

Nanoparticle-Engineered Solar PV Cells: A Comprehensive Review on Performance Enhancement

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The growing global demand for sustainable energy has intensified research efforts to improve the Efficiency (Eff) and stability of solar Photo-Voltaic (PV) technologies. Among the various strategies explored, nanoparticle engineering has emerged as a promising approach to enhance light absorption, charge transport, and overall device performance in PV cells. This review presents a comprehensive analysis of recent advances in nanoparticle-integrated solar PV systems, focusing on their role in improving the optical, electrical, and thermal characteristics of PV devices. The current study investigates the impact of nanoparticles on PV performance enhancement, highlighting their mechanisms for 'Eff' enhancement and reduced energy losses. Furthermore, this review discusses different integration techniques and evaluates their impact on key PV performance parameters, such as power conversion efficiency, short-circuit current density, and fill factor. Additionally, this study addresses critical challenges related to nanoparticle stability, large-scale fabrication, toxicity, and long-term device reliability. Finally, future research directions are outlined for next-generation High-'Eff' solar PV systems. This review provides a consolidated framework for understanding the potential of nanoparticle engineering in PV technology and highlights pathways toward the development of cost-effective and high-performance solar energy systems.

Keywords: Nano particles, Solar PV cells, energy efficiency, temperature, performance enhancement

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In recent years, there are several methods to replace the Si-based normal Solar Cells (SCs) or Photo-Voltaic (PV) 'SCs' are available. Also, there are many research is going on to reduce the cost of electricity generation. The main cost is the production cost and large-scale production of the 'SCs' and to improve the life time of the 'SCs'. Therefore, there is a necessity to reduce the production cost of the 'SCs' and to improve the Power (P) conversion 'Eff' [1, 2]. In PV 'SCs' the solar spectrum can be converted directly to electricity and in the photo electrochemical 'SCs' the solar energy can be converted to chemical energy have attracted many research groups. In terrestrial applications, 'SCs' are playing a major role in use for solar energy conversion. The technology is purely based on the p-n junction and the Schottky barrier effect that gives the use of the PV performance characteristics of the suitable and selectable semiconductor i.e. Si [3]. The conversion 'Eff' of the 'SCs' with nanoparticles was enhanced which is relatively higher than that of the standard 'SCs' [4].

The transition toward large-scale renewable energy deployment, particularly in rapidly developing economies, highlights the need to optimize 'P' generation mixes and overcome policy and technological barriers to reduce emissions and support sustainable energy expansion [5]. Dye-sensitized 'SCs' (DSSCs) are emerging low-cost PV 'SCs' inspired by photosynthesis, utilizing a TiO₂-based photoanode, electrolyte, and catalytic counter electrode, with ongoing research focused on improving efficiency, materials, and commercialization potential [6]. The uniformity in the doping leads to better cell efficiency. The researchers produced that the Si modules made from wire sawn wafers which enhances the 'Eff' and with the lowest production [7]. Basu et al., reported that surface-texturized single crystalline Si solar cell (SC) a system with surface pre-treatment for light trapping produced cell efficiency. Also, it is noted that improved light absorption through controlled surface texturization [8]. Goodrich et al., stated that Monocrystalline silicon PV modules a system

incorporating manufacturing improvement roadmaps generated 'Eff' with least production cost. Furthermore, it is observed that technology roadmaps indicate further reduction in module manufacturing cost [9]. Espinosa and Krebs reported that organic tandem 'SCs' a system with the enhanced life cycle and least environmental footprint compared to conventional PV. Also, it is noted that organic tandem PV shows improved sustainability potential [10]. Wang et al., stated that dye-sensitized SC with carbon counter 3D honeycomb-like structured graphene electrode a system incorporating biomass-derived porous carbon electrode generated better conversion efficiency. Furthermore, it is observed that Carbon electrode provides comparable performance to electrodes [11]. Yamaguchi et al., reported that multi-junction concentrator 'SCs' a system with triple junction structure produced better conversion 'Eff' than plain PV cell. Also, it is noted that maximum 'Eff' achieved under concentrator PV systems [12]. Candelise et al., stated that the solar PV market cost analysis with incorporating assisting technology improves the cost dynamics which generates continuous reduction in PV modules price. Furthermore, it is observed that technology advancement identified as key factor in cost reduction [13]. Olya and Pirkarami reported that solar photocatalytic batch reactor system with photoelectron catalytic dye degradation produced high dye removal 'Eff' using solar P. Also, it is noted that solar-assisted photocatalysis reduces external energy consumption [14]. New non-vacuum processed technology showed enhancement in the conversion 'Eff' and better potential in the medium term in order to succeed on the market [15]. Palm et al., reported that CIS Thin-Film ('TF') solar modules system with Ga and sulfur composition optimization produced peak efficiency. Also, it is noted that it improved the module performance through material composition control [16]. Crystalline silicon on glass PV technology has makes it possibly the most promising 'TF' PV option. With the minimal material usage in the production without thick transparent conducting oxide layer to provide lateral conductance. Furthermore, it is observed that 'TF' CSG technology identified as promising low-material PV option [17]. Yamamoto et al., reported that Si:H/transparent inter-layer/microcrystalline Si 'TF' integrated large area SC module with better efficiency. Also, it is demonstrated that the proposed cell produces high-'Eff' 'TF' silicon module [18]. Heuer et al., stated that double-layer encapsulation with 250 nm Ta-Si-O and 15 nm Ta-Si-N which is able to protect a 'TF' SC against the degradation in the accelerated aging test. Therefore, this cause a diffusion barrier is a good perspective as encapsulation of flexible CIS solar modules and observed that Effective humidity diffusion barrier improving module durability [19]. Many research studies show that the 'TF' solar PV 'SCs' offer low material use with improved energy efficiency. Additionally, this emerging technology is found to be a promising alternative to crystalline 'SCs' due to its low 'Eff' and degradation [20]. Furthermore, it is observed

that the industrial 'TF'-PV technology incorporated with advanced module manufacturing with optimum scale generated better production capacity every year [21]. Accurate identification of transitions between the layers during the laser scribing was achieved with low error and high sensitivity, precision and specificity. The highest performance was achieved when applying the customized classification method and analyzed spectral band [22, 23]. Mono-Si PV systems have the highest life cycle energy requirement and the Thin-Film ('TF') PV systems (CdTe and a-Si systems) have the lowest energy demand. The CdTe PV system has the shortest life due to its lower energy demand and having the relatively high conversion 'Eff' [24]. The maximum 'P' output of the studied modules available is strongly dependent and proportional to the received solar radiation intensity and to a lesser extent of the ambient temperature [25]. Amorphous silicon and CIS 'SCs' showed the better performance ratio than the mono- and multi-crystalline silicon 'SCs' in the research study. The CIS 'SCs' are preferred instead of amorphous silicon 'SCs' and also it is promoted instead of following the market trend of mono- and multi-crystalline silicon 'SCs' we can go for CIS 'SCs' [26, 27]. The energy storage is the biggest problem happening in this current energy scenario. For this solar converted electric energy is stored in the lead-acid batteries. High cost and the improved technologies are led to use the polycrystalline-Si instead of the single crystal wafers and also for the improvement in the solar conversion 'Eff' [28]. Spray-CVD synthesis of SnO₂ thin films via controlled hydrolysis of SnCl₄ enables the formation of conductive, homogeneous layers suitable for heterojunction solar devices, with performance influenced by film conductivity [29]. Now the research has led to the development of the next second [30], third [31] and fourth [32] generation of the 'SCs' for reducing the cost and to improve the performance in the characteristics of the 'SCs' [33]. The second generation of the 'SCs' are 'TF' technology in the different materials (amorphous silicon, a-Si, cadmium indium selenide, CIS, silicon films on indium tin oxide, t-Si are produced [34]. These poly layer 'SCs' provide good performance in cost reduction in production of 'SCs' due to materials savings, low operating temperature and integrated cell insulation, high automation in series [35]. Material of CIGS-'SCs' (Cu, In, Ga, S) and semiconductors like GaAs are favorably used and the solar energy conversion 'Eff' is improved [36]. But the major problem in the 'TF' 'SCs' are difficult module, limited stability. That's why they have small market share about 12% of the total PV market [37]. Quantum dots in the nanoporous materials also had been investigated in the theoretically solar energy conversion of more (double of the practically existing 'SCs' efficiency) [38]. Due to the less thickness of thin crystalline SI films, it's a widely most used material [39]. Cadmium telluride and amorphous Si and similar 'TF' materials are also having good performance characteristics [40]. Due to some problems in the technologies like stability and

