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REVIEW

Photovoltaic Technology: Power Conversion Efficiency of Solar Cells

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In recent years, there are several types of solar cells that have been reported due to their continually improving power efficiency, straightforward solution production methods, portability, lightweight nature for wearability and cost-effective material components. In this work, we have concentrated on the latest advancements in solar cells related to their properties and uses. Furthermore, various layers, such as electron transport layers and hole transport layers were described. Subsequently, the constraints and cell efficiency were reported in specific solar cells. Finally, the photovoltaic parameters of the devices, band gaps and carrier mobility were reported as well. Dye sensitized solar cells made with natural dyes offer unique benefits in energy usage. The primary factors include its efficiency, eco-friendly dyes, remarkable device performance, sustainable energy generation, and adaptable solar product incorporation. Although dye sensitized solar cells that use natural dyes as sensitizers, offer numerous advantages, they experience lower efficiency in comparison to traditional silicon based solar cells. The choice of plant components significantly influences the devices' overall efficiency. Consequently, a thorough investigation has been conducted to examine the plant's components that have demonstrated improved outcomes regarding device efficiency. The efficiency of organic solar cells has significantly improved in the past decade, thanks to advancements in a range of high-performance organic electron-donor and electron-acceptor materials, such as polymers, small molecules and fullerenes, used in the photo-active layer. Effective molecular design approaches for various types of organic solar cells are studied and promising research pathways are emphasized. It was noted that the efficiency of perovskite solar cells has exceeded 25% owing to high-quality films achieved through low-temperature synthesis methods, alongside advancements in suitable interface and electrode materials. In the thin film based solar cells, the research findings confirmed that power conversion efficiency, fill factor, open circuit voltage and short circuit current density is strongly dependent on experimental conditions.

Keywords: Organic solar cells, Semiconductor band gap, Photovoltaic, Energy efficiency, Energy consumption.

INTRODUCTION

Solar cells are used in various applications because they can transform sunlight into electrical energy. They energize a range of items from tiny gadgets such as calculators to extensive solar farms that provide power to whole neighborhoods [1]. In addition, solar cells are vital for energizing satellites and various space related devices, and they are progressively being used in transportation, including solar powered vehicles. Silicon-based solar cells, classified as first-generation solar cells, currently account for over 80% of the global installed capacity and hold approximately 90% of the market share. Due to their comparatively high efficiency [2], they are the most frequently utilized cells. A silicon solar panel operates in the same manner as various other kinds of solar panels. When sunlight hits the silicon solar cells, they absorb the photons from daylight and transform them into free electrons. The electrons flow through the electric cables and provide electrical energy to the power grid [3]. The solar inverter converts the direct current generated by sunlight into alternating current. It is subsequently sent through the cables to power various devices and appliances.

The thin film solar cells using cadmium telluride, copper indium gallium diselenide or amorphous silicon have been developed as a more affordable alternative to crystalline silicon cells. This second-generation solar cell provides enhanced

mechanical properties that are suitable for flexible uses [4], though this entails the possibility of decreased efficiency. The defining trait of technology is the cell's thickness. In contrast to silicon wafer cells, which feature light absorbing layers typically 350 microns thick, thin film solar cells possess light absorbing layers that are merely one micron thick. Manufacturers start their process by applying multiple layers of a semiconductor which absorbs light, onto a substrate made of glass, metal or plastic. The substances used as semiconductors do not need to be thick as they efficiency absorb energy from sunlight.

Third generation solar cells mark a new phase in photovoltaic technology, aiming to address the shortcomings of previous generations and possibly exceed the theoretical efficiency boundaries [5]. They utilize cutting edge materials and methods to attain high power conversion efficiency, while also being possibly inexpensive to manufacture. This type of solar cells encompasses a diverse array of methods, spanning from cost effective low efficiency systems such as dye sensitized and organic solar cells to costly high efficiency systems (III-V multi-junction cells). Multi-junction solar cells are made up of multiple p-n junctions created from different semiconductor materials. Each junction generates electric current when exposed to light of varying wavelengths. Thus, enhancing the conversion of incoming sunlight into electricity and the device's overall efficiency. The idea of using diverse materials with varying band gaps has been proposed to capture the greatest number of photons, and this is referred to as a tandem solar cell. A complete cell could be constructed using identical or varied materials, allowing for a wide range of potential designs.

Fourth generation photovoltaic cells merge the affordability of polymer thin films with metal oxides, graphene and their derivatives. Graphene based photovoltaic cells [6] provide significant benefits for solar energy use, such as the possibility of flexible, transparent and highly efficient solar cells. The distinct properties of graphene, including its excellent carrier mobility, exceptional mechanical strength and optical transparency, render it a viable material for multiple components in photovoltaic devices.

This article provides an overview of different types of solar cells constructions, operating principles, key problems and prospective efficient materials. This work focuses on organic solar cells, thin film based solar cells, perovskite solar cells and dye sensitized solar cells. In addition, photovoltaic parameters such as power conversion efficiency will be studied in specific designed solar cells.

METHODOLOGY

To collect the relevant research articles on solar technologies, the authors performed an extensive literature review covering publications from 1979 to 2025. The databases consulted included Google Scholar, Taylor & Francis, ACS Publications, Scopus, Wiley Online Library, ScienceDirect and MDPI. Keywords used in the search included organic solar cells, band gap, silicon-based solar cells, thin-film solar cells, perovskite solar cells, dye-sensitized solar cells, semiconductor materials and photovoltaic parameters.

Dye-sensitized solar cells (DSSCs): Dye sensitized solar cells (DSSCs) have emerged as a viable technical and economical substitute for p-n junction photovoltaic systems. In the late 1960s, it was found that illuminated organic dyes could generate electricity in electrochemical cells. The four essential components for a DSSC are the working electrode, sensitizer, redox mediator and counter electrode [7]. The DSSC is a structure consisting of working electrode immersed in sensitizer and sealed against a counter electrode that has a thin layer of electrolyte, using hot melt tape to avoid electrolyte leakage.

The working electrode is developed by applying a thin film of oxide semiconducting materials onto a transparent conducting glass such as fluorine doped tin oxide coated glass slide (FTO) and indium tin oxide (ITO). These oxides have a broad energy band gap ranging from 3 to 3.2 eV. The use of the anatase allotropic form of titanium dioxide (TiO_2) is preferable in DSSC compared to the rutile form because it possesses a higher energy band gap of 3.2 eV, while the rutile form has a band gap of approximately 3 eV. Due to it's non-toxicity, greater affordability and easy availability, TiO_2 is primarily used as a semiconducting layer [8]. Nonetheless, these semiconductor layers capture only a limited amount of light in the UV spectrum. Therefore, these working electrodes are subsequently immersed in a blend of a light sensitive molecular sensitizer and a solvent. Once the film is immersed in the dye solution, the dye forms a covalent bond with the TiO_2 surface. Owing to the electrode's highly porous structure and extensive surface area, many dye molecules adhere to the nanocrystalline TiO_2 structure, leading to enhanced light absorption at the semiconductor surface.

The dye is the element of DSSC that enables the highest absorption of incoming light. The colorant must be glowing. The dye absorption spectra must span the ultraviolet, visible and near infrared regions. The highest occupied molecular orbital (HOMO) ought to be situated far from the TiO_2 conduction band surface, while the lowest unoccupied molecular orbital (LUMO) should be positioned close to the TiO_2 surface. Consequently, it should be elevated relative to the potential of the TiO_2 conduction band. The HOMO level should be lower than that of redox electrolytes. The outer edge of the dye must be hydrophobic to improve the longevity of cells [9]. Because it leads to reduce direct interaction between the electrolyte and the anode.

An electrolyte consists of distinct elements and the redox pair must effectively regenerate the oxidized dyes. It must possess long-lasting chemical, thermal and electrochemical stability. Furthermore, it must be non-corrosive when in contact with DSSC components. Moreover, it must facilitate movement of charge carriers, improve conductivity and establish efficient connection between the working electrode and counter electrode [10]. Finally, the absorption spectra of an electrolyte must not coincide with the absorption spectra of the dye.

In DSSC, counter electrode is typically made using platinum (Pt) or carbon. Both the working and counter electrodes are securely sealed together and then an electrolyte is introduced using a syringe. The counter electrode facilitates the reduction of the triiodide/iodide (I_3^-/I^-) liquid electrolytes and gathers holes from the hole transport materials. Platinum is

used as a counter electrode due to its greater efficiency, but its replacement became essential due to its high cost and limited availability [11]. Consequently, various substitutes have emerged to take the place of platinum in DSSC, such as carbon, carbonyl sulfide, iron selenide and cobalt nickel.

Photovoltaic parameters in dye-sensitizer solar cells: The electron transport layer is crucial for enhancing electron movement and slowing down electron recombination in a photoelectric device. Titanium dioxide thin film doped with magnesium was effectively synthesized using the modified sol gel method. The prepared photoanodes were soaked in N719 dye in pure ethanol and sensitized for a day at an ambient temperature [12]. Subsequently, the sensitized photoanode was washed with ethanol to eliminate the dye molecules that were physically adsorbed on the surface. A counter electrode made of ITO coated with platinum (Pt) was created using the magnetron sputtering method. The sensitized photoanode was placed between the platinum counter electrodes. The atomic ratio of magnesium to titanium was modified to alter the light transmittance, band gap and photoelectric properties of TiO_2 films. Furthermore, Mg-doped TiO_2 film was used as the compact layer in dye sensitized solar cells. The findings suggest that the reduced amount of non-lattice oxygen and the modified energy band structure have a substantial influence on promoting increased photoelectron generation and minimizing recombination losses in solar cells. Moreover, the findings from electrochemical impedance spectroscopy and open circuit voltage decay indicated that the solar cell using a 15% Mg doped TiO_2 showed the lowest electron transport impedance and the greatest electron lifetime. Consequently, the DSSC using a 15% Mg doped TiO_2 layer achieves the highest photoelectric conversion efficiency of 7.84% surpassing the pure TiO_2 compact layer by 17.66%.

Gamma-irradiation offers an effective method to boost the performance of inexpensive, platinum free counter electrode by augmenting the quantity of active sites, thus enhancing their catalytic effectiveness in solar cells [13]. Novel chitosan @polyvinyl alcohol@titanium dioxide (CPT) hybrid films were produced as a catalytic counter electrode and exposed to various *in situ* gamma-irradiation doses aimed at enhancing their microstructural and physico-chemical properties. The surface properties of the treated composites enhanced gradually with rising gamma-doses, achieving optimal values at 30 KGy (for example, apparent porosity 72.2%, average roughness 5.3 μm) when compared to the unmodified counter electrode materials. Extended gamma-irradiation improved DSSC efficiency, reaching 6.45% at 10 KGy and 7.14% at 0 KGy. The high energy gamma-photons promoted the movement of charge carriers in the CPT compounds while minimizing recombination by establishing conditions that favour charge separation. Consequently, enhanced mobility and decreased resistive constraints lead to extended lifespans and more efficient charge transfer within the solar cell. In this context, the optimized yield of 8.57% and the short circuit photocurrent density of 19.1 mA/cm^2 for the CPT catalytic counter electrode were attained following 30 KGy of surface modification. In relation to the unaltered samples, effectiveness rose by 41.2%. The improvement in photovoltaic performance was ascribed to the incorporation of rich oxygen free radicals into the CPT structure, which established continuous pathways for swift electron transfer process.

Jaafar *et al.* [14] explored that the effects of TiO_2/eggshell composite at various ratios through the sol gel method, aimed at creating photoanodes in DSSC. The absorption spectrum showed a decrease in the energy band gap as eggshell concentration rose, resulting in an improvement in the solar cells. Incorporating eggshell improves the electrochemical characteristics of the photoanode. The electrochemical impedance spectroscopy (EIS) findings confirmed that adding eggshell can reduce charge transfer resistance and improve efficiency to 2.95% with a natural dye sensitizer for TiO_2/eggshell composite 3:10. Machine learning integration was used k-Nearest Neighbors (kNN) to forecast the maximum efficiency based on different samples during EIS studies. The kNN method showed DSSC with TE 3:10 demonstrated peak efficiency, achieving a prediction accuracy of 90%.

The counter electrode (CE) is an essential part of DSSC, gathers electrons from the external circuit and promotes the redox reaction in the electrolytes. It greatly influences photovoltaic efficiency, durability over time and expense of the device. Platinum coated FTO glass substrates are a valuable and commonly used counter electrode because of their outstanding electrical conductivity and remarkably electrocatalytic performance for reducing redox species in the electrolyte, with iodide/triiodide-based solutions being the predominant redox pairs used. Nonetheless, the corrosive properties and rarity of platinum restrict its application as a counter electrode in solar cells. To tackle these problems, comprehensive studies have been carried out to investigate different counter materials. Different options, such as carbon-based materials, conductive polymers like polyaniline (PANI), poly(3,4-ethylenedioxythiophene) (PEDOT), poly(3,4-ethylenedioxythiophene) polystyrene sulfonte (PEDOT:PSS) and polypyrrole (PPy) along with inorganic compounds such as transition metal sulfides, nitrides and carbides, have been effectively used as counter electrodes.

The PEDOT:PSS is composite in which PEDOT delivers electrical conductivity, while PSS serves as a counter ion to stabilize the charge and enhance the water solubility and processability of PEDOT. Polystyrene sulfonate is a sulfonated form of polystyrene. Some of the sulfonyl groups lose protons and have a negative charge. The other elements PEDOT is a conjugated polymer that possesses positive charges and is derived from polythiophene. The charged macromolecules combine to prepare a macromolecular salt. Kumar *et al.* [15] developed SnSe-rGO/PEDOT nanostructures and assessed their capabilities as counter electrodes. The solar cells made with SnSe-rGO/PEDOT:PSS counter electrode reached an efficiency of 8.78%, better than 8.13% efficiency using Pt counter electrodes. These results indicate that SnSe-rGO/PEDOT nanostructures have significant potential as a cheaper and more effective substitute for platinum in solar cells.

