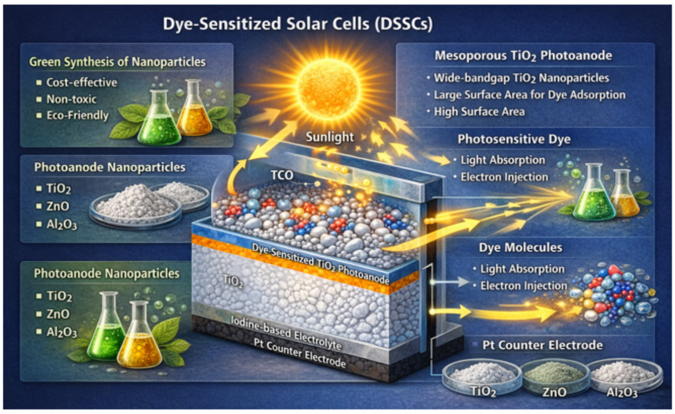

Figure 2 Dye-sensitized solar cell diagram and components.

Challenges and future outlook

Despite the immense promise of nanomaterials in enhancing solar energy conversion efficiency, several challenges must be addressed before their widespread commercialization can be realized.

Material stability and durability

One of the most significant challenges is the long-term stability of nanomaterials under operating conditions. Many nanomaterials are susceptible to degradation upon exposure to moisture, oxygen, and ultraviolet radiation. For example, the stability of quantum dots and perovskite materials is a major concern for their practical application in solar cells.[16] Developing robust encapsulation strategies and synthesizing more stable nanomaterials are critical areas of ongoing research.

Scalability and cost of production

While many novel nanomaterials have been successfully synthesized in the laboratory, scaling up their production to an industrial level cost-effectively remains a major hurdle. The synthesis of high-quality, monodisperse nanoparticles often requires complex, expensive procedures. Developing simple, scalable, and low-cost manufacturing techniques is essential for the economic viability of nanomaterial-enhanced solar cells.

Environmental and health concerns

The potential environmental and health impacts of nanomaterials need to be carefully assessed. The toxicity of certain nanomaterials, such as those containing heavy metals like cadmium and lead, is a significant concern. The entire life cycle of nanomaterial-based solar cells —from synthesis to disposal and recycling —needs to be considered to ensure their sustainability. Further research is required to understand the long-term effects of nanomaterial release into the ecosystem.

Citation: Al-Mamun AM. A review of nanomaterials for enhancing solar energy conversion efficiency. *Material Sci & Eng.* 2026;10(1):1–6.
DOI: 10.15406/mseij.2026.10.00261

Table 3 Environmental and safety considerations for photovoltaic nanomaterials

Nanomaterial class	Potential hazard	Exposure pathway	Mitigation/Research strategy
Heavy-Metal quantum Dots (CdSe, PbS)	Cellular toxicity due to the leaching of heavy metal ions (Cd^{2+}, Pb^{2+}).	Inhalation during manufacturing; leaching from waste panels in landfills.	Development of non-toxic alternatives (e.g., InP, Carbon QDs); robust encapsulation.
Silver Nanoparticles/ Nanowires	Ecotoxicity to aquatic organisms; potential to act as an antimicrobial agent, disrupting ecosystems.	Runoff from manufacturing facilities or degraded solar panels.	Use of protective coatings (e.g., silica); development of closed-loop recycling processes.
Carbon nanotubes (CNTs)	Asbestos-like inflammatory response in lungs for certain types of long, rigid CNTs.	Inhalation of airborne particles during synthesis and handling.	Functionalization to reduce airborne potential; strict workplace safety protocols (HEPA filters).
Metal oxides (TiO_2, ZnO)	Generally considered low toxicity, but the long-term effects of nano-form are still under investigation.	Inhalation; skin contact during production.	Standard industrial hygiene; further long-term toxicological studies.

Future trends and prospects

The field of nanomaterials for solar energy is continuously evolving, with several exciting future directions:

I. **Advanced nanomaterial design:** The development of novel nanomaterials with tailored optical and electrical properties will continue to drive efficiency improvements. This includes the exploration of multi-component nanoparticles, core-shell quantum dots, and hybrid nanomaterials.[18]

II. **Tandem and multi-junction solar cells:** Nanomaterials, particularly quantum dots with their tunable band gaps, are ideal for the fabrication of high-efficiency tandem and multi-junction solar cells that can harvest a broader portion of the solar spectrum.

III. **Flexible and transparent solar cells:** The use of nanomaterials like graphene and carbon nanotubes will enable the development of lightweight, flexible, and transparent solar cells for a wide range of applications, including building-integrated photovoltaics, wearable electronics, and portable power sources.[13]

IV. **AI and machine learning for materials discovery:** Artificial intelligence and machine learning are poised to accelerate the discovery and optimization of new nanomaterials for solar energy applications by rapidly screening vast material spaces.