all, the second-generation ‘SCs’ are not performed well in the market compared to the first-generation ‘SCs’ [41]. Despite significant advancements in PV technologies as shown in Table 1, existing studies reveal a lack of comprehensive understanding regarding the consistent and scalable integration of nanoparticles into ‘SCs’. Second-generation ‘TF’ ‘SCs’ offer cost-effective solutions with moderate efficiency, while third-generation technologies provide higher ‘Eff’ potential but face stability challenges, whereas nanoparticle-integrated PVs emerge as a promising approach to enhance performance across different SC generations. While numerous investigations report enhanced optical absorption and improved charge transport, the underlying mechanisms governing long-term

stability and interfacial interactions remain inadequately explored. Furthermore, variations in nanoparticle type, size, concentration, and dispersion techniques lead to inconsistent performance outcomes, making it difficult to establish standardized design guidelines. Limited attention has also been given to the thermal behavior and degradation characteristics of nanoparticle-enhanced systems under real operating conditions. In addition, challenges related to large-scale fabrication, cost-effectiveness, and environmental safety continue to hinder commercial adoption. Therefore, a systematic investigation addressing these gaps is essential to develop the reliable, efficient, and economically viable nanoparticle-engineered PV systems for next-generation solar energy applications.

Table 1. SC Generations and Performance Characteristics.

Generation	Materials	Efficiency	Advantages	Limitations
1 st	Crystalline silicon	< 10%	Reliability and commercial adoption	Manufacturing cost
2 nd	Thin-film	10 to 15%	Lower material, flexible substrates	Stability and durability
3 rd	Dye-sensitized, quantum dots	< 25%	low-cost fabrication	Commercial deployment
Nano-structured	Nanoparticle-electrodes, nanowires	> 25%	Improved light trapping, tunable optical properties	Scalability and stability

Table 2. Nanoparticles Investigated for PV Performance Enhancement.

Nanoparticle	Application	Role	Impact
TiO ₂	Photoanode layer in dye-sensitized SCs	Electron transport and dye adsorption	Improved photoelectron generation
ZnO	Semiconductor layer or composite electrode	High electron mobility and enhanced charge transport	Increased photocurrent
Au	Plasmonic layer in PV structures	Localized surface plasmon resonance	Enhanced optical absorption
Ag	Surface coating or embedded plasmonic particles	Light scattering and trapping	Increased short-circuit current density
CuO	Surface coating in thermoelectric hybrid systems	Improved thermal conductivity	Improved electrical and thermal performance
CNT	Electrode material or composite structure	High electrical conductivity and electron transport	Improved electrical and thermal performance

APPLICATIONS OF NANOPARTICLES IN SCS

The cooling of ‘SCs’ improves the ‘Eff’ of solar devices [42, 43]. The thermal conductivity and the viscosity of the Nano-Fluids (NF) are the factors which enhance the performance of the ‘SCs’ [44, 45]. From the observations it was found that the performance characteristics of the ‘SCs’ are depend on the cell temperature [46]. Cell performance decreases with increasing cell temperature owing to the reduced open-circuit voltage and overall ‘Eff’ [47]. Higher operating temperatures accelerate recombination losses, thereby lowering the ‘P’ output and long-term system reliability [48]. NF are used as cooling media for ‘SCs’ [49]. The initial NF used in the ‘SCs’ for the cooling is Al₂O₃/water [50]. Adding NF to the working medium for the cooling process increases the Nusselt number and heat transfer rate with respect to the concentration volume ratio of nanoparticles in the nano-fluids [51, 52].

NANOPARTICLES IN FIRST GENERATION SC TECHNOLOGIES

GaAs with a band gap ‘P’ of a few micrometers in thickness generates an energy conversion ‘Eff’ higher than that of crystalline Si and also with low-cost substrates such as Si or germanium (Ge) [53]. TiO₂-doped ‘SCs’ have better PV parameters and efficiencies than pure SCs. The P-Conversion-‘Eff’ of crystalline TiO₂ powdered ‘SCs’ increased to 2.65% compared to that of amorphous powdered ‘SCs’ [54]. Polycrystalline Si wafers, which are lower-cost, are used to form a highly transmissive surface and increase light absorption by 40% relative increase in absorption. Polycrystalline is sliced into blocks and into thin wafers, which show better cell performance [55]. An antireflection nanostructure on the Si surface shows that the reflectivity is decreased to less than 5%, and the short-circuit current is increased [56]. As shown in Table 3, many strategies have been followed

to improve the ‘Eff’ of PV cell performance by adding nanoparticles.

Nano-crystalline CuAlO₂ particles (35 nm) generated a high photocurrent in p-type DS‘SCs’ compared to p-type DS‘SCs’ causes enhancement in the current ‘Eff’ [57]. Using a simple brush-painted TIO anode showed enhancement in the optical transmittance of 85.48% and low sheet resistance of 28.25 Ω. RTA enhances the electrical, optical, and structural properties of brush-painted TIO anodes [58]. Vapor texturing can effectively increase the ‘Eff’ of mc-Si ‘SCs’ 0.5% increase in ‘Eff’ compared to acid textured wafers, 0.7% increase in ‘Eff’ compared to that wafers acid textured EFG mc-Si wafers with higher short circuit current density and low cost [59]. Si:H deposited ‘SCs’ on the modulated texture showed the improved EQE and JSC of +5 % compared to the ‘SCs’ deposited on flat glass / etched AZO substrates. Modulated surface textures have enhanced scattering and improved light trapping in ‘TF’ ‘SCs’ [60]. The polymeric gel processed SC has higher short circuit current of 13.24 mA/cm², fill factor of 64.1%, and P-Conversion-‘Eff’ of 6.21%. In addition, it has a higher Rtr and lower Rct than conventional paste [61]. The ‘Eff’ of nanotextured SC was enhanced from 6.1% to 10.2% under normal conditions. The CuI particles, which are prepared from the Si wafer by etching in Cu(NO₃)₂/HF and reacting in I₂/ethanol solution, are well controlled by tuning the etching time for the size and density of CuI particles with the silicon. The ‘Eff’ of these CNT–Si ‘SCs’ was enhanced by 6.0% with suitable CuI particle sizes and the reaction timings [62-63]. The highest density of nanoparticles on the surface gives rise to the best performance of the ‘SCs’ [64]. Al particles of 139 to 614 nm with good mono-dispersity addition of an organic surfactant oleic acid to the precursor solution of Al electrodes with relatively high densities without any damage [65]. Magnetron sputtering deposition is used to obtain high-quality carbon-supported platinum nanoparticles, which show better performance on the characteristics of the ‘SCs’ [66].

Table 3. Nanoparticle-Based Performance Enhancement Strategies in SCs.