Akman and co-workers [16] introduced a functional nanocomposite to enhance the Cu_2S film by using single layer graphene (SLG) structures *via* chemical vapor deposition and applied this nanocomposite as a counter electrode (CE) alongside CdSe/ZnS core/shell quantum dots for a highly stable and efficient quantum dot sensitized solar cells. Furthermore, Cu_2S

film is synthesized directly on the SLG substrate using the electrodeposition method. Using this nanocomposite as counter electrode, we achieved a remarkable efficiency of 3.93%. This exceptional achievement is due to the increased surface area from the formation of nanoflower shapes, decreased charge transfer resistance, enhanced catalytic stability and surface smoothness coupled with effective adhesion. More crucially, there was no observable color change or detachment from the surface for the Cu_2S@SLG structure, indicating that the SLG framework plays a vital role in protecting the Cu_2S structure from sulfur ions in the electrolyte and enhancing the adhesion of the Cu_2S structure to the surface, thereby averting its degradation. As a results, the Cu_2S@SLG nanocomposite can serve as an efficient means to enhance the efficiency of solar cells.

A new quaternary composite featuring conductive poly-(3,4-ethylenedioxythiophene):polystyrene sulfonate (PEDOT:PSS) functionalized multiwalled carbon nanotube (f-MWCNT), nitrogen doped reduced graphene oxide (Nr-GO) and TiO_2 have been introduced as an economical counter electrode for DSSC [17]. The conductivity and structural characteristics of MWCNT have been adjusted by mixing it with PEDOT:PSS. A minor (25%) addition of conductive polymer diminishes the agglomeration and enhances the solution dispersion of MWCNT, which is obstructed by van der Waals and π–π stacking interactions of the individual tubes. The diminished agglomeration promotes effective electron transport routes, as shown by electrochemical impedance spectroscopy (EIS) and electron imaging methods. Of the three quaternary compounds analyzed, the 2:1:1 ratio of f-MWCNT/Nr-GO/TiO_2 demonstrates exceptional performance, exhibiting a charge transfer resistance of 7.27 Ω.cm^2 and a cathodic peak current density of -17.08 mA/cm^2. The cell attains an impressive photoconversion efficiency of 4.25% under standard testing conditions at AM 1.5G. The solar cells built with this quaternary composite counter electrode show enhanced cyclability and sustained chemical stability even following 500 reversible redox cycles.

Salam and co-workers [18] introduce an affordable DSSC that uses a TiO_2/ZnS heterostructure, with enhanced performance resulting from vacuum annealing of the TiO_2/ZnS layer. TiO_2 nanoparticles were deposited onto FTO glass substrates by using doctor blade method. The best sensitization of TiO_2 with N719 dye was reached after soaking for 20 h at a concentration of 0.2 mM, resulting in an efficiency of 1.91%. The photoanode was modified by applying ZnS onto the TiO_2 layer through the successive ionic layer adsorption and reaction method at 20 ºC, and then the heterostructure was treated to a vacuum annealing at 200 ºC for 2 h. The use of vacuum annealed TiO_2/ZnS as photoanode results in a notable enhancement in the external quantum efficiency within the UV-visible spectrum. The optimized device demonstrated an efficacy of 2.27%, an open circuit voltage of 0.67 V, a short circuit density of 7.59 mA/cm^2 and a fill factor of 44.79%.

Transition metal oxides typically exhibit lower conductivity than metals owing to their semiconducting properties. Therefore, adding a conducting polymer [19] such as polyaniline (PANI) can greatly enhance the conductivity of the resulting composites. This synergistic mix creates conductive routes, boots charge movement and enhances overall electrochemical performance, making it a promising candidate for counter electrode use. The $FeCo_2O_4$ (FCO) displays a flower like nanosheet configuration, while PANI presents an uneven coral reef structure. A flower-like structure is similar observed in the FCO/PANI composite. The composite surface seems rough and porous, enhancing the electrode-electrolyte contact as indicated by the contact angle measurement. The FCO/PANI composite shows the greatest electrocatalytic activity and the least charge transfer resistance with PANI, FCO and Pt following in order. The efficiencies of solar cell built with FCO, PANI, FCO/PANI and platinum counter electrodes are 4.22%, 5.58%, 6.38% and 3.58%, respectively.

Polymers have reliably shown to be a practical choice for improving the catalytic properties of molybdenum diselenide [20]. Choosing the right option promotes continual exfoliation, increases the surface area and boosts the flexibility of the dichalcogenide. Researchers used two beneficial conducting polymers, specifically poly(3,4-ethylenedioxythiophene) (PD) and polyaniline (PANI) to improve the performance of $MoSe_2$ in the solar cells. An ideal percentage is vital for creating a consistently disturbed, uniform and well separated system that enhances electrocatalytic sites and conductive attributes while offering flexibility *via* PD. Moreover, PD is used on its own, without the support of an additional polymer. Electrochemical studies show that composites exhibit excellent electrocatalytic capabilities, fast electron transfer rates and improved current flow in comparison to bare materials. The electrochemical analysis of the developed hybrid system revealed the effectiveness of significant electrocatalysts an outstanding device performance, achieve power conversion efficiency of 8.65%.

Pristine Zn_2SnO_4, Zn_2SnO_4-SnO_2 and Zn_2SnO_4-ZnO composites were prepared through simple solid-state calcination to prepare the photoanode for solar cells [21]. The analysis of XRD verifies the existence of multiple phases that depend on the stoichiometric ratio of the precursor materials. The examination of surface morphology shows that the Zn_2SnO_4-SnO_2, and Zn_2SnO_4-ZnO composites display micro-sheet and micro-rod structures, respectively. The composite materials exhibit an increased level of dye loading, resulting in superior performance compared to the unmodified Zn_2SnO_4 sample. An improved band alignment of the synthesized composite materials with other layers results in an increased carrier density. The composite photoanodes demonstrated greater efficiency (6.26% for Zn_2SnO_4-SnO_2 and 4.48% for Zn_2SnO_4-ZnO) compared to the pure Zn_2SnO_4 photoanode (3.7%).

Tang *et al*. [22] encourage the use of Zn_2SnO_4 nanoparticles in solar cells. A maximum light to electricity efficiency of 3.8% (fill factor of 0.66, open circuit voltage of 0.62 V, short circuit density of 9.3 mA/cm^2) has been attained. When compared to zinc oxide and SnO_2 as its basic component oxides, a Zn_2SnO_4 cell exhibits greater stability against acidic dyes than a zinc oxide cell, while outperforming a SnO_2 cell significantly. The findings indicate that multication oxides which offer a broad spectrum of compositions and adjustable properties, show significant potential as novel electrode materials for solar cells.

The mobility of TiO_2 is quite low (1 cm^2/Vs), which may restrict electron collection at the front electrode. When the devices are designed for use in semi-transparent solar cell

applications, these losses must be mitigated to maximize the obtainable photocurrent. Thus, Zn_2SnO_4 can serve as an alternative electron collection material to TiO_2 for the electron collection layer. The advantages of Zn_2SnO_4 compared to TiO_2 include its elevated band gap (3.6 to 3.7 eV) and increased electron mobility (10-15 cm^2/Vs). Furthermore, the electron affinity of Zn_2SnO_4 is about 0.1 eV greater than that of TiO_2, which enhances the efficiency of photoelectron collection from dye. Zinc stannate nanoparticles are produced *via* solvothermal techniques. The synthesized nanoparticles exhibit a face centered cubic spinel structure, as confirmed by X-ray diffraction (XRD) method [23]. Transmission electron microscopy (TEM) images show that the synthesized nanoparticles have a size of about 20 nm. A paste comprising synthesized nanoparticles are created for preparing photoanodes to be used in semi-transparent dye sensitized solar cells. As constructed devices featuring dye adsorbed Zn_2SnO_4 based photoanodes showed an efficiency of 0.86%.

The cubic spinel Zn_2SnO_4 and zeolite imidazole framework-8 (ZIF-8) nanoparticles were used as photoanode materials. The Zn_2SnO_4 was produced in an easy and economical way *via* hydrothermal method. The Zn_2SnO_4/ZIF-8 nanocomposite was applied onto TiO_2 compact layer to minimize charge recombination [24] at the interface between the transparent conductive oxide and mesoporous layer. The findings indicated that incorporating ZIF-8 into Zn_2SnO_4 enhanced the photovoltaic efficiency of the constructed devices. Additionally, in relation to pure Zn_2SnO_4, Zn_2SnO_4 + 15% ZIF-8 enhanced the open circuit voltage from 0.64 V to 0.77 V and the short current density from 6.89 to 11.27 mA/cm^2. The Zn_2SnO_4 + 15% ZIF-8 photoanodes enhanced the power conversion efficiency by approximately 195%, from 2.02% to 3.94% compared to the pure Zn_2SnO_4 photoanode. This was because the Zn_2SnO_4 + 15% ZIF-8 nanoparticles exhibited the fastest electron transport rate, optimal electron collection efficiency and the highest charge recombination resistance, all of which greatly enhanced device efficiency.

The rGO-containing Ce-doped Zn_2SnO_4 photoanodes are prepared *via* a simple ultrasonic assisted hydrothermal method [25]. The XRD peaks verified the successful preparation of the Ce-doped composite, preserving the fundamental spinel cubic structure of Zn_2SnO_4 and the effective attachment of rGO. Brunauer-Emmett-Teller analysis validated a larger specific surface area of 124.7 m^2/g for the rGO/Ce-doped Zn_2SnO_4 hybrid photoanodes. Achieving power conversion efficiency of 7.19%, an open circuit voltage of 0.85 V, a short circuit current density of 15.86 mA/cm^2, and a fill factor of 0.74, the solar cells using Ce-doped Zn_2SnO_4/rGO photoanodes showed the highest efficiency among the devices. The research demonstrated that the strategic integration of rGO and cerium into the Zn_2SnO_4 photoanode greatly enhances the power conversion efficiency values, highlighting an effective method for improving photovoltaic efficiency through material alteration process.

The hierarchical sphere and broccoli like array films of Zn_2SnO_4 grown on fluorine doped tin oxide glass substrates are prepared using *in-situ* solvothermal method [26]. The ethyleneglycol, ethylenediamine and polyvinylpyrrolidone K30 combined with NaOH in a mixed solvent are crucial for defining the product morphology. The 3D hierarchical Zn_2SnO_4 sphere photoanode used in solar cells improved power conversion efficiency (0.83%) compared to the broccoli-like array (0.69%), due to the greater N719 dye loading and enhanced light scattering ability.

A revised sol-gel method was used to synthesize $SrTiO_3$ nanostructures [27]. Various ligands were used to modify the sol gel process. A sandwich style solar cell was prepared using the as-deposited $SrTiO_3$. Eosin yellow has been used to enhance the sensitivity of the solar cells. The values of fill factor (0.59), open circuit voltage (62 mV), short circuit current (1.6 mA/cm^2) and power conversion efficacy (0.58%) were reported. The XRD findings indicate that the crystalline size grew as the annealing temperature rose, affecting the reduction of dislocation density and lattice strain [28]. TEM results show a spherical grain with an inter-planar distance of 0.27 nm. Brunauer-Emmett-Teller (BET) analysis indicates that sample has specific surface area of 20.97 m^2/g. TGA verifies that the synthesized materials remain stable up to 1000 ºC. The samples are used as photoanode for solar cells. Findings indicate that the highest efficiency of 1.12%, open circuit voltage of 0.63 V and short circuit current of 3.36 mA/cm^2. For $SrTiO_3$, Ti atoms are situated in six-fold octahedral coordination, akin to the titanium configuration found in anatase (TiO_2) and can be regarded as a doped TiO_2 structure. TiO_2 and $SrTiO_3$ share an identical band gap value of 3.2 eV, but $SrTiO_3$ possesses a greater flat band potential compared to anatase. Since, the conduction band of $SrTiO_3$ is 0.2 eV above that of anatase, it is anticipated that $SrTiO_3$ will produce better photovoltage. The $SrTiO_3$ is a promising material for the advancement of solar cells of its suitable band position.

Heterostructure $SrTiO_3$-TiO_2 (ST-TNTAs) nanotube arrays on fluoride doped SnO_2 conductive glass (FTO) were created using a three step *in-situ* hydrothermal method [29]. The ST-TNTAs featured TiO_2 nanotubes that vertically developed on the FTO substrates in a single crystallized rutile phase, whereas $SrTiO_3$ grains in the cubic perovskite phase were evenly spread across the TiO_2 surface. The sandwich types all solid-state dye sensitized solar cells were constructed using TiO_2 nanorods, nanotubes and ST-TNTAs as the respective photoanodes. After $SrTiO_3$ is deposited, the Fermi level position of the composite semiconductor increases, leading to a rise in open circuit voltage. At the same time, both the short circuit current density and the photoelectrical conversion efficiency initially rose and the fell with the quantity of $SrTiO_3$. When compared to TiO_2 nanorods and nanotubes, ST-TNTAs exhibited the highest photoelectrical conversion efficiency (5.42%) and external quantum efficiency in the visible spectrum along with the lowest electron transfer resistance. This further confirmed that $SrTiO_3$ served as an effective medium for electron transfer between TiO_2 and the photosensitizer.

Guoy & Yin *et al.* [30] introduce a new kind of $SrTiO_3$/TiO_2 nanosheet heterostructure developed through a simple hydrothermal technique. These substances offer a large surface area and porous surface, enhancing the dye loading ability and consequently increasing the photogenerated charges that contribute to the photocurrent. The production of heterostructures with a uniquely aligned band gap energy configuration can effectively separate photogenerated charge carriers.

Measurements of photoluminescence emission, electrochemical impedance spectroscopy and incident photon to electron conversion efficiency indicate a reduced recombination rate of photogenerated electrons and holes, along with an extended electrons lifetime for solar cells. The efficiency and the short circuit current density are improved compared to those of pure TiO_2 nanosheets. Solar cells also showed a peak short circuit current density of 12.55 mA/cm^2 and a maximum efficiency of 7.4% values.

Tang & Yin *et al.* [31] developed a new Sr-doped TiO_2/$SrTiO_3$ nanorod array heterostructure using a simple two-step hydro-thermal method. The treatment of rutile TiO_2 nanorod in $Sr(NO_3)_2$ solution leads to the self-doping of Sr into the TiO_2 lattice and the production of Sr-doped TiO_2/$SrTiO_3$, causing a shift in optical response properties from the UV range to the visible range. The separation of photogenerated electrons and holes can be efficiently achieved through the production of $SrTiO_3$/Sr-doped TiO_2 with a unique aligned band gap energy configuration. The capacity for dye loading on the hetero-structures can be enhanced *via* the functionalization bonding of the hydroxide group on the electrode material surface. Solar cells reached the highest efficacy of 4.7% almost 1.5 times greater than the unmodified TiO_2 photoanode (3.1%).