V. **Circular economy approaches:** Developing sustainable manufacturing processes and efficient recycling methods for nanomaterial-based solar cells will be crucial for their long-term viability.

Conclusion

Nanotechnology has undoubtedly opened a new frontier in the quest for highly efficient, cost-effective solar energy conversion. Nanomaterials, with their unique and tunable properties, offer a powerful toolkit to overcome the limitations of conventional solar cell technologies. From enhancing light absorption through plasmonic effects and nano structuring to improving charge transport with high-mobility materials, nanotechnology's contributions are multifaceted and profound. We have reviewed the significant progress in integrating various nanomaterials into different types of solar cells, resulting in remarkable improvements in performance.

However, the path to widespread commercialization is not without its obstacles. The challenges of long-term stability, scalable and cost-effective manufacturing, and potential environmental and health concerns must be diligently addressed through continued research and development. The future of nanomaterial-enhanced solar energy is bright, with ongoing innovations in material design, device architecture, and manufacturing processes. By harnessing the power of the small, we can unlock the immense potential of solar energy and pave the way for a sustainable and clean energy future for generations to come. The continued synergy between nanoscience and photovoltaic research will be instrumental in realizing this vision.

Acknowledgment

None.

Funding

None.

Conflicts of interest

The author declares that there is no conflicts of interest

References

1. Ali A, El-Mellouhi F, Mitra A, et al. Research progress of plasmonic nanostructure-enhanced photovoltaic solar cells. *Nanomaterials*. 2022;12(5):788.
2. Garnett E, Yang, P. Light trapping in silicon nanowire solar cells. *Nano Letters*. 2010; *10*(3):1082–1087.
3. Cheng, N, Liu P, Qi F, et al. Multi-walled carbon nanotubes act as charge transport channel to boost the efficiency of hole transport material free perovskite solar cells. *J Power Sources*. 2016;332:24–29.
4. Li X, H Choy W C, Huo L, et al. Dual plasmonic nanostructures for high performance inverted organic solar cells. *Advanced Materials*. 2012;24(22):3046–3052.
5. Shaghouli E, Granpayeh N, Manavizadeh N. Plasmonic enhanced ultra-thin solar cell: A combined approach using fractal and nano-antenna structure to maximize absorption. *Results Phys.*2023;50:106600.
6. Akimov Y A, Koh WS. Design of plasmonic nanoparticles for efficient subwavelength light trapping in thin-film solar cells. *Plasmonics*. 2011;6:155–161.
7. Pala R A, White J, Barnard E, et al. Design of plasmonic thin-film solar cells with broadband absorption enhancements. *Advanced Materials*. 2009;21(34):3504–3509.
8. Kelzenberg M, Boettcher S, Petykiewicz J, et al. Enhanced absorption and carrier collection in Si wire arrays for photovoltaic applications. *Nature Mater*. 2010;9(3):239–244.

9. Lynn Yarris. Trapping sunlight with silicon nanowires. *Berkeley Lab News*. 2010.

10. Martin Foldyna, Linwei Yu, Soumyadeep Misra, et al. Using nanowires to enhance light trapping in solar cells. *SPIE Newsroom*. 2013.

11. Aqoma H, Lee S H, Imran I F, et al. Alkyl ammonium iodide-based ligand exchange strategy for high-efficiency organic-cation perovskite quantum dot solar cells. *Nat Energy*. 2024:324–332.

12. Shadrokh Z, Sousani S, Gholipour S, et al. Incorporation of carbon nanotubes in hole transport materials for perovskite solar cells. *Int J Sustain Energy*. 2023;*42*(1):461–473.

13. Li P, Chen C, Zhang J, et al. Graphene-based transparent electrodes for hybrid solar cells. *Front Mater.* 2014;1:112904.

14. Wu J, Becerril H A, Bao Z, et al. Organic solar cells with solution-processed graphene transparent electrodes. *Appl Phys Lett.* 2008; *92*(26):263302.

15. Park H, Rowehl J A, Kim K K, et al. Doped graphene electrodes for organic solar cells. *Nanotechnology*. 2010;21(50):505204.

16. Park N G. Perovskite solar cells: An emerging photovoltaic technology. *Materials Today.* 2015;18(2):65–67.

17. Lin Y-S, Chen W-H. Dye-sensitized solar cells with modified TiO_2 scattering layer produced by hydrothermal method. *Materials*. 2025;18(2):278.

18. Aftab S, Goud BS, Ali Z, et al. Advancements in nanomaterials for solar energy harvesting: challenges, innovations, and future prospects. *Chem Eng J*. 2025;516:164224.

Citation: Al-Mamun AM. A review of nanomaterials for enhancing solar energy conversion efficiency. *Material Sci & Eng.* 2026;10(1):1–6.
DOI: 10.15406/mseij.2026.10.00261