Strategy	Nanomaterial	Mechanism	Outcome
Anti-reflective nanostructures	SI nanostructures	Reduced surface reflection	Higher photocurrent generation
Plasmonic enhancement	Ag or Au	Light scattering enhancement	Improved optical absorption efficiency
Nanocomposite electrodes	TiO ₂ /ZnO/NiO	Improved charge separation	Increased PV conversion efficiency
Nanowire architectures	Nanowires	Improved charge carrier transport	Higher quantum efficiency
Nanoporous photoelectrodes	Nanoparticle-porous films	Increased surface area for dye adsorption	Improved light harvesting capability

NANOPARTICLES IN SECOND GENERATION SC TECHNOLOGIES

Multilayer films (100 nm to 23 nm) on conducting glass enhance light scattering, resulting in an increased cell 'Eff' of 10.2% [67]. Plasmonic metal nanoparticles integrated via dewetting enhance SC performance by improving light absorption, and the 'Eff' is strongly influenced by the particle size, surface conditions, and anti-reflection coating thickness. The overall cell 'Eff' of the proposed cell affords better results than those of the base cell [68, 69]. The introduction of a gold island film between the emitter and base of a silicon semiconductor diode structure increases SC 'Eff' [70]. Crystalline Si p-n junctions show the better performance against the normal Si SCs. The nanocrystalline n-type CdTe as a window layer in an n-CdTe/p-Cd junction SC with an effective band gap of 2.8 eV shows better cell performance [71]. The CuO coating on the TEG surface enhances solar energy conversion 'Eff' with improved heat conduction of 4.83% and 1.48%, respectively [72]. The concentration of organogels and their dispersions of P₃HT gel particles are colloidally stable, and their solutions have low viscosity, which is suitable for processing into 'TF' devices [73]. It has been demonstrated that the distance and size of metallic nanoparticles also play a major role in increasing the P-Conversion-'Eff' of organic 'SCs' [74]. Tellurium-rich CIT films on (TO/CdS/CIT/Au) increase the short circuit current density (J_{sc}), open circuit voltage (V_{oc}), fill factor (FF), and P-Conversion-'Eff' (η) to 20 mA/cm², 480 mV, FF, and 43%, respectively [75]. Dye-Sensitized 'SCs' (DSSCs) with TiO₂/NiO composite particles enhance the P-Conversion-'Eff' of DS'SCs' owing to the effects of the NiO barrier and the n-'P' junction [76]. Inverted bulk hetero-junction polymer 'SCs' and ZnO: P3HT hybrid 'SCs' show improvements in the P-Conversion-'Eff' with ZnO [77].

NANOPARTICLES IN THIRD GENERATION SC TECHNOLOGIES

Quantum effects in semiconductor and silicon nanowires shows a high efficient on solar energy conversion [78, 79]. The crystalline titanium dioxide coatings of nanofibres diameter of 200 nm provides a large specific area to produce dye sensitized 'SCs' [80]. By applying the NPT structure on the surfaces of the 'SCs' the P-Conversion-'Eff' is increased by a current equivalent of 1.25 and 1.39 mA/cm² for 3.3 mm borosilicate glass (BSG) [81]. Photo-catalytic micron thick TiO₂ coatings was deposited on both the titanium metal and the FTO coated glass with 40 nm TiO₂ nanoparticle shows the better performance of the SC [82]. copper-cobalt oxides 'TF' coatings on highly reflective aluminum substrates using 0.25 M copper and 0.25 M cobalt (Cu/Co ratio as 1) with dip-speed 120 mm/min (four cycles) shows the better optical 'Eff' [83]. A single-crystal (TiO₂) nanowire on the

TiO₂ surface shows the high absorption with the better overall 'Eff' of 9.3% [84]. Heating the deposited nanoparticles at a low temperature during cold spraying the ability of retains lead the plastic-based flexible SCs. Compared to the 'Eff' of the 'SCs' with TiO₂ films deposited without heating particle of 2.7% is much higher than the 'Eff' of situ particle heating at 300 °C of 4.4%. This approach will enhance the 'Eff' of the 'SCs' by deposition of TiO₂ films towards the highly efficient flexible dye-sensitized 'SCs' [85]. The TiO₂ films prepared from S₁ and S₂ results the higher IPCE compared to the films of NC of similar thickness, the increase in IPCE values for S₁ and S₂ at shorter wavelength region due to their higher dye loading capacities. The higher IPCE value of 600 nm leads to increase the interaction between the photons and the dye molecules. In N-S₁ and N-S₂, the dye-loading is increased due to the TiO₂ nanoparticles between the TiO₂ spheres [86]. Devices with the ZnO nano-flakes and nanoparticles layers coated from solutions of 0.5 mg/mL concentration with the nano-flakes shows high PCE value of 3.08% compared to the normal 'SCs' 2.37% [87]. ZnO based DSSC depends on increasing the P-Conversion-'Eff' by increasing the light harvesting 'Eff' [88]. Dye-sensitized nanoparticle ZnO and Fe₂O₃ 'SCs' showed the high conversion 'Eff' with I_{sc} 490 mA/cm², V_{oc} 0.7 V, FF 0.62 and Z₀.02% [89]. The DSSC with the ZnO/TiO₂ nanoparticles shows the better photoelectron compared to the ZnO/TiO₂ layer or film and better DSSC performance [90]. DSSC on a cyclic electron transport initiated by one photoreaction lacks cooperative energy distribution and limits the energy conversion 'Eff' above 12% [91] and the photo energy conversion efficiencies (PCE) of the SC reached to 3.9% [92]. The P-Conversion-'Eff' of DSSC is proportional at a fixed annealing temperature increases with the annealing duration [93]. Depositing the optimum amount of ZnO on the TiO₂ electrode it will increase the band gap of the working electrode and also enhances the P-Conversion-'Eff' of a DSSC by the formation of a thin ZnTiO₃ layer between the ZnO and the TiO₂. This thin ZnTiO₃ layer modulates the competition of electron recombination and injection between the processes [94]. Different sizes and morphologies of ZnO nanoparticles from 11 to 41 nm have been successfully prepared by using the thermal dry and wet chemical methods with the morphology control by CTAB surfactant. This sample shows high biological activity against several microorganisms [95]. TiO₂ anchored ZnO 'TF' electrodes shows high cell performance compared to the single TiO₂ electrode for DSSCs, the TiO₂/ZnO/TiO₂ [96]. The nano-flakes are around 100 to 200 nm with a flake thickness of less than 10 nm which completely cover the outermost surface, provides the larger surface area for dye absorption which increases the 'Eff' of DS'SCs' [97]. Au NPs improved the overall conversion 'Eff' of the DSSCs. The overall conversion 'Eff' was increased 0.94% for an Au NPs deposited on TiO₂ nanorod compared to