Novel electrode comprises an inner nanoporous TiO_2 with Nb_2O_5. The findings indicate that this Nb_2O_5 layer creates an intrinsic energy barrier [32] at the interface between the electrode and the electrolyte. This barrier decreases the recombination rate of the injected electrons with their corresponding holes. A comparison between two alike solar cells, which differ solely in their nanoporous electrodes, indicates that the solar cells use the new electrode outperform the conventional cells across all metrics. This advantage leads to a 35% rise in total conversion efficiency from 3.6 to 5%.

Zinc oxide electrodes with nanostructured porous features for solar cell were covered with niobium oxide layer through the sol gel method [33]. Coating solutions were prepared by combining niobium pentaethoxide with ethanol. A dip coating method was used with a slow withdrawal rate of 100 μm/s. The coated electrodes were subjected to heat treatment at temperatures ranging from 400 to 600 ºC. X-ray photoelectron spectroscopy (XPS) verified the presence of niobium in the coated electrodes. As anticipated, niobium oxide films served as an energy barrier between the ZnO and the electrolyte. The open circuit voltage of the cells with the coated electrodes increased to 0.768 V which was due to the reduction of recombination between photogenerated electrons and oxidized species in the electrolytes. Another advantage of the coating was that the growth of ZnO particle grains in the electrodes was suppressed, and the short circuit photocurrent density remained comparatively high owing to significant amounts of adsorbed dyes. The overall efficiency was raised to a peak of 5.19% showing the appropriate coating method was crucial for enhancing the performance of ZnO based solar cells.

Thermal energy is essential in the phase transformation of niobium oxide films, and when used as a blocking layer, these films can control charge transfer in solar cells. Niobium oxide films developed *via* the radio frequency (RF) magnetron sputtering method [34] experienced sequential phase transition from amorphous to orthorhombic and ultimately to monoclinic phases when exposed to post deposition annealing. At an annealing temperature of 900 ºC, the simultaneous presence of orthrohombic and monoclinic phases with a notable surface morphology is observed. The Ni_2O_5 blocking layer ate the FTO/TiO_2 interface impacted the photovoltaic parameters with the blocking layer in the orthorhombic phase proving to be the most effective at reducing charge recombination, achieving an efficiency of 7.3%. The enhancement in open circuit voltage can be anticipated as a movement of the Fermi level towards the conduction band edge of the TiO_2 due to the structural altercation of the Nb_2O_5 blocking layer. Thermal stability of the FTO was studied, revealing that its electrical and optical property remained exceptionally stable up to 600 ºC with significant changes starting from 700 ºC.

Kim & Moon [35] outlined the application of Nb_2O_5 coated TiO_2 3D porous electrodes in solar cells. Researchers used bilayer inverse opal structures as a framework for 3D porous structures and regulated the number of Nb_2O_5 coatings, which defined the concentration of the Nb_2O_5 layer. The consistency of the Nb_2O_5 coating was analyzed through elemental mapping with SEM and TEM techniques. Photovoltaic assessments showed an efficacy of 7.23% with 3.3% coating of Nb_2O_5 on TiO_2 structures. The Nb_2O_5 greatly enhanced the short circuit current density.

Cho *et al*. [36] examined the impact of Nb_2O_5 blocking layer created *via* the sol gel method applied to titanium foil electrode in solar cells. The blocking layer created directly on the working electrode physically isolates the working electrodes from the electrolyte and stops electron back transfer from the electrode to the electrolytes. The conditions for gel processing and the temperature of heat treatment used in creating the Nb_2O_5 blocking layer have been demonstrated to influence the performance of the solar cells, with optimal values of these parameter established. A sol reaction duration of 45 min and a heat treatment temperature of 550 ºC have been found to yield optimal cell performance (efficiency of 6.18%, fill factor of 0.694, open circuit voltage of 0.672 V, short circuit current of 13.2 mA/cm^2). The addition of Nb_2O_5 blocking layer boosts solar cell efficiency by 39.7% significantly surpassing the 24.6% improvement observed in a comparable cell with a TiO_2 blocking layer during standard illumination conditions.

Mesoporous submicrometric particles of orthorhombic Nb_2O_5 were prepared using straight-forward method [37] involving the hydrolysis of niobium ethoxide in an alcoholic solution with 1-hexadecylamine as a structure directing agent, followed by a hydrothermal method. By adjusting the solvent and the ratio of reactants to solvent, one can obtain various morphologies ranging from almost monodisperse beads to peanut shaped particles, aggregates of sintered spheres and a combination of different morphologies. The prepared materials were evaluated as photoanodes in solar cells. Following the enhancement of the photoanode thickness and its chemical treatment to strengthen the interparticle connections. The solar cells were prepared using N719 dye and stable iodide base electrolyte. An impressive efficiency rate of 3.4% was observed by using peanut shaped particles created with 2-propanol as solvent at the maximum reactant/solvent ratio employed.

Yen *et al*. [38] developed Nb_2O_5 film on fluorine doped tin oxide (FTO) photoanode through a simple dip-coating method. The results indicated that the blocking effect of Nb_2O_5 relies on the intensity of illuminance. The blocking effect is minimal under strong light conditions since the reduced reverse charge does not significantly impact the high-level injection of photo excited charges. The blocking effect is crucial for enhancing efficiency since the charge flux from photon injection considerably decreases under low intensity lightening (300-6000 lux). The performance of solar cells with a blocking layer can increase by 10% to 53% under low intensity light and this enhancement in efficiency is linked to better fill factor.

Thin film-based solar cells

Binary compounds: Cadmium telluride (CdTe) technology stands as the most successful commercially available thin film solar cell. By 2018, first solar had produced over 17 GW CdTe solar modules. To comprehend the mechanisms underlying efficiency loss in CdTe solar cells, the properties of nanoscale charge transport and grain boundaries in CdTe were methodically explored using photon excitation microscopy and scanning probe microscopy. The charge transport within the films is greatly influenced by the grain size, the passivation of grain boundaries and $CdCl_2$ heat treatment. A notable rise in yield stress was observed in CdTe crystal when comparing mechanical tests conducted in the dark and during the illumination, indicating that its mechanical characteristics are influenced by light. Moreover, the mechanical characterization through the nanoindentation method suggests that the substrate temperature during the deposition may also affect the elastic modulus of the films. For flexible applications, CdTe is a soft semiconductor with a significant lattice mismatch with the window layer CdS, which could affect the reliability of flexible CdTe solar cells. A significant quantity of dislocations and stacking faults in the CdTe film can lead to substantial irreversible deformation. The nanoscale mechanical properties of CdTe films under solar module operation are underexplored and the built-in electric field across the CdTe films might lead to device deterioration in addition to the widely recognized degradation caused by ion electromigration.

Binary antimony selenide (Sb_2Se_3) films hold great potential as an absorber material in inorganic chalcogenide compound photovoltaics due to their appealing anisotropic optoelectronic properties. Nonetheless, Sb_2Se_3 solar cells experience intricate and unusual intrinsic defects arising from the low symmetry of the quasi-1D crystalline structure, leading to a significant voltage loss that restricts maximum power conversion efficiency. Duan *et al.* [39] reported the fabrication of compact films exhibiting robust (001) orientation, excellent crystallinity, reduced deep level defect density, fewer trap states and minimal non-radiative recombination loss through injection vapor deposition. This deposition method produces higher quality films than close spaced sublimation and co-evaporation methods. The prepared film could achieve power conversion efficiency of 10.12%, due to minimized carrier recombination and superior carrier transport and extraction. This approach thereby creates a novel and efficient path for producing high quality films and other superior chalcogenide semiconductors.

Zinc telluride (ZnTe) is considered a promising photovoltaic material due to its favorable absorption coefficient, improved conversion efficiency and low cost in material production. The cell's performance was evaluated using SCAPS-1D [40]. XRD analysis revealed that all spin coated ZnTe films exhibit a cubic phase. The defining optical band gap values fell between 1.77 to 2.18 eV. The SEM images showed that the surface of the films annealed at 400 ºC exhibits superior coverage with homogeneity, excellent uniformity and fewer voids compared to the other annealed samples. The EDS analysis shows that all the films are rich in tellurium possess p-type conductivity. The maximum power conversion efficiency recorded was 17.45%, featuring open circuit voltage (V_{oc}) of 1.41 V, short circuit current density (J_{sc}) of 14.01 mA/cm^2 and fill factor of 88.53% for the optimal ZnTe thickness of 1184 nm, annealed at 400 ºC. The device identifies zinc sulfide, indium tin oxide, platinum and aluminum the buffer layers, transparent conductive oxide, back metal and front metal, respectively.

The morphology, optical properties and composition of zinc sulfide thin films prepared though the thermal evaporation method [41] were studied. The as-deposited ZnS films demonstrated excellent smoothness and displayed (111) preferential orientation. A band gap of 3.72 eV was derived from the optical transmittance spectra. The power conversion efficiency of the hydrogen doped AZO/ZnS/textured p-Si heterojunction solar cells reached 8.83%. The unencapsulated solar cell showed no degradation for over 2400 h, demonstrating the device's excellent stability.

Undoped and sodium doped ZnS films with concentrations of 1, 5, 10 and 15% were deposited on glass and silicon substrates using spray pyrolysis [42]. The photovoltaic properties of ZnS/Si heterostructure cells were studied through current voltage measurements. Band gap energy of the ZnS films decreased from 3.66 eV to 3.42 eV, while the film's resistivity reduced from 5.17×10^5 Ω·cm to 2×10^5 Ω·cm, as the sodium doping concentration was increased. The photovoltaic performance of the ZnS/Si heterostructure cell observed enhancement, raising its power conversion efficiency from 2.2 to 5.06%.

Thin film photovoltaic cells made up of CdS/Cu_2S demonstrate conversion efficiency greater than 9% have been developed and constructed [43]. Certain cell designs are developed based on an examination of the optical and electronic loss mechanisms that occur within the cells. Modifications to the materials and engineering of the fabrication process are then implemented to reduce the energy conversion losses. The current cell structure comprises five layers of films that are successfully applied onto a copper substrate is 35 μm thick. Besides the material control needed for every component layer, it is essential to ensure that electrical, chemical, mechanical and morphological compatibilities at the interfaces between each adjacent layer to accomplish the intended cell performance. The findings indicated that a completely optimized solar cell using a CdS/Cu_2S junction will reach a practical conversion efficiency limit near 11%. It is expected that practical conversion efficiency of 15-15% can be attained using a CdZnS/Cu_2S junction configurated to generate the highest open circuit voltage achievable with Cu_2S as the absorbing layer.

Cadmium sulfide (CdS) is part of the II-VI group and is usually deficient in sulfur, featuring sulfur vacancies along with a high electron affinity. This enables CdS to readily gain electrons, making the material n-type in character. The electron-hole pairs formed are distinctly separated with the electrons showing a high degree of localization. Thus, it is the most extensively studied nanocrystalline semiconductor for use as a photoanode in photoelectrochemical cells due to its appropriate band gap, extended lifetimes, significant optical properties, outstanding stability, straightforward fabrication and various devices applications. Jia *et al*. [44] prepared nanocrystalline CdS films on indium doped tin oxide glass substrates using a doctor's blade method. The original CdS powder was initially synthesized through a hydrothermal method and subsequently milled into a paste for screen printing by incorporating ethyl cellulose as a binder and terpineol as a solvent. A photocurrent of 3.51 mA/cm^2, a fill factor of 0.44, an open circuit voltage of 0.5 V, and a conversion efficiency of 2.2% were achieved under simulated solar light when the films were subjected to annealing at 380 ºC in air for 30 min. The highest quantum efficiency of 5.5% was achieved at the wavelength of 500 nm.

Results indicate that the CdS/CdTe solar cell exhibits significant series resistance, which negatively impacts the efficiency of energy conversion in the solar cells [45]. The thermal evaporation method was used to prepare both active layers (CdS and CdTe), which were then tested separately. It was found that 300 nm CdS window layer exhibits the lowest series resistance along with the highest light absorption. The 5-7 μm absorber layer captured over 90% of the incoming light with a minimal series resistance. It was observed that a deposited cell without heat treatment demonstrates that the increase in short circuit current diminished as light intensity rise. This kind of deposited cell exhibits low conversion efficiency. The energy conversion efficiency was enhanced through heat treatment, adding a heavily doped layer at the rear of the cell, and reducing contact resistivity by using materials with resistivity under 1 mΩ·cm^2. The efficiency of energy conversion was enhanced by over 7%. It was observed that minor variations in the thickness of CdS significantly impacted transmission. It should be stressed, however, that further reduction of CdS will enhance the resistivity of the layer, negatively impacting the electrical characteristics of the layer. A thicker CdTe layer is applied to ensure that the entire light is absorbed within this layer. CdTe film shows transmittance at short wavelength (500 nm), however, the transmittance becomes more evident at wavelengths exceeding 800 nm. The absorption edge moved to shorter wavelengths at an elevated annealing temperature (250 ºC). It is evident that the CdS sample treated at 250 ºC exhibited the lowest resistivity and consequently the highest photogenerated current. This is due to the absorption coefficient is extremely high, which is inversely related to resistivity. The material turns more n-type due to over-abundance of cadmium in the under layer and increased diffusion at grain boundaries or impurities included in the deposit.

The preparation of CdS/CdTe films was carried out using the YAG laser ablation technique [46]. The measured properties were V_{oc} 0.6V, I_{sc} 13 mA/cm^2, fill factor 0.4, power conversion efficiency 3%. In addition, the enhancements particularly in V_{oc} and fill factor, are anticipated by modifying the suitable composition of the CdTe films. A mass production technique for thin film solar cells is suggested by using a Mutli-target system.

Highly efficient CdS/CdTe solar cells featuring thin CdS films have been prepared using ultra-thin CdS films with a thickness under 0.1 μm. CdS films were deposited onto transparent conductive oxide/glass substrates using the metal organic chemical vapor deposition method [47]. CdTe films were then deposited using the close spaced sublimation method. The screen printing and sintering technique produced electrodes made of carbon and silver. The performance of cells is mainly influenced by the electrical and optical properties of CdS films. Researchers began developing superior CdS films and identified distinct variation between high and low quality CdS films based on analyses from scanning electron microscopy, atomic force microscopy and secondary ion mass spectroscopy. By managing the quality of CdS films, a photovoltaic conversion efficiency of 10.5% has been attained for a solar cell area of 1376 cm^2 under Air Mass 1.5 condition. This study presents a theoretical examination of a novel kind of thin films solar cells structured as glass/ITO/CdS/PbS/Al structure [48]. The transmission spectrum was determined by considering the multi-reflection effect from all cell layers and the absorption effects in the ITO and CdS layers. The computations of spectral internal quantum efficiency were conducted based on the recombination at the front and the back surfaces of the lead sulfide (PbS) layers. The losses from recombination in the space-charge region were examined. This study overlooked the impact of the metallic back contact, resulting in incomplete absorption losses occurring in the film an absorber layer. The results indicate that the 2 μm thickness of the absorber layer is inadequate to capture all the photons transmitted from the window layer (CdS) and the choice of these films (PbS) thicknesses is aligned with the experimental implementation of these devices. The optical and recombination losses result in 82% reduction in current density (I_{sc} 7.28 mA/cm^2) at PbS thickness of 0.5 μm. While these losses are reduced to 67% (I_{sc} 16 mA/cm^2) at a thickness of 2 μm. The power density output and cell efficiency improved as the thickness of the effective layer increased. The highest cell efficiency of 4.13% was achieved at a thickness of 2 μm.

A boosted conversion efficiency of approximately 3.1 for PbS/CdS thin film solar cells, achieved without using quantum dots [49], is shown by concentrating on the source of the improvement. The optical band gap of the PbS absorber is enhanced to a greater level by employing near room temperature deposition in chemical baths. The highest band gap of approximately 1.6 eV for p-type PbS, achieved at 40 ºC, creates a favorable band alignment with an n-type CdS layer for efficient light absorption and charge transfer. Both open circuit voltage and current density rise significantly to 280 mV and 20.93 mA/cm^2, respectively, through optimal alignment of the relative band gaps. The differences in crystallite size, surface roughness, the stoichiometric ratio of S/Pb and carrier concentration were examined as essential factors concerning the enhanced band alignment and photovoltaic characteristics.

Ternary compounds: Copper indium telluride serves primarily as a significant I-III-VI2 semiconductor, which is

used in the thermoelectric, photoluminescent, nanowire and photovoltaic applications. The direct band gap of $CuInTe_2$ ranges from 0.91 to 1.02 eV at ~27 ºC, which is marginally narrower than that of $CuInSe_2$ thin films (1.04 eV). A narrow band gap absorber (less than 1 eV) is essential for using the bottom cells in multi-junction solar cells. In comparison to $CuInS_2$ and $CuInSe_2$, $CuInTe_2$ offers a more pronounced quantum confinement effect and a larger Bohr radius, benefiting from the covalent characteristics of tellurium.

Jia *et al*. [50] showcased the ability of stearic acid to control the production of $CuInTe_2$ nanocrystals and out-lined a simple synthetic method for $CuInTe_2$ nanocrystals. The XRD confirmed the nanocrystals as sphalerite phase. The energy of the band gap was measured at 1 eV through the optical absorption spectra of the nanocrystal's dispersion. $CuInTe_2$ coatings were generally p-type and the testing apparatus was made up of layered configuration comprising Au/$CuInTe_2$/CdS/ZnO/indium tin oxide. $CuInTe_2$ nanocrystals were prepared using spray coating from a toluene dispersion and the annealing was not required for the nanocrystal layer. The results show the photovoltaic performance of a standard device exhibiting an open circuit voltage of 342 mV, a short circuit current density of 10.651 mA/cm^2, a fill factor of 0.335 and a power conversion efficiency of 1.221% under AM 1.5 conditions. The incident photon conversion efficiency (IPCE) aligned with the absorbance spectra. The comparatively evaluated IPCE of 22.5% for wavelengths ranging from 400 to 500 nm decreased at longer wavelengths. The robust photovoltaic reaction of IPCE in the 400-500 nm range may have resulted from the cadmium sulfide layer. The extended wavelength IPCE cutoff at 1250 nm matches the optical band gap (1.02 eV), while the steep decline in IPCE for wavelengths below 400 nm was due to zinc oxide light absorption.

$CuIn_3Te_5$ films (thickness ranging from 1.8 to 4 μm) were deposited on both uncoated and Mo-coated soda lime glass substrates [51] at a substrate temperature of 250 to 400 ºC *via* a single step co-evaporation process using a molecular beam epitaxy system. Well-formed (112) oriented grains were achieved by increasing the film thickness at a substrate temperature of 250 ºC. Cathodoluminescent analysis and temperature dependent Hall measurements suggest that the presence of shallow defect levels in the films developed at elevated temperatures. A maximum efficiency solar cell (temperature 250 ºC and film thickness 4 μm) achieved a total area (0.504 cm^2) of 6.28%. The mechanisms of recombination in CdS/$CuIn_3Te_5$ films are examined using the temperature dependent electrical characteristics of the films and their solar cells.

A method for preparing nanocrystalline $CuInS_2$ films with high purity at low temperatures (less than 350 ºC) is developed using a low-toxicity molecular precursor solution [52] that includes $In(OH)_3$ and Cu_2O in butyldithiocarbamate acid and ethanol under ambient conditions. The as-deposited films showed a copper deficient composition and band gap values ranging from 1.53 to 1.58 eV. Researchers created a planar heterojunction solar cell designed as FTO/CdS/$CuInS_2$/spiro-OMeTAD/Au. The top device using $CuInS_2$ film treated at 350 ºC achieves an average power conversion efficiency of 1.79% and demonstrates strong stability. According to the XRD patterns, all the films show three diffraction peaks at 28º, 46.5º and 54.7º, which correspond well to the (112), (204)/(220) and (112)/(316) crystal planes of the chalcopyrite phases, respectively. Based on diffraction peak (112), the average grain size is estimated to be approximately 4.3, 6.9 and 8.1 nm for the as-deposited films subjected to annealing different temperatures.

Septina *et al*. [53] demonstrated the ink-based production of $CuInS_2$ based materials at low temperatures. Molecular ink consisting of metal chlorides and thiourea dissolved in methanol was applied *via* spin coating onto soda lime glass substrates with am molybdenum coating. The samples were subsequently positioned on a hot plate (temperature was 250 ºC) to facilitate the formation of films and eliminate the solvent and secondary products. It was observed that no additional processing such as high temperature sulfurization was conducted. The proposed structure's solid-state photovoltaic performance (lacking platinum catalyst) was assessed with PEC analysis. The cell exhibits a relatively elevated open circuit voltage of 0.82 V with a photocurrent density of 7.4 mA/cm^2, like the one observed in PEC configuration (8.8 mA/cm^2). Nonetheless, the comparatively low fill factor (34.84%) restricts the power conversion efficiency of the cell (2.11%), likely due to bulk recombination within the CIS films.

Solar cells based on $CuInS_2$ are fabricated [54] using a rapid thermal process (RTP). Copper and indium are later deposited as a layered elemental stack *via* DC magnetron sputtering onto substrates of float glass coated with molybdenum. Researchers used a sequential method involving metallic layers of copper and indium quick heated in elemental sulfur vapour. All samples are prepared with excess copper, maintaining an atomic ratio of [Cu]/[In] = 1.8. To form $CuInS_2$, a swift thermal method is carried out in a specially designed halogen lamp furnace using a quartz tube as the reaction chamber. The samples are quickly warmed by radiation from the front to 600 ºC. From te SEM images, the grain size measures approximately 1-2 μm, like layers produced by a standard heating process. The cross section displays a sealed layer and tops the back contact, although this layer is quite uneven. Therefore, the presence of pin holes in the absorber layer cannot be ruled out based on these observations. The bonding of the absorber layer to the molybdenum back contact appears to be inadequate. The absorber layers produced by this process exhibit excellent crystallinity, as indicated by XRD. Solar cells made from these RTP absorbers have achieved a total area efficiency of 11.4% (A=0.5 cm^2).

The effective conversion of solar energy using $CuInS_2$ films is also reported [55]. The p-type absorber with a higher copper content is prepared through the thermal co-evaporation method. A copper to indium ratio in the range of 1 to 1.8, can be accepted with minor losses in solar -to-electrical conversion. Copper excess phases (CuS) are eliminated through the chemical reactions. The cell configuration glass/Mo/p-$CuInS_2$/n-CdS/ZnO/Al produces 10.2% under simulated AM 1.5 conditions. A sharp increase in the current collection at 1.5 eV suggests an adequate diffusion length for minority carriers within the absorbing $CuInS_2$ layers. A maximum quantum yield of 83% is achieved at a wavelength of 560 nm. The reduction of the quantum yield at 500 nm is related to the light absorption in the thin layers with a band gap of 2.42 eV.

Since minority carriers generated within experience highly efficiency interface recombination, unlike electrons from the absorbed layers, the resulting current is diminished. It should be noted that the significant deviation in molecularity present in the as-deposited state is eliminated following the cyanide treatment. Therefore, variations in composition can be accepted because of the chemical modification of the film's make-up. This revised method could enable future scaling up of this kind of solar cells.

Cu-In precursors were prepared through the electro-deposition method [56]. The process was conducted potentiostatically (-0.8 V to -1 V *versus* Ag/AgCl electrode) in water solution with $CuCl_2$ and $InCl_3$. The pH of the solution was adjusted by adding HCl, yielding a pH range of 3.22 to 1.74. To produce $CuInS_2$, the Cu-In precursor films that were deposited initially were subjected to annealing in sulfur vapour at 500 ºC for 60 min. Grain enlargement during the annealing process was noted in the scenario of Cu-rich films. Thin films of $CuInS_2$ were prepared through the sulfurization of Cu-In precursors that were electrodeposited. The morphological enhancements allowed to produce solar cells with electrodeposited Cu-In precursors. Morphology analyses indicated that a film exhibiting excellent morphology and grain size of 1 μm can be achieved without the addition of HCl. The concentration of HCl had a minimal impact on the composition of the films. A conversion efficacy of 1.3% was achieved through photovoltaic properties.

$CuInSe_2$ absorber layers for thin film solar cells were produced by selenizing amorphous Cu-In-S nanoparticles, which were developed *via* a low temperature colloidal method without the need for external heating [57]. This work used two approaches to achieve highly dense absorbed films. The initial method involved modifying the surface of nanoparticles through the chelate complexation with ethanolamine, while the second method capitalized on the lattice expansion that resulted when the sulphur atoms in the precursor particles were substituted with selenium during the selenization process. The combination of these two approaches facilitates the creation of highly dense films and devices made with the absorber films exhibited efficiency of 7.94% under AM 1.5 illumination without an anti-reflection coating.

A straightforward and direct coating method for preparing $CuInSe_2$ films was outlined, using an inexpensive and eco-friendly precursor solution [58]. The precursor solution was prepared by blending metal acetate, ethanolamine and ethanol. The simple creation of a precursor solution without requiring the pre-fabrication of nanoparticles allows for quick and straightforward processing. The solution's high stability in air additionally guarantees the precursors preparation and film deposition in normal conditions without a glove box. The solar cell made with the absorber film prepared through this method exhibited an initial conversion efficiency reaching as high as 7.72%.

Quaternary compounds: Zhi *et al*. [59] use the single step co-evaporation method for CZTS (Cu_2ZnSnS_4) solar cells on soda lime substrates. To begin with, the reduction in series resistance resulting from the removal of ZnS blocking layer enhances the power conversion efficiency. Higher purity CZTS films are achieved by limiting the re-evaporating of volatile phases containing tin, resulting in a significant improvement in overall photovoltaic performance. The decline in efficiencies with high tin vapour suggests that the saturation level of tin content is vital in CZTS formation during the decomposition. Rather than relying on remedial annealing, which begins solely at the surface, on-site deposition and reaction enhance lateral uniformity by consistently controlling the film growth and ensuring improved film quality and integrity. By implementing prompt optimizations, a power conversion efficiency of 4.3% is attained along with a significant open circuit voltage of 608 mV. The findings confirmed the feasibility and practicality of the single-step co-evaporation method. The decomposition of CZTS, also referred to as chemical equilibrium, is examined at various substrate temperatures. Temperature conditions should be chosen since CZTS thin films can experience significant decomposition and loss of compactness at excessively high temperatures. From the viewpoint of chemical dynamics, the elimination of tin is essential to the decomposition process of CZTS films. By managing those unstable components, the produced devices achieve notable improvement in photovoltaic performance.

Yan *et al*. [60] report a certified 11% efficiency thin film solar cell exhibiting a high open circuit voltage of 730 mV, achieved through heat treatment to mitigate heterojunction recombination. This thermal treatment enhances elemental interdiffusion, causing cadmium atoms to directly occupy zinc or copper lattice positions and encourages sodium buildup alongside a local copper shortage in the heterojunction area. As a result, new phases develop at the hetero interface leading to a more favorable conduction band alignment that helps decrease non-radiative recombination. Researchers also showcase a certified centimeter scale (1.11 cm^2) photovoltaic device with 10% efficiency. This marks the first kesterite cell of standard centimeter size to surpass 10%.

Through the vacuum process, Tajima *et al*. [61] produced Cu_2ZnSnS_4 solar cells that demonstrated an efficiency of 8.4%. This is the maximum efficiency documented for pure sulfide produced by any technique. In line with existing literature, the best composition is copper deficient and zinc abundant, even with the formation of secondary phases such as ZnS. Despite a very thin absorber thickness (~ 600 nm), a good short circuit current was achieved. Time resolved photoluminescence measurements indicate a minority carrier diffusion length in the range of several hundred nanometers and efficient collection of photo carriers throughout the full thickness of the absorber. The films were deposited on Mo-coated soda lime glass substrate using thermal evaporation method in a vacuum setup featuring Knudsen-type sources. The substrate temperature throughout the growth process was maintained at a relatively low level (about 150 ºC) to reduce the risk of secondary phase formation at the CZTS/Mo interface caused by the high volatility of tin sulphide. Following evaporation, a brief duration (5 min) anneal at atmospheric pressure was conducted at 570 ºC. The remaining device structure includes 90-100 nm thick CdS deposited *via* chemical bath, 80 nm intrinsic ZnO and 450 nm Al doped ZnO through sputtering method, Ni-Al metallic fingers and a 100 nm MgF_2 anti-reflection layers.