0.31% of bare TiO₂ nanorod array. And the samples are quite stable and no corrosion occurs between metal NPs and the electrolyte when the testing [98]. Lower transient photo induced current of 0.049 mA/cm² and open circuit photo voltage of -0.219 mV.cm⁻² on TiO₂NPs/TiO₂NTAs electrode with an enhanced effective photoelectron catalytic (PEC) 'Eff' of 63.6% [99]. The band gap of the TiO₂ nano particles 3.43 eV was reduced to 3.29 eV due to the adsorption of dye rich in betanin dye. Due to reduction in the band gap, the conversion 'Eff' is improved [61%]. Dye-sensitized 'SCs' (DSSCs) show the P-Conversion-'Eff' with the optimization to analyze the interaction among the process parameters which involves in the manufacturing process of the cell [100]. The direct mixing of natural dye shows the uniform adsorption and light to electron conversion efficiency. The band gap of the synthesized TiO₂ nano particles is also reduced from 3.43 eV to 3.29 eV with the light to electron conversion 'Eff' of 0.69% [101]. The performance of the TiO₂ scattering layer was significantly improved with the increase of accelerating gas flow rate by the improvement of the particle-particle interaction due to the higher impact pressure from higher powder particle velocity at higher accelerating gas flow rate and the energy conversion 'Eff' was improved from 3.88 to 4.70% [102]. The TiO₂ particles are applied in the working electrode of DSSC to extend the retention period of light in the cell. Due to the rise in the temperature, the average particle size of TiO₂ particles was also increased. The P-Conversion-'Eff' of the DSSC was increased due to increase in the average particle size of TiO₂ [103]. TiO₂ NT as an electron transport film shows the performance of the device was improved by 3.4% conversion 'Eff' [104]. A 'TF' of TiO₂ is formed on the indium tin oxide (ITO) conductive glass under normal temperature and 20–50 nm which increases the cell performance [105,106]. HPA-incorporated TiO₂ nano-disc film electrodes showed high PCE (higher than 6%) [107]. The P-conversion 'Eff' of DS'SCs' 7.21% is improved by screen-printed commercial Pt counter electrode of 7.59% with the optimum dosage (1:3~1:1) for a composite CE material in mass ratio of MWCNTs/PANI [108]. The performance of the DSSC was increased due to the effects of the Fe₂O₃ co-semiconductor and the size reduction [109]. The P-Conversion-'Eff' of the DS'SCs' was increased by the weight ratio of submicron-sized YVO₄:Eu³⁺, Bi³⁺ at SiO₂ particles core-shell particles [110]. Natural dyes as light harvesting elements in DS'SCs' can contribute to a sustainable solution for the future energy production and the environmental impacts also had been better than other 'SCs' [111]. The TiO₂/dye composite particles which have nano-crystalline TiO₂ layer sandwiched between an ITO substrate and a layer of TiO₂ /dye composite particles was prepared. The short-circuit photocurrent of the DSSC with this sandwich TiO₂ 'TF' exceeded the conventional DSSC [112]. LaNPDS deposited nanoparticles on polymer substrate has the capable of flexible SC and increase

the solar energy conversion 'Eff' which is closely packed by the nanoparticle structure based on the 'TF' without any additional of thermal sintering process [113]. Nanowires which has the smallest dimension for the enhanced charge generation, separation and transportation shows the better performance against the normal SCs. The main advantage of this one dimensional nanostructure is they have unique chemical, structural and physical properties with the enhanced solar energy harvest and conversion [114]. The unique geometric and other properties of the nanowire arrays works on low optical reflection and enhance the light trapping and absorption [115]. The optimized geometry and architecture was analyzed with the full potential of the one-dimensional homogeneous and heterogeneous nanowire for enhanced solar energy conversion [116]. The 1D nanostructure Coating (nanoparticles or films) for the high surface area, high electron transport characteristics which promotes the performance of the 'SCs' [117].

CHALLENGES

The first challenge in using NF in solar devices is the high cost of NF owing to the difficulties in their production and application. Another main problem is the instability and agglomeration of nanoparticles during application. When using NF in a flow owing to their high viscosity and pressure drop, the pumping 'P' in the application is also high. To determine the optimum, 'Eff' of the system, different volume ratios of nanoparticles have been applied in research, which is also not easy. In addition to the commonly reported issues related to cost, nanoparticle stability, and increased pumping 'P', several other technical and operational challenges remain significant barriers to the large-scale implementation of nanoparticle-assisted solar PV technologies. One major concern is the long-term durability and reliability of nanoparticles under continuous solar irradiation. Prolonged exposure to high-intensity sunlight, ultraviolet radiation, and elevated operating temperatures can cause chemical degradation or surface modification of nanoparticles, which may gradually reduce their optical and thermal enhancement properties. This degradation can ultimately affect the overall performance and lifespan of PV systems that incorporate nanomaterials. Another important challenge is the compatibility of nanoparticles with PV cell materials and encapsulation layers. Certain nanoparticles may interact chemically with semiconductor surfaces, polymer layers, or encapsulating materials, potentially leading to corrosion, surface defects, or reduced electrical conductivity. These interactions can negatively influence the charge transport mechanisms within the PV cell, thereby lowering the conversion 'Eff' over extended periods of operation. The uniform dispersion of nanoparticles within base fluids or coatings also remains a critical challenge. Even when advanced dispersion techniques, such as ultrasonication or

surfactant stabilization, are applied, maintaining a stable and homogeneous nanoparticle distribution during long-term operation is difficult. A nonuniform distribution may lead to localized optical losses, sedimentation, or inconsistent thermal behavior, which reduces the reliability of experimental results and the repeatability of system performance.

In addition, scalability and manufacturing integration present major technological challenges. Most nanoparticle-enhanced PV concepts have been demonstrated at the laboratory scale, where precise control over nanoparticle size, morphology, and concentration can be maintained. However, translating these controlled experimental conditions into industrial-scale PV module manufacturing requires significant advancements in fabrication techniques, quality control, and process standardization. Environmental and health considerations must also be carefully considered when deploying nanoparticle-based technologies. The potential environmental impact of nanoparticle leakage, disposal, or recycling remains a concern, particularly for metal-based nanoparticles, such as silver, copper, or cadmium compounds. The lack of comprehensive regulations and standardized safety protocols for handling nanomaterials may pose additional barriers to commercialization. Finally, the optimization of nanoparticle parameters, including particle size, morphology, concentration, and optical properties, remains a complex research challenge. Different PV technologies, such as silicon-based SCs, dye-sensitized SCs, and perovskite SCs, require different nanoparticle characteristics for optimal enhancement. Achieving the best combination of these parameters without introducing additional energy losses or stability issues continues to be an active area of investigation.

CONCLUSION

Nanoparticles are applied to improve performance characteristics in many thermal engineering systems. This study presents a review of the applications of nanoparticles in solar systems and demonstrates how to enhance their performance. The experiments and numerical investigations discussed herein enhance the 'Eff' by applying nanoparticles to solar systems at reasonable volume fractions. In addition, different nanoparticles with different volume fractions of different sizes indicate that the optimum volume fraction yields the maximum effect on performance enhancement. From an environmental perspective, studies have shown that by applying nanoparticles to solar systems, emissions can be controlled. From an economic perspective, nanoparticles in solar systems result in annual fuel savings and cost savings. Nanoparticles and nanotechnology should be applied to all solar applications (solar PV SCs, solar concentrators, solar flat plate collectors, solar ponds, solar thermoelectric 'SCs' and solar stills). In future the development and advancement in the

nanotechnology will bring down the challenges in the application of nanoparticles in the solar systems. Furthermore, continued advancements in nanomaterial synthesis, surface modification techniques, and dispersion technologies are expected to significantly improve the stability and effectiveness of nanoparticles in solar energy systems. Future research should focus on large-scale implementation, long-term operational reliability, and environmentally sustainable nanomaterials to ensure that nanoparticle-assisted solar technologies become practical and economically viable for widespread renewable energy deployment.