To enhance the photovoltaic characteristics of solar cells, researchers examined how the thickness of the prepared films and the post annealing temperature after CdS deposition influence the photovoltaic properties of solar cells using a two-layer CZTS configuration. With the deposition of thin CdS layer (40 nm) and subsequently high temperature annealing (603 K), Shin *et al*. [62] observed a significant rise in short circuit current density due to the improved external quantum efficiency in the 400 to 800 nm wavelength range. The top CZTS cell demonstrated a conversion efficiency of 9.4% in the active region (9.1% in the specified area). Furthermore, researchers developed a CZTS cell with an open circuit voltage of 0.8 V by carefully adjusting the composition of the CZTS layers. The fundamental manufacturing technique for the CZTS cells is outlined. Initially, 0.7 μm thick layer of Mo electrodes was prepared on alkali glass substrates *via* sputter deposition. A two-layer configuration was used for the CZTS absorber layers with an overall thickness of approximately 1200 nm. To create the initial CZTS layers, precursors were applied through electron beam and RF magnetron sputtering using Cu, Sn and ZnS targets to establish a Cu/Sn/ZnS/Mo/alkali-glass configuration, which was subsequently sulfurized at 853 K for 20 min in H_2S and nitrogen atmospheric pressure. The rates of heating and cooling were 5 and 10 K/min, respectively. The second CZTS layers were fabricated in a similar manner by depositing another set of precursors to produce ZnS/Sn/Cu/CZTS/Mo/alkali-glass and sulfuring them in H_2S-N_2 gas at 773 K for 1 h. The XRD profiles of one or two layered CZTS do not show any impurity phases, whereas the Raman spectroscopy verifies that the layer was CZTS. Nevertheless, the Raman peaks at 287 and 373 cm^{-1} are weak, indicating that the CZTS exhibits some structural disorder. MoS layer is observed at the CZTS/Mo and ZnS interface in the CZTS layer as confirmed by STEM-EDX, and the CZTS layer exhibits a porous structure. The existence of phase disorder, the microstructure, and the MoS layer might result in elevated Rs and diminished mobility, thereby reducing the photovoltaic performance.

A multistage co-evaporation technique for the direct fabrication of CZTS films without supplementary atmospheric sulfurization was examined [63]. To achieve consistent films, *in situ* monitoring of the film growth was established by assessing the apparent substrate temperature with a pyrometer. The results supplied strong proof that the formation of the CZTS phase was notably postponed due to the re-evaporation of Sn-S based compounds during the initial part of first stage, resulting in the primarily creation of a prevailing (CuS + ZnS) structure that existed alongside a minor quantity of CZTS. The formation of the CZTS phase was aided by the (CuS + ZnS) precursor through a transition from copper rich to copper poor conditions, exhibiting a significant change in substrate temperature during the subsequent stage, while the marginally separated CuS phase was almost entirely used under (Zn + Sn + S) flows. As a result, CZTS films featuring densely packed grains with a single kesterite structure were effectively fabricated under elevated tin and sulfur flux conditions, even at moderate substrate temperature below 500 ºC. The most efficient solar cell with a glass/Mo/CZTS[Cu/(Sn + Zn)] = 0.71, Zn/Sn = 1.6]/CdS/ZnO:Ga structure and a NaF precursor layer achieved on active area was 3.83% (fill factor = 0.603, J_{sc} = 11.3 mA/cm^2, V_{oc} = 567 mV).

Highly effective copper zinc tin selenide film was prepared using the electrodeposition method. A copper-poor, zinc-rich metallic alloy precursor film is deposited directly from a single aqueous bath [64] using a constant current, and the precursor transforms into CZTSe films when annealed in a selenium atmosphere at temperatures between 400 to 600 ºC. The crystallization of CZTSe initiates at 400 ºC and finishes at 500 ºC with crystal growth persisting at increased temperatures. Due to the trade-offs between improved crystallinity and subpar physical characteristics, CZTSe films were treated at 550 ºC demonstrate optimal and stable device performance, achieving an active efficiency up to 8%. Additional examination of the electronic characteristics and a comparison with a leading device created from a hydrazine-derived solution indicated that conversion efficiency may be enhanced by fine tuning factors such as film thickness, anti-reflection coating, $MoSe_2$ development and p-n junction design.

Nano-ink solution method was used as an inexpensive approach for producing $Cu(In,Ga)Se_2$ film solar cells [65]. The study examined the sonochemical production of CIGSe nanocrystals in the nano-ink by incrementally combining the reactants. To obtain the optimal stoichiometry of $Cu(In_{0.7}Ga_{0.3})Se_2$ for adjusting the band gap and producing high efficiency photovoltaic cells, the synthetic conditions, hydrazine concentration and quantity of gallium precursors used were studied. With the rise in hydrazine concentration, a loss of gallium was observed in the CIGSe products and the amount of Ga in the reactant mixture significantly influenced the metal stoichiometry of the synthesized CIGSe nanocrystals. The production of thin film solar cells showed a conversion efficiency of 5.17%.

Thin film photovoltaic devices were also prepared through selenization of oleylamine-capped $Cu(In,Ga)Se_2$ nanocrystals were sintered [66] at elevated temperatures (more than 500 ºC) in the presence of selenium vapour. The performance of the devices changed notably with the [Ga]/[In+Ga] ratio in the nanocrystals. The maximum power conversion efficiency was 5.1% under air mass 1.5 global light, with [Ga]/[In+Ga] = 0.32. The changes in power conversion efficiency with composition are partly due to band gap tuning and optimization, yet the primary effect of nanocrystal composition seems to be on the quality of the sintered films. The [Cu]/[In+Ga] ratio was observed to be significantly affected by the [Ga]/[In+Ga] level, which seems to be linked to the morphology of the sintered film. Consequently, just minor alterations in the [Ga]/[In+Ga] ratio led to notable differences in device performance.

Liu *et al*. [67] reported the direct production of extensive $Cu(In,Ga)Se_2$ nanotip arrays through a single step Ar^+ milling method without any template. By managing milling duration and incident angles, the length of CIGS nanotip arrays with variable tilting orientations can be accurately regulated. The criteria for forming these nanotip arrays have been addressed with respect to surface curvature, various components and crystal quality, leading to a significantly anisotropic milling effect. The nanotip arrays exhibit extremely low reflectance of less than 0.1% at incoming wavelengths ranging from 300

to 1200 nm. The open circuit voltage and short circuit current were found to be 390 mV and 22.56 mA/cm^2, resulting in a fill factor and efficiency of 59% and 5.2%, respectively. Unlike the CIGS film solar cells that achieve an efficiency of 3.2%, the nanostructured nanotip arrays can experience an efficiency boost of approximately 160% owing to their superior light absorption capabilities resulting from the nanostructure. The advantages of the present method involve the most recent technique through a template free direct fabrication process of nanostructured nanotip arrays, allowing for manageable dimensional and large-scale manufacturing without a post selenization steps.

Tokita *et al*. [68] suggested new In(OH)$_3$:Zn^{2+} buffer layer to prepare high efficiency CIGS solar cells. This buffer layer was applied using a solution made up of $ZnCl_2$, $InCl_3$ and thiourea. The buffer layers demonstrated excellent crystallinity and uniform film coverage for extremely thin films on the uneven CIGS surface, with no optical absorption loss at shorter wavelengths. The benefits of Zn^{2+} ions lie in its doping influence on the CIGS surface area, leading to increase efficiency and minimal light soaking effect. The solution of pH was modified to pH 3.6 to regulate the deposition rate. The quartz was used as substrate during the formation of films *via* molecular beam epitaxy method. In(OH)$_3$:Zn^{2+} films exhibitted elevated resistivities of 2.1×10^8 Ω·cm and transmittance exceeding 95% within the visible spectrum. Researchers anticipated two outcomes from this new buffer layer. The first is the preparation of a passivation layer on the CIGS surface, and the second is zinc doping within the CIGS layer, leading to the development of a buried junction. A cell efficiency of 14% (V_{oc} = 0.575 V, I_{sc} = 32.1 mA/cm^2, fill factor = 0.758) was attained by using a specific buffer layers, without using the light soaking effect.

Penternary compounds: Recently, the earth abundant kesterite $Cu_2ZnSn(S,Se)_4$ absorber material has been extensively researched for thin film solar cells (TFSCs) applications, due to its affordable, non-toxic components and appropriate optoelectronic characteristics. The maximum power conversion efficiency (PCE) of CZTSSe films was approximately 13% [69] is significantly lower than the Shockley-Queisser limit (31%) and the efficiency of CIGS films (23.4%) and CdTe films (22.1%) equivalents. Several strategies have been formulated and efforts have been undertaken to enhance the PCE of kesterite. These investigations have demonstrated that the performance of the device is primary influenced by the design and the production of each layer. For example, a minor alteration in the compositional ratio of a CZTSSe absorber layer can lead to subpar device performance because it can easily cause a high occurrence of anti-site defects and secondary phases. Likewise, alterations in the deposition conditions of transparent conducting oxide (TCO) result in changes to their optoelectronic properties, which impact the device's PCE. It indicates that comprehensive experiments need to be conducted to achieve an additional advancement in PCE. Nonetheless, in the multi-layered thin film solar cells, the ongoing optimization of each layer leads to energy loss and the depletion of available material resources, which ultimately raises the expense of experimentation and requires more human effort. Consequently, to reduce the duration and total expense of the experiments, it is recommended to use high throughput machine learning (ML) analysis methods.

The initial stage in the ML supported design of TFSCs involves pinpointing potential rules and heuristics linked to the synthesis conditions like annealing duration, temperature, pressure, compositional ratio and so on. In this context, the primary fabrication process of devices, annealing parameters, and compositional ratios are used to develop the ML models of the thin film solar cells. The engineering of band gap energy and the influence of the S/Se ratio on thin film solar cells device performance could be another aspect of the investigation and is therefore deemed outside the scope of the current ML study. The production of CZTSSe films has been developed by Karade *et al*. [70]. The tri-layer stacked metal precursors (Cu/Sn/Zn) were applied onto a Mo-coated soda lime glass substrate using the direct current (DC) sputtering technique at ambient temperature. Furthermore, the metallic precursors underwent soft annealing in an argon environment and were later subjected to annealing in a graphite box using a chamber type rapid thermal annealing system within a chalcogen vapour atmosphere. Following the annealing process, the chamber was permitted to cool naturally, and the annealed films were taken out at room temperature.

The annealed thin films underwent KCN treatment to eliminate the secondary phases from the absorber surface. The n-type CdS layer was developed using chemical bath deposition method to form a p-n junction. The i-ZnO and AZO films were applied using radio frequency sputtering. Ultimately, to construct the TFSC devices, an aluminum metallic grid was developed using a DC sputtering method with the Al/AZO/i-ZnO/CdS/CZTSSe/Mo/glass configuration. To achieve this, more than 25000 data points were extensively gathered by producing over 1300 CZTSSe devices and evaluating them through different ML methods. Through comprehensive ML analysis, it is determined that i-ZnO thickness is the primary factor [70], while the Zn/Sn compositional ratio and sulfo-selenization temperature are also crucial governing elements affecting thin or thick i-ZnO thickness to reach over 11% PCE value. Considering these essential governing factors, the utilized random forest ML prediction model for PCE demonstrated an adjusted R^2 exceed 0.96.

A study on a two-step selenization approach to regulate the growth kinetics of a CZTSSe film from an aqueous solution for enhanced solar cell efficiency is reported [71]. Through the synergistic use of high and low temperature selenization to enhance CZTSSE phase formation, introducing advantages point defect states, arrange the interfacial energy band structure, and maintain superior surface microstructure, an overall cell efficiency of 12.5% has been realized. These findings highlight the importance of regulating the crystallization growth of CZTSSe to enhance device performance. The excellent cell efficiency attained here is like that of cells based on hydrazine or DMSO solutions, which would help in advancing the development of CZTSSE solar cells towards a broader range of film fabrication methods.

Raising the sulfur content to expand the bandgap enhances the voltage but often sacrifices efficiency. Antunez *et al*. [72] reported the significant advancements on this key issue by developing the solar cells with elevated sulfur levels that

demonstrate efficiency reaching 11.89% and open circuit voltages of up to 670 mV. In a multistep procedure, operational solar cells are detached from their growth substrates, after which a back contact with high work function is applied. Using this method, researchers created a series connected device that generates 5.7 V when exposed to sunlight and ~2V under lighting conditions.

A highly efficient CZTSSe thin film solar cell was prepared using an electrochemical deposition method [73], then subjected to thermal annealing. The Cu-Zn-Sn alloy films were deposited on Mo-coated glass substrate *via* a one-pot electrochemical method, and the metallic precursor films were subjected to anneal in a mixed environment of selenium and sulphur, resulting in CZTSSe films with band gap energies between 1 and 1.2 eV. The compositional alteration of the S/(S+Se) ratio reveals a trade-off between photocurrent and photovoltage, leading to an ideal band gap of about 1.14 eV. Moreover, the higher sulfur content close to the p-n junction decreases the dark current and interface recombination, leading to a further improvement in the open circuit voltage. Because of the medications in composition and interfaces, the top CZTSSe-based film solar cells show a conversion efficiency of 9.9%, ranking it among the highest efficiency documented to date for electrochemically deposited CZTSSe thin film solar cells.

Perovskite solar cells: Perovskite solar cells are a promising technology enabling renewable electricity generation and utilize perovskite materials (generally hybrid organic inorganic lead or tin halide-based perovskites) as the light capturing layer. These devices provide possibilities for high efficiency, low cost of fabrication, and flexible or light weight design, so they are considered for a variety of applications including building-integrated photovoltaics. Despite their early stage of development, perovskite-based solar cells have yet to demonstrate significant efficiency improvements that could surpass the theoretical limits of traditional silicon-based cells and accelerate the transition to a carbon-neutral society. Building integrated photovoltaic (BIPV) denotes the integration of photovoltaics into building elements which are naturally considered as a standard part of the building *e.g.* roof tiles, skylights or facade panels, which are used to generate electrical power and support the building itself [74]. Building-integrated photovoltaics are not added to a structure as an afterthought; instead, they are incorporated into the design from the outset, providing a more holistic and seamless solution. Perovskite solar cells use materials with a perovskite structure–most commonly organic-inorganic hybrid ($CH_3NH_3PbX_3$) in the form of a thin film. Thin-film devices are constructed from thin layers of material that are either deposited in a vacuum or printed, indicating their compatibility with scalable and flexible manufacturing processes [75], coated or deposited on a substrate. High efficiency perovskite solar cells have made rapid progresses [76], which have reached over 25% in lab. Many workers have also conducted study on thin-film perovskite cells combined with platinum polycrystalline silicon tandem solar cells in Mentor, Ohio. Compact perovskite cells have now achieved efficiencies of approximately 32.5%. The flexibility and versatility of perovskite solar cells make them suitable for numerous applications, from flexible solar panels to even tandem solar cells coupled with silicon [77].

Photovoltaic parameters in perovskite solar cells: The low stability of organic charge transport materials and the expensive or corrosive properties of meal electrode materials impede the real-world commercial use of perovskite solar cells. In this context, carbon-based perovskite solar cells using affordable carbon materials and natural prevention of moisture penetration are anticipated to be strong contenders for extensive real-world applications [78]. The studies on carbon based perovskite solar cells primarily concentrate on carbon serving as materials for hole transfer layers and counter electrodes. The carbon layer can be created using straightforward blade coatings or through screen printing. The equipment for high vacuum in metal electrode preparation is now unnecessary. Consequently, the device design and fabrication process can be streamlined.

Typically, perovskite solar cells that use carbon electrodes are made flowing the formation of perovskite and the application of other hole transport materials such as PTAA or spiro-OMeTAD. Carbon serves a similar function as Ag or Au in back contact. The carbon-based perovskite solar cells are produced without the use of any additional hole transfer layer materials. Carbon materials can be applied as hole transfer layers either prior to or following the preparation of the perovskite layer. Carbon based perovskite solar cells without hole transfer layer materials offered several advantages [79]. They can be prepared at low temperatures and carbon materials possess inherent hydrophobicity. Carbon layers can also hinder efficiency migration in perovskite solar cells, which is a primary factor contributing to the decline in performance of metal electrode based perovskite solar cells. Nonetheless, the inadequate interface quality between the carbon film and hole transfer materials restricts the performance of carbon-based perovskite solar cells. Conversely, in carbon-based perovskite solar cells without a hole transport layer, the materials used for carbon hole transport layers are ineffective at efficiently separating photo-generated electrons and holes due to the relatively high work function of carbon.

Spiro-OMeTAD is the predominant hole transport layer materials used in $MAPbI_3$ solar cells due to its higher conduction band position [80] and lower valence band position compared to perovskite. These band positions enable the movement of holes from $MAPbI_3$ to spiro-OMeTAD while preventing the backward transfer of electrons due to thermodynamic principles. Nonetheless, spiro-OMeTAD exhibited low conductivity and has reduced intrinsic charge carrier mobility.

Jiang *et al.* [81] used a multi-functional hole transport layer, a dopant free spiro-OMeTAD combined with carbon nanotubes (CNTs-spiro) to connect the interface between carbon and perovskite and enhanced the energy band alignment in carbon-based perovskite solar cells. The power conversion efficiency of perovskite solar cells featuring the CNTs-spiro layer (10.45%) shows a 17.5% improvement over the perovskite solar cells lacking the CNTs-spiro layer (8.62%). The non-encapsulated devices exhibited remarkable stability when exposed to air, light or environmental conditions. Transparent conductors made from silver; nanowires are anticipated to see broad application in optoelectronic devices [82]. Nonetheless, when applied in perovskite solar cells, it faces significant corrosion due to the lead halide hybrid perovskite. Nickel electro-

plating is used to alter the transparent conductor for problem resolution. Nickel electroplating has been observed to enhance conductance while also boosting corrosion resistance and oxidation resistance of the transparent conductor. Furthermore, SnO_2 quantum dots are used to smooth the conductor surface, while ITO sputtering is used to enhance the film conductivity even more. Subsequently, perovskite solar cells are made on the altered transparent conductors. Scanning the current voltage curves under simulated irradiation demonstrated that a power conversion efficiency of 18.37%. Transient photocurrent/photovoltage decay profiles and impedance spectroscopy measurements indicate that nickel treated transparent conductors can facilitate an effective charge extraction process while slowing down charge recombination. The storage stability of device is observed, retaining 80% of their initial performance after being stored in the dark for 432 h.

Poly(bis(4-phenyl)(2,4,6-trimethylphenyl)amine) (PTAA) was selected as the carrier transport layer, while polymethylmethacrylate (PMMA) was chosen as interface modification layer, aimed at enhancing the low-temperature durability of solar cells by alleviating mechanical stress and controlling the strain type of perovskite. It was observed that the $MAPbI_3$ solar cells incorporating PC61BM and PTAA transport layers showed unique low-temperature properties when compared to those with TiO_2 and spiro-MeOTAD transport layers. In particular, the open circuit voltage and short circuit current showed a consistent rise, while the factor tended to improve at first and then quickly diminished as the temperature decreased for the device lacking PMMA. Consequently, the decline in fill factor is a significant reason for the slowdown of power conversion efficiency a round and beneath the phase transition temperature. The introduction of the PMMA interlayer significantly enhanced the open circuit voltage, effectively mitigated the decline of fill factor, and lowered the crystallographic phase transition temperature of $MAPbI_3$ from 170 to 130 K, thereby greatly boosting the photovoltaic efficiency of $MAPbI_3$ solar cells at low temperatures [83]. Consequently, an optimal efficiency of 22.4% at 90 K was reached, surpassing the control device peak efficiency of 21.1% at 170 K. This efficiency is the highest reported among all $MAPbI_3$ solar cells with a p-i-n structure at low temperatures.

A design of triphenylene derivative (T-6TPA) with triphenylamine groups grafted as dopant free hole transporting layers has been reported [84]. The greater π-conjugation in T-6TPA results in a high hole mobility of 2.06×10^{-3} $cm^2/V{\cdot}s$. Furthermore, the extraction of interfacial holes in T-6TPA was greatly improved when the molecules were introduced into the perovskite prior to the deposition of the hole transporting layers. The infiltration technique using the anti-solvent dripping approach enhanced power conversion efficiency from 18.5% to 20.3% surpassing another additive doping method (anti-solvent dripping = 19.3%). The efficiency of anti-solvent drip-ping is due to the formation of a consistent and uniform hole transport channel. The hydrophobic properties and elevated glass transition temperatures of T-6TPA also provided remark-able moisture and thermal stabilities, allowing the initial power conversion efficiency to maintain 80% for 60 days in air or 600 h at 60 °C.

The inorganic halide perovskite $RbGeBr_3$ shows semiconductor properties with a direct band gap of 1.49 eV in its cubic form. Fullerene, also known as buckyball (C60) has been extensively used in perovskite solar cells technology due to its exceptional properties as an electron transport layer. Fullerene serves as a vital electron transport layer material, enabling the effective transfer of electrons in photovoltaic devices. Its unique spherical, cage-like formation made up of 60 carbon atoms featuring a conjugated π-electron system, facilitates excellent electron mobility, which minimizes charge recombination losses and enhances the overall efficiency of the devices. The properties of the electron transport medium C60 and several organic and inorganic hole transfer materials, along with the inorganic perovskite $RbGeBr_3$, have been studied in various perovskite solar cells [85]. Among all these engineered structures, the FTO/C60/$RbGeBr_3$/NiO/Au structure has demonstrated the greatest efficiency of 16.48%, alongside an open circuit voltage of 0.92V and a short circuit current of 22.25 mA/cm^2. Furthermore, by replacing the nickel contact with a gold contact, the achieved efficiency was roughly the same value.

Phase separation due to halide ion movement when illuminated is a significant obstacle hindering the commercialization of mixed halide perovskites. Easy and efficient method is presented to reduce the photoinduced phase segregation in the $FA_{0.83}Cs_{0.17}Pb(I_{0.6}Br_{0.4})_3$ mixed halide perovskite film by using tetraoctylammonium chloride (TOAC) as an additive and for surface passivation [86]. The findings indicated that TOAC significantly minimizes halide ion migration, maintains the stability of the perovskite phase and hinders phase segregation, especially in the additive passivation combined setup. Solar cells made from mixed-halide perovskite using this dual TOAC method reach an efficiency of 15.8%, demonstrating improved stability during prolonged light exposure and minimized hysteresis. TOAC, characterized by its bigger organic cation framework and extended alkyl chains, presents further potential advantages. Longer alkyl chains can offer better hydrophobic shielding from moisture related degradation and might provide distinct control over perovskite crystallization and grain boundary passivation when compared to shorter chain variants. By minimizing defects, TOAC lessens leakage, ion migration and charge recombination, resulting in a notable reduction in defect density, enhanced charge recombination resistance, and extended carrier lifetimes. Significantly, these improvements have been noted in both iodine-exclusive and mixed-halide perovskite solar cells.

The sensitive surface of inorganic perovskite worsens the decline in photovoltaic efficiency and the long-term durability of inorganic perovskite solar cells. Researchers present an easy surface reconfiguration method [87] by *in situ* creating a 0D Cs_4PbI_5Br capping layer on the top of the 3D $CsPbI_2Br$ perovskite to enhance both the efficiency and stability of inorganic perovskite solar cells. The *in-situ* development of 0D Cs_4PbI_5Br capping layer leads to the establishment of 0D/3D bilayer perovskite heterostructure, significantly enhancing the stability of $CsPbI_2Br$ perovskite and facilitating the development of an advantages energy level structure for charge extraction. In the meantime, the surface reconfiguration triggers secondary crystallization of perovskite, which significantly enhances perovskite morphology, diminishes perovskite defects and elevates perov-

skite quality. As a result, the constructed carbon-based $CsPbI_2Br$ perovskite solar cell exhibits a power conversion efficiency of 15.24% with an open circuit voltage of 1.33 V. In addition, the unencapsulated device retained 94% of the original efficiency after 1080 h under ambient conditions, indicating excellent long-term stability. In contrast to 3D and 2D inorganic perovskites, 0D Cs_4PbX_6 inorganic perovskites exhibit greater environmental stability and reduced ion migration due to their composition of isolated $[PbX_6]^{4-}$ octahedral separated by Cs^+ ions. In addition, 0D Cs_4PbX_6 inorganic showed a favourable lattice compatibility with 3D $CsPbX_3$ perovskites since they share the identical $[PbX_6]^{4-}$ octahedron found in $CsPbX_3$ perovskites. As a result, it is anticipated that the growth of 0D Cs_4PbX_6 layer on the surface of 3D $CsPbI_2Br$ perovskite will create a 0D/3D bilayer perovskite heterostructure, which should serve as a particular efficient approach to passivate defects at the grain boundaries and surface of $CsPbI_2Br$ perovskite and improved the stability of the solar cells.

Utilizing a hot-press-assisted additive engineering approach to fabricate semi-transparent perovskite solar cells can enhance sunlight utilization and improve power conversion efficiency. Nevertheless, concurrently passivating the defects in perovskites while achieving high performance semi-transparent perovskites solar cells continues to pose a challenge. 2-(2,2,2-Trifluoroethoxy)aniline (2TFA) was added to the perovskite precursor to obtain high quality films. The 2TFA consists of an anilino central structure and a varied trifluoroethoxyl featuring a unique trifluoride group acting as peripheral components, which were added to the perovskite precursor to create high quality perovskite films for enhanced efficiency and stability. The incorporation of F and NH_2 groups into the aromatic ring is due to their vital role as essential building blocks for optoelectronic materials to enhance their fundamental properties including defect passivation, structural stability and the modulation of energy level alignment. The 2TFA altered perovskite solar cells [88] achieve a leading power conversion efficiency of 24.1% and maintain 85% of their original power conversion efficiency after being stored in ambient air for 600 h. Moreover, semi-transparent perovskite solar cells are fabricated through thermal compression techniques. The semi-transparent perovskite solar cells modified with 2TFA provide an optimal power conversion efficiency of 14.52% an average visible light transmittance of 5.18% and a light utilization efficiency of 0.75%.

Semi-transparent perovskite solar cells offer considerable benefits in the areas of building integrated photovoltaic and stacked tandem solar cells. Transparent top electrodes of semi-transparent perovskite solar cell typically composed of transparent conducting oxides (TCO), are primarily produced through intricate vacuum methods such as sputter deposition method. Conversely, new thermocompression technology has demons trated to be an easy and efficient approach for producing semi-transparent perovskite solar cells. The production of solar cells through hot pressing technology involves layering two independently processed half devices of solar cells while applying heat and pressure. Thermocompression technology eliminates the need for TCO deposition on perovskite and electron transport layer preventing possible damage from deposition and lowering expenses.

Yang *et al*. [89] studied the impact of three organic additives namely 4-cyclopentene-1,3-dione (CPD), maleimide (HPD) and 3,4-dibromo-1*H*-pyrrole-2,5(2*H*,5*H*)-dione (BrPD) in $CsPbIBr_2$ perovskite films. The additives develop different chemical interactions, such as coordination bonds, hydrogen bonds and ionic bonds, with I^- ions and under coordinated Pb^{2+} ions, where BrPD exhibits the strongest interaction. This interaction controls crystallization and enhances film structure. Films modified with BrPD exhibit the largest grain size and optimal light stability, effectively inhibiting light-induced phase segregation, promoting carrier transport and enhancing overall device performance. The bromine atoms in BrPD are essential for preventing the formation of iodine vacancies, thereby greatly enhancing the phase stability of $CsPbIBr_2$ perovskite when exposed to light. BrPD-altered $CsPbIBr_2$ solar cells reached a power conversion efficiency of 11.34%, exceeding the control (8.96%) and other additives. Moreover, BrPD-modified devices exhibit remarkable stability, maintaining 94% of their original power conversion efficiency after 60 min of continuous light exposure. Remarkably, BrPD shows a detectable rise in the nitrogen and bromine atoms, which can be linked to the distinctive molecular structure of this additive. As expected, the lone pair of electrons on the oxygen atoms of carbonyl group in all three additives is expected to interact with under coordinated Pb^{2+} ions within the perovskite lattice. Furthermore, the nitrogen atoms in both HPD and BrPD establish hydrogen bonds with halide ions, which contributes to the stabilization of the perovskite structure. Interestingly, the bromine atom in BrPD is expected to form ionic bonds with lead ions thereby improving the overall stability of the solar cells.