REFERENCES

1. Fthenakis, V. (2009) Sustainability of photovoltaics: The case for thin-film solar cells. *Renewable and Sustainable Energy Reviews*, **13(9)**, 2746–2750.
2. Shirland, F. A. and Rai-Choudhury, P. (1978) Materials for low-cost solar cells. *Reports on Progress in Physics*, **41(12)**, 1839–1879.
3. Wang, G., Kuang, S., Wang, D. and Zhuo, S. (2013) Nitrogen-doped mesoporous carbon as low-cost counter electrode for high-efficiency dye-sensitized solar cells. *Electrochimica Acta*, **113**, 346–353.
4. Ming, Z., Song, X., Mingjuan, M. and Xiaoli, Z. (2013) New energy bases and sustainable development in China: A review. *Renewable and Sustainable Energy Reviews*, **20**, 169–185.
5. Kaygusuz, K. (2012) Energy for sustainable development: A case of developing countries. *Renewable and Sustainable Energy Reviews*, **16(2)**, 1116–1126.
6. Olya, M. E., Pirkarami, A., Soleimani, M. and Bahmaei, M. (2013) Photoelectrocatalytic degradation of acid dye using Ni–TiO₂ with the energy supplied by solar cell: mechanism and economical studies. *Journal of Environmental Management*, **121**, 210–219.
7. Endo, E. and Tamura, Y. (2003) Cost-effectiveness analysis of R and D on solar cells in Japan. *Solar Energy Materials and Solar Cells*, **75(3-4)**, 751–759.
8. Basu, P. K., Dhasmana, H., Udayakumar, N., Khan, F. and Thakur, D. K. (2010) Regulated low cost pre-treatment step for surface texturization of large area industrial single crystalline silicon solar cell. *Solar Energy Materials and Solar Cells*, **94(6)**, 1049–1054.
9. Goodrich, A., Hacke, P., Wang, Q., Sopori, B., Margolis, R., James, T. L. and Woodhouse, M. (2013) A wafer-based monocrystalline silicon photovoltaics road map: Utilizing known

- technology improvement opportunities for further reductions in manufacturing costs. *Solar Energy Materials and Solar Cells*, **114**, 110–135.
10. Espinosa, N. and Krebs, F. C. (2014) Life cycle analysis of organic tandem solar cells: When are they warranted? *Solar Energy Materials and Solar Cells*, **120**, 692–700.
 11. Wang, G., Wang, D., Kuang, S., Xing, W. and Zhuo, S. (2014) Hierarchical porous carbon derived from rice husk as a low-cost counter electrode of dye-sensitized solar cells. *Renewable Energy*, **63**, 708–714.
 12. Yamaguchi, M., Takamoto, T. and Araki, K. (2006) Super high-efficiency multi-junction and concentrator solar cells. *Solar Energy Materials and Solar Cells*, **90(18-19)**, 3068–3077.
 13. Candelise, C., Winkler, M. and Gross, R. J. (2013) The dynamics of solar PV costs and prices as a challenge for technology forecasting. *Renewable and Sustainable Energy Reviews*, **26**, 96–107.
 14. Olya, M. E. and Pirkarami, A. (2013) Cost-effective photoelectrocatalytic treatment of dyes in a batch reactor equipped with solar cells. *Separation and Purification Technology*, **118**, 557–566.
 15. Abermann, S. (2013) Non-vacuum processed next generation thin film photovoltaics: Towards marketable efficiency and production of CZTS based solar cells. *Solar Energy*, **94**, 37–70.
 16. Palm, J., Probst, V. and Karg, F. H. (2004) Second generation CIS solar modules. *Solar Energy*, **77(6)**, 757–765.
 17. Green, Martin A., Paul A. Basore, Nathan Chang, Clugston, D., Egan, R., Evans, R. and Hogg, D. (2004) Crystalline silicon on glass (CSG) thin-film solar cell modules. *Solar Energy*, **77(6)**, 857–863.
 18. Yamamoto, Kenji, Akihiko Nakajima, Masashi Yoshimi, Toru Sawada, Susumu Fukuda, Takashi Suezaki and Mitsuru Ichikawa. A high efficiency thin film silicon solar cell and module. *Solar Energy*, **77(6)**, 939–949.
 19. Heuer, H., Wenzel, C., Herrmann, D., Hübner, R., Zhang, Z. L. and Bartha, J. W. (2006) Thin tantalum–silicon–oxygen/tantalum–silicon–nitrogen films as high-efficiency humidity diffusion barriers for solar cell encapsulation. *Thin Solid Films*, **515(4)**, 1612–1617.
 20. Lee, T. D. and Ebong, A. U. (2017) A review of thin film solar cell technologies and challenges. *Renewable and Sustainable Energy Reviews*, **70**, 1286–1297.
 21. Diehl, W., Sittinger, V. and Szyszka, B. (2005) Thin film solar cell technology in Germany. *Surface and Coatings Technology*, **193(1-3)**, 329–334.
 22. Catchpole, K. R., McCann, M. J., Weber, K. J. and Blakers, A. W. (2001) A review of thin-film crystalline silicon for solar cell applications. Part 2: Foreign substrates. *Solar Energy Materials and Solar Cells*, **68(2)**, 173–215.
 23. Diego-Vallejo, D., Ashkenasi, D., Lemke, A., and Eichler, H. J. (2013) Selective ablation of Copper-Indium-Diselenide solar cells monitored by laser-induced breakdown spectroscopy and classification methods. *Spectrochimica Acta Part B: Atomic Spectroscopy*, **87**, 92–99.
 24. Amrouche, B., Sicot, L., Guessoum, A. and Belhamel, M. (2013) Experimental analysis of the maximum power point's properties for four photovoltaic modules from different technologies: Monocrystalline and polycrystalline silicon, CIS and CdTe. *Solar Energy Materials and Solar Cells*, **118**, 124–134.
 25. Amin, N., Lung, C. W. and Sopian, K. (2009) A practical field study of various solar cells on their performance in Malaysia. *Renewable Energy*, **34(8)**, 1939–1946.
 26. Peng, J., Lu, L. and Yang, H. (2013) Review on life cycle assessment of energy payback and greenhouse gas emission of solar photovoltaic systems. *Renewable and Sustainable Energy Reviews*, **19**, 255–274.
 27. Ludin, N. A., Mustafa, N. I., Hanafiah, M. M., Ibrahim, M. A., Teridi, M. A. M., Sepeai, S., Zaharim, A. and Sopian, K. (2018) Prospects of life cycle assessment of renewable energy from solar photovoltaic technologies: A review. *Renewable and Sustainable Energy Reviews*, **96**, 11–28.
 28. Memming, R. (1980) Solar energy conversion by photoelectrochemical processes. *Electrochimica Acta*, **25(1)**, 77–88.
 29. Badawy, W., Decker, F. and Doblhofer, K. (1983) Preparation and properties of Si/SnO₂ heterojunctions. *Solar Energy Materials*, **8(4)**, 363–369.
 30. Nozik, A. J. (1975) Photoelectrolysis of water using semiconducting TiO₂ crystals. *Nature*, **257(5525)**, 383–386.