Cesium tin triiodide ($CsSnI_3$) perovskite, made entirely of inorganic substances, has attracted considerable interest as a promising alternative form solar application. This is mainly due to its ability to possibly reach high efficiency while ensuring environmental sustainability. In theory, solar cells using black orthorhombic $CsSnI_3$ as the light absorbing material, which has a direct band gap of 1.3 eV, could achieve the Shockley-Queisser limit of 33% efficiency in converting electricity. Tin-based perovskite solar cells offered a lead-free option. Researchers present thiosemicarbazide-modified carbon nanotubes to reduce defects [90] and enhance charge transport in fully inorganic $CsSnI_3$. The S=C=N groups communicated with tin ions, reducing the trap states. It was observed that carbon nanotube was able to improve carrier extraction, power conversion efficiency reached 23.34% and stability achieved 91.3% after 800 h.

Raj *et al*. [91] introduced a framework predicted by machine learning (ML) to assess the performance and environmental stability of an innovative lead-free perovskite solar cell with the configuration of FTO/AZnO/$Cs_2CuSbCl_6$/MoO_3. The optical studies verified that $Cs_2CuSbCl_6$ demonstrates substantial UV absorption with little loss, making it a proficient absorber. Following that SCAPS-1D simulations refined photovoltaic parameters, resulting in open circuit voltage of 1.58 V, short circuit current density of 21.82 mA/cm^2, fill factor of 91.12% and power conversion efficiency of 31.5%. $Cs_2CuSbCl_6$ exhibiting a band gap of 1.7 eV, is among the most appropriate materials for the absorber layer. This band gap enables the material to capture a substantial amount of visible and UV

light spectrum, crucial for effective energy conversion. The material is ideal for capturing light, guaranteeing that most sunlight photons are absorbed and transformed into electrical energy. The band gap is narrow enough to absorb a wide spectrum of sunlight, positioning it as a great option for improving the efficiency of perovskite solar cells.

FTO having a band gap of 3.48 eV, is used as a layer of transparent conducting oxide (TCO). The elevated band gap guarantees that FTO stays clear to visible light, permitting the light to reach the absorber layer with minimal losses. The aim function of FTO is to serve as a conductive electrode that aids in the removal of electrons from the absorb layer. The wide band gap of FTO prevents it from absorbing solar energy, thereby allowing more light to reach the absorber layer without loss in intensity. Consequently, it facilitates effective electron extraction while ensuring transparency to optimize photon uptake.

Al-doped ZnO (AZnO) which has a band gap of 3.33 eV, functions as the electron transport layer in the solar cells. The larger band gap enables AZnO to move effectively electrons from the absorber layer to the FTO electrode, minimizing the recombination losses. The band gap guarantees that it stays transparent within the visible spectrum, stopping it from absorbing light. By promoting the effective movement of electrons and reducing recombination, AZnO plays a role in improving the overall efficiency of the solar cells.

MoO_3 serves as a hole transport layer, exhibiting a band gap of 3.17 eV. The band gap enables MoO_3 to effectively transmit holes from the adsorber layer while preserving its transparency to visible light. However, this somewhat reduced band gap in comparison to AZnO enables MoO_3 to extract effectively holes while not absorbing large amounts of sunlight. This facilitates seamless hole transport and reduces recombination, assuring that the charge carriers arrive at the electrodes with minimal losses. The alignment of the band gap among these materials is essential for effective charge separation and transport. The variations in band gap among the materials facilitate the efficient injection and extraction of electrons and holes, reducing recombination losses. This ensures that the generated electron-hole pairs are efficiently separated and transported, contributing to the overall high efficiency of the solar cells. The careful selection of materials based on their band gap properties is crucial for optimizing device performance.

Yuan *et al*. [92] incorporated lithium acetate into the interface between the electron transport layer and perovskite. Lithium acetate acts both as a crystallization modulator and defect passivator by means of lithium ions diffusion and interactions mediated by acetate. This dual-interface modification approach achieves concurrent bulk phase passivation and dual interactions passivation in solar cells. It lowers defect density, improves crystallization, boosts carrier transport and minimizes non-radiative recombination. Consequently, the dual interface altered solar cells reach a peak power conversion efficiency of 25.48%. Moreover, the unshielded devices show significantly enhanced stability, maintaining over 90% of their initial performance in ambient air for 1200 h and surpassing 80% after a 1000 h thermal stability test performed at 85 ºC. Producing high quality perovskite films is essential for achieving high power conversion efficiency. Due to the nature of the solution deposition process, precisely controlling the stoichiometric ratios between components is challenging. Typically, surplus PbI_2 is frequently found in organic-inorganic hybrid perovskite, resulting from stoichiometry discrepancies in precursor solutions, incomplete conversion or perovskite degradation, influencing solar cell performance in either in a positive or negative manner. It is shown that an appropriate excess of PbI_2 (1 mol) enhances the growth of high quality $CsPbI_3$ films with larger grains and fewer defects, leading to an improved power conversion efficiency from 12.57 % (control samples) to 14.39% along with increase stability. Adding an appropriate quantity of excess PbI_2 (0.5-2 mol) can enhance the power conversion efficiency with the 1 mol excess PbI_2 sample showing the efficiency of 14.39%, open circuit voltage of 1.071 V, shot circuit current of 19.14 mA/cm^2 and fill factor of 70.18%. However, an excess of 3 mol of PbI_2 leads to a reduced power conversion efficiency (12.13%) due to compromised film quality [93].

The dark current density for the device containing 1 mol% excess PbI_2 is clearly less than that of the control device, indicating a reduction in leakage current. The current leakage in a solar cell is typically associated with the non-radiative recombination of injected charges and reducing it signifies the passivation of defect states. Based on EIS studies, resistance to charge recombination is observed in solar cells. The obtained resistance to charge recombination values as 3436 Ω for the control solar cell and 7727 Ω for the one containing 1 mol% excess PbI_2. This suggests that the charges would experience greater resistance to recombination in the solar cells with a mol% excess PbI_2 compared to those in the control solar cells, which facilitates efficient charge extraction to electrodes and subsequently enhances photovoltaic performance. Ultimately, the non-encapsulated solar cells are kept in air in dark to evaluate their stability. After being tested for 500 h, the device maintained 74.8% of its initial power conversion efficiency, whereas the control device retained just 65.3% of its original power reconversion efficiency. The enhanced stability is attributed to the better quality of the perovskite films and decreased defect density, which slows down the degradation of perovskite.

The methylammonium tin iodide ($CH_3NH_3SnI_3$) has surfaced as a compelling option, showcasing considerable promise as a non-toxic substitute. Nevertheless, tin-based perovskite experience tin(II) oxidation, elevated background carrier concentrations and higher defect densities, all of which adversely affect stability and efficiency. The methylammonium tin iodide is selected due to its beneficial properties, including effectively visible light absorption and a reduced band gap. The model's device configuration is FTO/TiO_2/IDL/$CH_3NH_3SnI_3$/carbon, where TiO_2 functions as the electron transport layer, $CH_3NH_3SnI_3$ serves as the absorber layer [94]. At 300 K, the device shows an open circuit voltage of 0.886 V, a fill factor of 81.58%, a short circuit current density pf 30.68 mA/cm^2, and a power conversion efficiency of 22.23%. The thickness of the perovskite layers plays a vital role in influencing the solar cell's capability to effectively absorb solar radiation. To enhance photocurrent production, the active layer's thickness needs to be adequate for capturing light over various wavelengths. Nonetheless, if the layer gets excessively thick, the transport layers could have difficulty gathering the charge carr-

iers, resulting in the recombination of photogenerated carriers inside the absorber layer. This problem ultimately decreases the efficiency of the solar cells. As the thickness of the perovskite layer grows, the quantity of generated electrons and holes likewise escalated, enchaining both open circuit voltage and short circuit current density. External quantum efficiency (EQE) is an important metric for evaluating how well a solar cell transforms photons into charge carriers. As the perovskite layer gets thinner, its ability to adsorb photons at longer wavelength diminishes, leading a reduced generation of electron hole pairs. For wavelengths greater than 780 nm, the incoming light is not efficiently absorbed at energies beneath the material band gap, causing the EQE to fall to zero.

A multi-layer hole transport layer made from two chalcogenide thin films, selenium (Se) and copper selenide (CuSe), is produced using the physical vapor deposition method as a cost-effective replacement form the costly spiro-OMeTAD layer in heterojunction perovskite solar cells. The hole transport layer of selenium and copper selenide films were deposited to develop a total composite thickness of 150 nm by adjusting the thickness of each layer, resulting in 3 unique multilayered Se/CuSe/Se films configurations: 30/60/30, 50/50/50 and 40/70/40 nm, respectively [95]. SEM shows its nanofibrous structure with increased surface area, supporting the strengthening to improve charge transfer and reduce recombination. Both selenium and copper selenide function as p-type semiconductors with opto-electronic features that include a work function alignment with the $MAPbI_3$ layer, along with their excellent charge transfer properties. As a result, the heterojunction perovskite solar cells device with an active area of 0.5 cm^2 using a refined multi-layer hole transport-layer configuration reaches an efficiency of 7.04% and a short circuit current of 9.9 mA/cm^2. The enhanced interface between the Se/CuSe layers and the perovskite absorber greatly reduces charge recombination, resulting in improved open circuit voltage and overall device efficiency.

Organic solar cells: An organic solar cell refers to a solar cell that uses organic semiconductors for its absorbing layer. Generally, these consisted of either polymers or small molecules. For organic materials to be used in organic electronics, they must exhibit semiconducting properties, necessitating a significant degree of conjugation [96]. The conjugation of the organic compound leads to the delocalization of electrons linked to the double bonds throughout the full extent of conjugation. These electrons possess greater energies compared to other electrons in the molecule and are akin to valence electrons found in inorganic semiconductor materials.

Like other solar cell technologies, the aim of an organic solar cell is to produce electricity from sunlight. This occurs when the energy of light matches or exceeds the band gap [97], resulting in the absorption and excitation of an electron from the highest occupied molecular orbital (HOMO) to the lowest unoccupied molecular orbital (LUMO). The energized electrons will create a positively charged area referred to as a hole. Due to their opposite charges, electrons and holes attract each other and form an electron-hole pair known as an exciton. To generate usable electrical current in a solar cell, this exciton must be separated—a process called exciton dissociation.

Usually in an inorganic semiconductor, the force between the electron and hole (referred as exciton binding energy, E_b) is minimal enough to be surpassed by thermal energy at ambient temperature, around 2 meV. This is attributed to a high dielectric constant, indicating considerable screening between the electron and hole [98], which diminished the attraction between them. The simplicity of separating the electron and hole facilitates straightforward exciton dissociation. In comparison, organic semiconductors possess low dielectric constant, resulting in high E_b values between 0.3 and 0.5 eV. In organic semiconductors, thermal energy alone cannot facilitate exciton dissociation. To address this, a minimum of two distinct organic semiconductors is required in organic solar cells. The energy levels of the two distinct organic semiconductors are misaligned, with the variation exceeding E_b, which enables exciton dissociation at their interface.

Photovoltaic parameters in organic solar cells: Within the field of organic solar cell technology, ongoing studies focus on improving the photovoltaic characteristics of donor-π-acceptor materials to attain greater power conversion efficiencies [99]. This optimization specifically targets refining the conduction band and electrolytic properties to enhance performance. In response to the increasing need for innovative materials with improved optoelectronic properties in organic photovoltaic research, the researchers introduced compound BT05, which is among the nine new benzothiadiazole-based donor-π-acceptor materials and demonstrated a power conversion efficiency of 25%, exceeding the 18% achieved by the reference compound BTD-OMe. An elevated open circuit voltage of 1.74 to 2.26 eV, an increase in binding energy (1.99 eV), the highest wavelength value (470-476 nm), and a decrease in energy gap (4.25 to 4.65 eV) further support the power conversion efficiency and affirm the efficacy of the synthesized molecules (BT01-BT09). Experimental findings confirmed that BT01-BT09 molecules enhance organic solar cells capabilities and promote sustainable energy solutions *via* cutting edge technology. Of all the compounds, BT05 shows the highest open circuit voltage (2.26 V), 87% of fill factor and 25% of power conversion efficiencies.

Fullerene and its derivatives are extensively used as electron acceptors in indoor organic solar cells due to their spectral compatibility and preventable photodimerization. Fascinating findings related to fullerene materials come from the overlapping spectra of the active layer and man-made light sources. Moreover, low-intensity incident light prevents photodimerization and morphological instability in fullerene materials. The performance of devices using fullerene PC61BM based organic solar cells mixed with three distinct donor polymers was studied under indoor lighting conditions [100]. The devices showed significantly greater power conversion efficiencies in low light conditions compared to sun illumination. The highest performing PM6:PC61BM standard organic solar cells showed a peak power conversion efficiency of 7.94% with sun illumination and 23.27% under LED light source. In contrast to inorganic solar cells, organic solar cells show interior photovoltaic performance when exposed to sun illumination. Nonetheless, organic substances exhibiting high absorbance in the visible light spectrum (380-760 nm) present significant potential for indoor applications, aligning well with

artificial light sources used indoors such as LED, fluorescent lamps and incandescent bulbs.