- 56 Subramaniyan Chinnasamy, Ponmurugan, M., Rajasubramanian, V., Vinod, J., Navaneeth, B. S. Muthukumar, K. and Ramachandra Raju, K. Nanoparticle-Engineered Solar PV Cells: A Comprehensive Review on Performance Enhancement
31. Brown, G. F. and Wu, J. (2009) Third generation photovoltaics. *Laser and Photonics Reviews*, **3(4)**, 394–405.
32. Rehman, F., Syed, I. H., Khanam, S., Ijaz, S., Mehmood, H., Zubair, M., Massoud, Y. and Mehmood, M. Q. (2023) Fourth-generation solar cells: a review. *Energy Advances*, **2(9)**, 1239–1262.
33. Tyagi, V. V., Rahim, N. A. and Rahim, N. A. (2013) Progress in solar PV technology: Research and achievement. *Renewable and Sustainable Energy Reviews*, **20**, 443–461.
34. El Fanaoui, A., Douihi, N., Bakiz, B., Benhachemi, A., Taoufyq, A. and Ihlal, A. (2025) Innovative materials for energy storage systems and photovoltaic solar technologies: a review. *Nano-Structures and Nano-Objects*, **44**, 101562.
35. Al-Saleem, N. K., Al-Naghmaish, A., Madani, M., Alfawwar, W., Elbasiony, A. M., Alharthi, S., Haque, M. A. and Ghobashy, M. M. (2025) Multifunctional roles and advances of polymers in solar cell technologies: a review. *RSC Advances*, **15(43)**, 35998–36049.
36. Sivasankar, S. M., Amorim, C. D. O. and Cunha, A. F. D. (2025) Progress in thin-film photovoltaics: A review of key strategies to enhance the efficiency of CIGS, CdTe, and CZTSSe solar cells. *Journal of Composites Science*, **9(3)**, 143.
37. Ratnesh, R. K., Kumar, R., Singh, S., Chandra, R. and Singh, J. (2025) Recent advances in solar cell technology: addressing technological challenges, scenarios, and environmental implications in the development of sustainable energy solutions. *New Journal of Chemistry*, **49(17)**, 6861–6887.
38. Kumari, N., Chauhan, P., Sharma, V., Kaur, G. A., Kumar, S. and Shandilya, M. (2026) Next-generation perovskite solar cells empowered by carbon based materials: challenges and future opportunities. *Carbon Letters*, **1-40**.
39. Kirchartz, T., Yan, G., Yuan, Y., Patel, B. K., Cahen, D. and Nayak, P. K. (2025) The state of the art in photovoltaic materials and device research. *Nature Reviews Materials*, **10(5)**, 335–354.
40. Mohan, A., Heera, S., Anjana Nair, V. J. and Deepa, K. G. (2025) Thin Film Solar Cells: An Overview of Materials and Fabrication Methods. *Photon to Power: Harvesting the Sun*, **81-112**.
41. Mukwevho, N., Mkhohlakali, A., Ntsasa, N., Sehata, J., Chimuka, L., Tshilongo, J. and Letsoalo, M. R. (2025) Methodological approaches for resource recovery from end-of-life panels of different generations of photovoltaic technologies—A review. *Renewable and Sustainable Energy Reviews*, **207**, 114980.
42. Ismaeil, E. M. H., and Farooq, M. U. (2025) Review of cooling techniques for improving solar photovoltaic panel efficiency. *Sustainable Development*, **125(1)**, 193–219.
43. Fadhl, B. M., Makhdoum, B. M. and Guedri, K. (2025) A review on application of hybrid nanofluids for thermal management of solar PV modules. *Renewable Energy Research and Applications*, **6(1)**, 93–103.
44. Induranga, A., Galpaya, C., Vithanage, V., Indupama, A., Maduwantha, K., Gunawardana, N., Wijesekara, D., Amarasinghe, P., Nilmalgoda, H., Gunasena, K. and Perera, H., (2025) Nanofluids for heat transfer: advances in thermo-physical properties, theoretical insights, and engineering applications. *Energies*, **18(8)**, 1935.
45. Li, J., Zhang, X., Xu, B. and Yuan, M. (2021) Nanofluid research and applications: A review. *International Communications in Heat and Mass Transfer*, **127**, 105543.
46. Sharma, P. and Mishra, R. K. (2025) Comprehensive study on photovoltaic cell's generation and factors affecting its performance: A Review. *Materials for Renewable and Sustainable Energy*, **14(1)**, 21.
47. Manisha, Pinkey, Kumari, M., Sahdev, R. K. and Tiwari, S. (2022) A review on solar photovoltaic system efficiency improving technologies. *Applied Solar Energy*, **58(1)**, 54–75.
48. Khudhur, I. M., Ahmed, O. K. and Alomar, O. R. (2025) Enhancement of the performance of the PV/T collector by nano technology: A short review. *Environmental Progress and Sustainable Energy*, **44(6)**, e70065.
49. Ate, V. P., Lanjewar, P. B., Shelare, S. D., Malwe, P. D., Chan, C. K., Singh, S. and Varshney, D. (2025) Research article Advances in the synthesis and applications of hybrid nanofluids: Supporting SDG 7.3 on energy efficiency.
50. Priyadarshana, P. V. V., Induranga, A., Galpaya, C., Samarathunga, A. I. and Koswattage, K. (2025) A review on enhancement of solar photovoltaic (PV) system performance with water-based nano-fluid cooling systems. *Journal of Thermal Engineering*, **11(4)**.
51. Chotai, H., Ramani, R. V., Markna, J. and Kataria, B. (2025) Cu and CuO Nanoparticles in Heat Transfer Applications: A Comprehensive Review. *Journal of Advanced Mechanical Engineering Applications*, **6(2)**, 8–31.

- 57 Subramaniyan Chinnasamy, Ponnurugan, M., Rajasubramanian, V., Vinod, J., Navaneeth, B. S. Muthukumar, K. and Ramachandra Raju, K. Nanoparticle-Engineered Solar PV Cells: A Comprehensive Review on Performance Enhancement
52. Hansda, S., Hussein, A. K., Soren, S., Chattopadhyay, A., Majhi, D., Al-Sharif, Z. T., Alhassan, M. S. and Ben Hamida, M. B. (2026) Natural convection in wavy cavities with nanofluids: a comprehensive review. *Journal of Thermal Analysis and Calorimetry*, **1-40**.
53. Farajollahi, A. (2025) Nanotechnology in solar energy: From active systems to Advanced Solar cells. *Frontiers in Energy Research*, **13**, 1560718.
54. Yan, Y., Zhang, Y., Zhao, Y., Ding, F., Lei, Y., Wang, Y., Zhou, J. and Kang, W. (2025) Review on TiO₂ nanostructured photoanode and novel dyes for dye-sensitized solar cells application. *Journal of Materials Science*, **60(11)**, 4975–5005.
55. Peng, Z., Herfatmanesh, M. R. and Liu, Y. (2017) Cooled solar PV panels for output energy efficiency optimisation. *Energy Conversion and Management*, **150**, 949-955.
56. Aulakh, R. K., Singh, G., Pathak, D., Singh, R. I., Mittal, A. and Kohli, R. (2025) A Review on Progresses and Developments in Solar cell Technologies. *Journal of Solar Energy Research*, **10(3)**, 2501–2521.
57. Jahangeer Ahmed, Colin K. Blakely, Jai Prakash, Shaun R. Bruno, Mingzhe Yu, Yiyang Wu, Viktor, V. (2014) Polytetrafluoroethylene Scalable synthesis of delafossite CuAlO₂ nanoparticles for p-type dye-sensitized solar cells applications. *Journal of Alloys and Compounds*, **591**, 275–279.
58. Jin-A Jeong, Ye-Jin Jeon, Seok-Soon Kim, Boo Kyoung Kim, Kwun-Bum Chung, Han-Ki Kim (2014) Simple brush-painting of Ti-doped In₂O₃ transparent conducting electrodes from nanoparticle solution for organic solar cells. *Solar Energy Materials and Solar Cells*, **122**, 241–250.
59. Minkyu Ju, Nagarajan Balaji, Youn-Jung Lee, Cheolmin Park, Kyuwan Song, Jaewoo Choi, Junsin Yi (2012) Novel vapor texturing method for EFG silicon solar cell applications. *Solar Energy Materials and Solar Cells*, **107**, 366–372.
60. Zeman, M., Isabella, O., Jäger, K., Santbergen, R., Soltsev, S., Topic, M. and Krc, J. (2012) Advanced light management approaches for thin-film silicon solar cells. *Energy Procedia*, **15**, 189–199.
61. Bakhshayesh, A. M. and Mohammadi, M. R. (2013) Development of nanostructured porous TiO₂ thick film with uniform spherical particles by a new polymeric gel process for dye-sensitized solar cell applications. *Electrochimica Acta*, **89**, 90–97.
62. Wu, J. L., Chen, F. C., Hsiao, Y. S., Chien, F. C., Chen, P., Kuo, C. H., Huang, M. H. and Hsu, C. S. (2011) Surface plasmonic effects of metallic nanoparticles on the performance of polymer bulk heterojunction solar cells. *ACS Nano*, **5(2)**, 959–967.
63. Dou, B., Jia, R., Li, H., Chen, C., Jin, Z., Liu, X. and Xu, X. (2014) Enhanced electrode-contact property of silicon nano-textured solar cells via selective etching. *Solar Energy*, **99**, 95–99.
64. Tan, F., Qu, S., Wu, J., Wang, Z., Jin, L., Bi, Y., Cao, J., Liu, K., Zhang, J. and Wang, Z. (2011) Electrodeposited polyaniline films decorated with nano-islands: Characterization and application as anode buffer layers in solar cells. *Solar Energy Materials and Solar Cells*, **95(2)**, 440–445.
65. Lee, H. M. and Kim, Y. J. (2011) Preparation of size-controlled fine Al particles for application to rear electrode of Si solar cells. *Solar Energy Materials and Solar Cells*, **95(12)**, 3352–3358.
66. Fedotov, A. A., Grigoriev, S. A., Millet, P. and Fateev, V. N. (2013) Plasma-assisted Pt and Pt–Pd nano-particles deposition on carbon carriers for application in PEM electrochemical cells. *International Journal of Hydrogen Energy*, **38(20)**, 8568–8574.
67. Wang, Z. S., Kawauchi, H., Kashima, T. and Arakawa, H. (2004) Significant influence of TiO₂ photoelectrode morphology on the energy conversion efficiency of N719 dye-sensitized solar cell. *Coordination Chemistry Reviews*, **248(13-14)**, 1381–1389.
68. Borra, M. Z., Güllü, S. K., Es, F., Demircioğlu, O., Günöven, M., Turan, R. and Bek, A. (2014) A feasibility study for controlling self-organized production of plasmonic enhancement interfaces for solar cells. *Applied Surface Science*, **318**, 43–50.
69. Alkhalayfeh, M. A., Aziz, A. A. and Pakhuruddin, M. Z. (2021) An overview of enhanced polymer solar cells with embedded plasmonic nanoparticles. *Renewable and Sustainable Energy Reviews*, **141**, 110726.
70. Abdullah, M. M. (2013) Silicon Solar Cell Enhancement by Using Au Nanoparticles. *Int. J. Appl. or Innov. Engg. and Mant.*, **2(6)**, 49–56.
71. Singh, R. S., Rangari, V. K., Sanagapalli, S., Jayaraman, V., Mahendra, S. and Singh, V. P. (2004) Nano-structured CdTe, CdS and TiO₂ for thin film solar cell applications. *Solar Energy Materials and Solar Cells*, **82(1-2)**, 315–330.

72. Chang, H., Kao, M. J., Cho, K. C., Chen, S. L., Chu, K. H. and Chen, C. C. (2011) Integration of CuO thin films and dye-sensitized solar cells for thermoelectric generators. *Current Applied Physics*, **11(4)**, S19–S22.
73. Kilic, B., Turkdogan, S., Astam, A., Baran, S. S., Asgin, M., Cebeci, H. and Urk, D. (2017) Graphene-based copper oxide thin film nanostructures as high-efficiency photocathode for p-type dye-sensitized solar cells. *Journal of Photonics for Energy*, **7(4)**, 045502-045502.
74. Notarianni, M., Vernon, K., Chou, A., Aljada, M., Liu, J. and Motta, N. (2014) Plasmonic effect of gold nanoparticles in organic solar cells. *Solar Energy*, **106**, 23–37.
75. Lakhe, M. and Chaure, N. B. (2014) Characterization of electrochemically deposited CuInTe₂ thin films for solar cell applications. *Solar Energy Materials and Solar Cells*, **123**, 122–129.
76. Chuen-Shii, C. H. O. U., You-Jen, L. I. N., Ru-Yuan, Y. A. N. G. and Kuan-Hung, L. I. U. (2011) Preparation of TiO₂/NiO composite particles and their applications in dye-sensitized solar cells. *Advanced Powder Technology*, **22(1)**, 31–42.
77. Sekine, N., Chou, C. H., Kwan, W. L. and Yang, Y. (2009) ZnO nano-ridge structure and its application in inverted polymer solar cell. *Organic Electronics*, **10(8)**, 1473–1477.
78. Hochbaum, A. I. and Yang, P. (2010) Semiconductor nanowires for energy conversion. *Chemical Reviews*, **110(1)**, 527–546.
79. Peng, K. Q. and Lee, S. T. (2011) Silicon nanowires for photovoltaic solar energy conversion. *Advanced Materials*, **23(2)**, 198–215.
80. Paulmier, T., Bell, J. M. and Fredericks, P. M. (2008) Plasma electrolytic deposition of titanium dioxide nanorods and nano-particles. *Journal of Materials Processing Technology*, **208(1-3)**, 117–123.
81. Cui, H., Pillai, S., Campbell, P. and Green, M. (2013) A novel silver nanoparticle assisted texture as broadband antireflection coating for solar cell applications. *Solar Energy Materials and Solar Cells*, **109**, 233–239.
82. McDonnell, K. A., English, N. J., Stallard, C. P., Rahman, M. and Dowling, D. P. (2013) Fabrication of nano-structured TiO₂ coatings using a microblast deposition technique. *Applied Surface Science*, **275**, 316–323.
83. Amri, A., Duan, X., Yin, C. Y., Jiang, Z. T., Rahman, M. M. and Pryor, T. (2013) Solar absorptance of copper–cobalt oxide thin film coatings with nano-size, grain-like morphology: optimization and synchrotron radiation XPS studies. *Applied Surface Science*, **275**, 127–135.
84. Adachi, M., Murata, Y., Takao, J., Jiu, J., Sakamoto, M. and Wang, F. (2004) Highly efficient dye-sensitized solar cells with a titania thin-film electrode composed of a network structure of single-crystal-like TiO₂ nanowires made by the “oriented attachment” mechanism. *Journal of the American Chemical Society*, **126(45)**, 14943–14949.
85. Yao, H. L., Yang, G. J., Li, S., He, X. L., Fan, S. Q., Li, C. X. and Li, C. J. (2013) Synergistic effects of high temperature and impact compaction on the nano-TiO₂ film for the significant improvement of photovoltaic performance of flexible dye-sensitized solar cells. *Electrochimica Acta*, **87**, 940–947.
86. Kim, H. J., Jeon, J. D., and Kwak, S. Y. (2013) Highly dispersed mesoporous TiO₂ spheres via acid treatment and its application for dye-sensitized solar cells. *Powder Technology*, **243**, 130–138.
87. Mbule, P. S., Kim, T. H., Kim, B., Swart, H. C. and Ntwaeaborwa, O. M. (2013) Effects of particle morphology of ZnO buffer layer on the performance of organic solar cell devices. *Solar Energy Materials and Solar Cells*, **112**, 6–12.
88. Omar, A. and Abdullah, H. (2014) Electron transport analysis in zinc oxide-based dye-sensitized solar cells: A review. *Renewable and Sustainable Energy Reviews*, **31**, 149–157.
89. Reda, S. M. (2010) Synthesis of ZnO and Fe₂O₃ nanoparticles by sol–gel method and their application in dye-sensitized solar cells. *Materials Science in Semiconductor Processing*, **13(5-6)**, 417–425.
90. Lou, Y., Yuan, S., Zhao, Y., Hu, P., Wang, Z., Zhang, M., Shi, L. and Li, D. (2013) A simple route for decorating TiO₂ nanoparticle over ZnO aggregates dye-sensitized solar cell. *Chemical Engineering Journal*, **229**, 190–196.
91. O'regan, B. and Grätzel, M. (1991) A low-cost, high-efficiency solar cell based on dye-sensitized colloidal TiO₂ films. *Nature*, **353(6346)**, 737–740.
92. Sivakumar, R., Marcelis, A. T. and Anandan, S. (2009) Synthesis and characterization of novel heteroleptic ruthenium sensitizer for nano-crystalline dye-sensitized solar cells. *Journal of*

- Photochemistry and Photobiology A: Chemistry*, **208(2-3)**, 154–158.
93. Chou, C. S., Chou, C. S., Kuo, Y. T. and Wang, C. P. (2013) Preparation of a working electrode with a conducting PEDOT: PSS film and its applications in a dye-sensitized solar cell. *Advanced Powder Technology*, **24(1)**, 336–343.
94. Chou, C. S., Chou, F. C., Ding, Y. G. and Wu, P. (2012) The effect of ZnO-coating on the performance of a dye-sensitized solar cell. *Solar Energy*, **86(5)**, 1435–1442.
95. Mousa, M. A., Bayoumy, W. A. A. and Khairy, M. (2013) Characterization and photo-chemical applications of nano-ZnO prepared by wet chemical and thermal decomposition methods. *Materials Research Bulletin*, **48(11)**, 4576–4582.
96. Chao, C. H., Chang, C. L., Chan, C. H., Lien, S. Y., Weng, K. W. and Yao, K. S. (2010) Rapid thermal melted TiO₂ nano-particles into ZnO nano-rod and its application for dye sensitized solar cells. *Thin Solid Films*, **518(24)**, 7209–7212.
97. Chu, P. J., Wu, S. Y., Chen, K. C., He, J. L., Yerokhin, A. and Matthews, A. (2010) Nano-structured TiO₂ films by plasma electrolytic oxidation combined with chemical and thermal post-treatments of titanium, for dye-sensitized solar cell applications. *Thin Solid Films*, **519(5)**, 1723–1728.
98. Ghaffari, M., Cosar, M. B., Yavuz, H. I., Ozenbas, M. and Okyay, A. K. (2012) Effect of Au nano-particles on TiO₂ nanorod electrode in dye-sensitized solar cells. *Electrochimica Acta*, **76**, 446–452.
99. Cheng, X., Liu, H., Chen, Q., Li, J. and Wang, P. (2013) Enhanced photoelectrocatalytic performance for degradation of diclofenac and mechanism with TiO₂ nano-particles decorated TiO₂ nano-tubes arrays photoelectrode. *Electrochimica Acta*, **108**, 203–210.
100. Zainudin, S. N. F., Markom, M., Abdullah, H., Adami, R. and Tasirin, S. M. (2013) Optimized synthesis and photovoltaic performance of TiO₂ nanoparticles for dye-sensitized solar cell. *Particuology*, **11(6)**, 753–759.
101. Ananth, S., Arumanayagam, T., Vivek, P. and Murugakoothan, P. (2014) Direct synthesis of natural dye mixed titanium dioxide nano particles by sol-gel method for dye sensitized solar cell applications. *Optik*, **125(1)**, 495–498.
102. He, X. L., Yang, G. J., Li, C. J. and Li, C. X. (2014) Influence of accelerating gas flow rate on the particle cohesion in room temperature cold sprayed scattering layer for plastic-based dye-sensitized solar cells. *Applied Surface Science*, **288**, 416–422.
103. Chou, C. S., Guo, M. G., Liu, K. H. and Chen, Y. S. (2012) Preparation of TiO₂ particles and their applications in the light scattering layer of a dye-sensitized solar cell. *Applied Energy*, **92**, 224–233.
104. Chen, C. C., Jheng, W. D. and Lin, C. K. (2014) Large-area TiO₂ nanotube dye-sensitized solar cells using thermal-sprayed Ti layers on stainless steel. *Ceramics International*, **40(2)**, 3221–3226.
105. Chang, H., Wu, H. M., Chen, T. L., Huang, K. D., Jwo, C. S. and Lo, Y. J. (2010) Dye-sensitized solar cell using natural dyes extracted from spinach and ipomoea. *Journal of Alloys and Compounds*, **495(2)**, 606–610.
106. Chen, S. L., Su, H. T., Chang, H., Jwo, C. S. and Feng, H. J. (2010) TiO₂ nanoparticles produced by electric-discharge-nanofluid-process as photo-electrode of DSSC. *Chinese Journal of Chemical Physics*, **23(2)**, 231–236.
107. Parayil, S. K., Lee, Y. M. and Yoon, M. (2009) Photoelectrochemical solar cell properties of heteropolytungstic acid-incorporated TiO₂ nano-disc thin films. *Electrochemistry Communications*, **11(6)**, 1211–1216.
108. Niu, H., Qin, S., Mao, X., Zhang, S., Wang, R., Wan, L., Xu, J. and Miao, S. (2014) Axle-sleeve structured MWCNTs/polyaniline composite film as cost-effective counter-electrodes for high efficient dye-sensitized solar cells. *Electrochimica Acta*, **121**, 285–293.
109. Im, J. S., Lee, S. K. and Lee, Y. S. (2011) Cocktail effect of Fe₂O₃ and TiO₂ semiconductors for a high performance dye-sensitized solar cell. *Applied Surface Science*, **257(6)**, 2164–2169.
110. Wang, E. C., Mokkaapati, S., White, T. P., Soderstrom, T., Varlamov, S. and Catchpole, K. R. (2014) Light trapping with titanium dioxide diffraction gratings fabricated by nanoimprinting. *Progress in Photovoltaics: Research and Applications*, **22(5)**, 587–592.
111. Hug, H., Bader, M., Mair, P. and Glatzel, T. (2014) Biophotovoltaics: natural pigments in dye-sensitized solar cells. *Applied Energy*, **115**, 216–225.
112. Chou, C. S., Yang, R. Y., Weng, M. H. and Yeh, C. H. (2008) Preparation of TiO₂/dye composite particles and their applications in dye-sensitized solar cell. *Powder Technology*, **187(2)**, 181–189.

113. Ahn, S. H., Choi, J. O., Kim, C. S., Lee, G. Y., Lee, H. T., Cho, K., Chun, D. M. and Lee, C. S. (2012) Laser-assisted nano particle deposition system and its application for dye sensitized solar cell fabrication. *CIRP Annals*, **61(1)**, 575–578.
114. Feng, Z. Q., Wu, J., Cho, W., Leach, M. K., Franz, E. W., Naim, Y. I., Gu, Z. Z., Corey, J. M. and Martin, D. C. (2013) Highly aligned poly (3, 4-ethylene dioxythiophene)(PEDOT) nano-and microscale fibers and tubes. *Polymer*, **54(2)**, 702–708.
115. Kapadia, R., Fan, Z., Takei, K. and Javey, A. (2012) Nanopillar photovoltaics: materials, processes, and devices. *Nano Energy*, **1(1)**, 132–144.
116. Espitia-Mesa, G., Moreno-Villa, A., Tobón-Echavarría, S., Rivera, J. C. and Mejía-Gutiérrez, R. (2025) Modeling optimal PV surface of BIPVs for maximum energy yield through Genetic Algorithms. *Energy and Built Environment*, **6(4)**, 607–615.
117. Nithyapriya, M. S., Mariappan, S. M., Gopalakrishnan, S., Navaneethan, M. and Archana, J. (2025) A 3D/1D hierarchical nanostructure (SnS₂/MWCNT) as a highly efficient bifunctional electrode for Pt-free dye-sensitized solar cell and hydrogen evolution reaction. *International Journal of Hydrogen Energy*, **129**, 101–112.