A new type of non-fullerene acceptor compound has been developed for efficient organic solar cells. A significant fill factor (over 95%) accompanied [101] by a power conversion efficiency of 30.34% for D2APH1. A change in the absorption spectra for D2APH1 to D2APH4 has been observed due to redshift and a restricted energy band gap compared to the reference molecule. Furthermore, the engineered molecules demonstrated improved open circuit voltage levels and significant electron and hole mobility throughout metal electrodes. Simple exciton generation within an excited state results from low excitation energy and significant oscillation strength. Conjugation was crucial in light absorbing substances such as active layer electron absorbers. Conjugation not only led to a reduction in the band gap but also facilitates a quick and easy transfer of chargers between lower and higher energy states. Rings that include heteroatoms and feature extensive conjugations also assist in the prolonged charge transfer between various components of the active layer material when interacting with photons. Theoretically, the power conversion efficiency values for D2APH1 to D2APH4 were expressed as 30.64%, 29.21%, 30.1% and 29.39%, respectively. Following thorough analysis and discussion, it is concluded that modified molecules are effective candidates with enhanced power conversion efficiency for advanced solar cell applications. These molecules, which exhibit low re-organizational energy indicating high mobility of both electrons and holes, combined with red shifting in the absorption spectrum, are projected to enable high power conversion efficiencies in future organic solar cells. In the same way, a small energy band gap enhances the effortless movement of charges among molecular orbitals. Weak binding and excitation energies facilitate the easy dissociation of exciton in an exciting state.

Typically, the efficiency of tandem solar cells is enhanced by selecting active materials that have complementary absorption, but the efficiencies can additionally be boosted by equalizing the photocurrent among the identical sub-cells. Certainly, short circuit current in devices is restricted by the smaller short circuit current of the two sub-cells. Incompatible photocurrents may cause carrier buildup in the sub-cells, leading to a lower fill factor for the tandem cell. Generally, the ideal thickness for the sub-cell in tandem devices differs from that in single junction devices. Attaining the current balance in the tandem setup necessitates accurate modification of the thickness of every sub-cell. Consequently, an effective approach to control the optical field distribution in the tandem device is crucial for obtaining balanced photocurrents and ensuring efficiency while maintaining the fill factor. The balanced photocurrents of the sub-cells can be attained by meticulously adjusting the donor and acceptor ratios of the sub-cells. Moreover, the interconnecting layer (ICL) of tandem devices is essential for their efficiency. To begin with from an electrical perspective the ICL must offer comparable ohmic contacts to combine the open circuit voltage of the sub-cells without any loss. It must also be visually clear as attainable. Ultimately, from a mechanical standpoint, the ICL must be sufficiently rigid to stop solution entry during back cel processing.

Tandem organic solar cells are set to extend the efficiency boundaries even more and present a hopeful path for enhancing the performance of organic photovoltaic devices. Yu *et al*. [102] presented the production of a completely solution processed interconnecting layer composed of ZnO:PEI/PEI/PEDOT:PSS/2PACz for tandem solar cells. The PM6:BTP-eC9 active layer material was modified regarding its donor to acceptor ratio and film thickness for both the front and back sub-cells. The ICL demonstrated advantageous mechanical, electrical and optical properties. By using multi-dimensional modulation, both the front and rear sub-cells have been enhanced to achieve highly efficient homojunction tandem solar cells. The tandem solar cells consisted of indium tin oxide/PEDOT:PSS/2PACz/active layer/ICL/active layer/ PNDIT-F3N/Ag. This optimization achieved a power conversion efficiency of 19.9%, marking the highest efficiency reported so far for homojunction tandem solar cells. The power conversion efficiency of homojunction tandem solar cells can be significantly improved by optimizing interconnecting layers and the donor-to-acceptor ratio.

In recent years, leveraging big data and artificial intelligence (AI) to develop quantitative structure activity relationships has emerged a novel trend in today's material science domain. Machine learning (ML), a subset of AI, has achieved notable advancements in designing photoelectric materials, including predictions regarding efficiency, band gap and stability. Consequently, ML is highly compatible with the creation of organic solar cells, adeptly gaining insights from the data to uncover possible connections between the attributes and labels. In particular, the surge of studies on non-fullerene acceptors material has yielded ample data for ML methodologies. Consequently, using ML techniques in the materials design for organic solar cells can minimize the expense associated with the experimental trial and error, speeding up the development of high performance organic solar cells. The efficiency of power conversion in organic solar cells has surpassed 19% due to the advancements in the non-fullerene acceptors [103]. In this context, machine learning models using inputs from both molecular descriptors and fingerprints with various algorithms are examined to help in the investigation of non-fullerene acceptors. Even though the model using fingerprints showed somewhat lower performance metrics, it offers quicker and higher throughout calculations along with significantly improved generalization capabilities because of its reduced complexity, which helps prevent overfitting.

The exciton diffusion lengths were found to be 26 nm for ITIC and 34 nm for IT4F. The red shifted absorbance of IT4F relative to ITIC suggests that the addition of fluorine atoms lowers the molecule band gap [104]. The singlet-singlet exciton annihilation was used to quantitatively analyze exciton diffusion in ITIC and IT4F. In organic semiconductors, exciton annihilation takes place when two singlets come close to one another within a specific distance. During an annihilation event, one exciton disappears while transferring its energy to another exciton, which possesses more energy and quickly relaxes to its lowest excited state through non-radiative processes. The annihilation of singlet-singlet is greatly influenced by the exciton density and the diffusion coefficient of the excitons. The separation of excitons in the non-fullerene acce-

ptors (NFA) at the planar heterojunction interfaces of donor/acceptor using transient absorption measurement was analyzed. Ultimately, the planar heterojunction solar cells was developed using PM6/NFA bilayer configuration. Power conversion efficiency exceeding 7% for PM6/IT4F bilayers was ascertained. Even more significantly, the spin coating of the upper layer NFA has little effect on the morphology of the PM6 layer, indicating a distinct bilayer interface instead of a quasi-bilayer configuration that includes some bulk heterojunction. The findings indicate that improved exciton diffusion length along with effective exciton dissociation and charge generation are fundamental features for achieving high power conversion efficiency value.

A promising substance for organic solar cells is PTB7:PC71BM which boasts high electrical conductivity, solubility in multiple solvents, and the capability to be applied over extensive areas at low temperatures using economic methods. All excitons generated by light must be separated at the boundary between the donor and acceptor materials to reach high quantum efficiency. Furthermore, all charges produced must afterward arrive at their corresponding electrodes. Owing to its impressive mechanical, electrical, thermal and optical properties, graphene oxide served as an excellent material for the hole transport layer (HTL) in solar cells. Graphene oxide served as the HTL in PTB7:PC71BM solar cells, and the impact of graphene oxide on these cells was studied [105]. SCAPA-1D simulation software was used to model organic solar cells. The absorber layer thickness has been adjusted to 40 nm and the results indicated that graphene oxide enhances the efficiency of organic solar cells by promoting the separation of excitons and enhancing the charge transport properties of the devices. Graphene oxide is truly a promising substance for application as a hole transport layer in solar cells thanks to its distinctive properties. The structure and conductivity of graphene oxide enable it to effectively assist the flow of holes in the solar cells. Graphene oxide has the potential to enhance the durability and longevity of solar cells, especially in extreme environmental conditions. Graphene oxide can be manufactured through straight-forward and affordable techniques, which make it appealing for large-scale production.

An ITO/ZnO/P3HT:PCBM/MoO_3/Ag configuration was used with the goal of enhancing efficiency by incorporating various amounts of gold nanoparticles into the ZnO electron transport layer. Based on the optimal findings [106], incorporating 10% gold into ZnO enhanced the power conversion efficiency from 2.94% to 3.48%. As a result, an improvement in efficiency of almost 20% was realized. The enhanced efficiency is primarily attributed to increased current density resulting from plasmonic effects of gold nanoparticles. In the absence of gold nanoparticles, the current density was 8.14 mA/cm^2, which increased to 8.58 mA/cm^2 with 10% gold nanoparticle incurporation.

Nanoparticles have gained importance in technological progress due to their adjustable physico-chemical properties like melting point, wettability, electrical and thermal conductivity, catalytic effectiveness, light absorption and scattering, leading to improved performance compared to their bulk equivalents. Moreover, their fluorescence, ability to tune dimensions and high extinction coefficient render them appealing in various areas including digital devices, nanomedicine, and solar cells. Zinc oxide is among the promising options for an electron transport layer in organic solar cells. ZnO can enhance power conversion efficiency by gathering and removing electron carriers while preventing possible hole carriers. Moreover, this ZnO is regarded as an optical spacer and an oxygen barrier in solar cell devices, contributing to their stability and lifespan, ultimately leading to enhanced overall device performance. Absorption of ZnO can be improved by doping certain elements in appropriate quantities, enabling it to capture more light from the ultraviolet to the visible spectrum, which is achieved by reducing the band gap of zinc oxide.

Developing a suitable ternary component is regarded as an effective method to enhance photovoltaic efficiency. A new non-fullerene acceptor with a quinoxaline central core, referred to as BQ, was effectively produced [107]. The remarkable electron withdrawing ability of the quinoxaline core allows BQ to maintain a significant elevated lowest unoccupied molecular orbital energy level, leading to an exceptionally high open circuit voltage of 0.959 V when mixed with the polymer donor D18. By introducing BQ as the guest acceptor for the fabrication of ternary organic solar cells within the D18:N3 host system, a higher open circuit voltage of 0.846V was achieved, alongside a decreased non-radiative recombination cascade-like model ternary organic solar cells attained a remarkable power conversion efficiency of 18.9%, which can be ascribed to the complementary absorption, rapid exciton diffusion and dissociation, effective carrier transport and collection, suitable phase separation and minimized energy loss. Integrating additional donor or acceptor material into the binary system, ternary organic solar cells, is considered an effective approach to enhance both the overall photovoltaic performance and device stability concurrently, potentially achieving better functionality than the associated binary device.

Porphyrins have shown outstanding photovoltaic efficiency in organic solar cells when used alongside appropriate acceptors in molecular donor acceptor (DA) dyads. Perylenebisimides have become significant non-fullerene acceptor and numerous perylenebisimides derivatives have been included in donor acceptor motifs as acceptor [108]. Researchers outline the design and photovoltaic effectiveness of a new N-benzannulated perylenebisimide-porphyrin dyad along with its Zn^{2+} complex. Single crystal XRD studies reveal a non-coplanar configuration of the separate chromophores in the freebase dyad. The perylenebisimide and porphyrin chromophoric units exhibit head-to-tail intermolecular π–π stacking interactions with donor acceptor separation of 3.4 Å. Bulk heterojunction organic solar cells were developed through solution processing using both synthesized molecules as donor together with PC71BM as acceptor. The power conversion efficiencies were 7.25% and 9.1%, respectively. Perylene diimides constitute a prominent class of compounds with diverse applications in modern organic material-based devices. These molecules have a stiff polyaromatic backbone, with two imide groups located at the ends of their long axis. The imide groups enhance the solubility of these compounds and generally do not influence their electronic properties, due to the presence of nodal planes along the N–N axis. This category of molecules has been thoroughly studied as a multi-redox system for the contemporary

optoelectronic uses. Perylenebisimides are among the well-known members of this group due to their stability in chemical and photochemical contexts. Their photophysical properties render them effective materials ideal for organic photovoltaic and organic light emitting devices.

Fluorination methods have shown prominent advantages in enhancing the performance of non-fullerene acceptor (NFA) based devices. The incorporation of fluorine can be analyzed from three perspectives such as adjusting physico-chemical properties, enhancing donor-acceptor (D-A) properties and influencing molecular packing behaviours. Currently, fluorination methods are divided into direct fluorination and indirect fluorination, which includes trifluoromethylation. The fluorination of central units in non-fullerene acceptors remains under-explored due to the absence of substitution sites in traditional Y-series acceptors. To systematically investigate the influence of various central unit fluorination strategies on the molecular stacking and, in turn, solar cell performance, researchers employed a newly developed phenazine-based (CH) series [109]. These non-fullerene acceptors were characterized by central unit mono-fluorination (CH-F), mono-trifluoromethylation (CH-CF) and a combination of fluorination and trifluoromethylation (CH-FCF), respectively. Among these, CH-FCF based blended films exhibit enhanced molecular interactions and crystallinity, an outstanding fibrillar network structure and improved charge generation/transport efficacy. As a result, the binary organic solar cells using CH-FCF attained the highest power conversion efficiency of 18.4% surpassing those using CH-F (17.34%) and CH-CF (17.62%). These findings highlight the importance of synergistically controlling the core unit of small molecule acceptors *via* various fluorination techniques to influence molecular packing and consequently improve the photovoltaic performance of devices.

Organic solar cells (OSCs) can generate electric energy by capturing and transforming solar energy. The semi-transparent organic solar cells (ST-OSCs) selectively permit partial light penetration to achieve vibrant colors. Consequently, the light absorption of semitransparent organic solar cells is comparatively low, which will inevitably result in performance declines of solar cells. Microcavity based semitransparent organic solar cells (STOSC) have emerged as a significant topic in green energy harvesting research area due to their broader potential uses in coloured photovoltaic glass, building integrated photovoltaics, among others. Zhong *et al*. [110] suggest a MgF_2 microcavity designed as Au/Ag/MgF_2/Ag for semitransparent organic solar cells, enabling high peak transmittance to be attained at a reduced cost of power conversion efficiency. The device configuration of semi-transparent organic solar cells consisted of glass/ITO·ZnO/PTB7-Th:IEICO-4F/MoO_3/Au/Ag/MgF_2/Ag. By merging the high transmittance of MgF_2 microcavities with the low absorption of IEICO-4F at blue light wavelengths, a vibrant semi-transparent organic solar cell with excellent blue light transmittance can be achieved. The active layer of the IEICO-4F exhibited significant optical absorption in the near infrared wavelength range, while demonstrating low absorption in the visible range. The findings indicate that the maximum transmittance of semi-transparent organic solar cells achieved a significant level of 48% at 440 nm, while the power conversion efficiency attained 10.4%. This impressive peak transmittance is attained despite a power conversion efficiency decrease of around 5% in comparison to the control opaque device. The power conversion efficiency loss rate at every peak transmittance is the minimum compared to the reported values for similar semi-transparent organic solar cells. By altering the thickness of MgF_2, semi-transparent organic solar cells of various colors can be achieved, demonstrating a peak transmittance exceeding 32% and a power conversion efficiency loss rate below 7.25%.

Suo *et al*. [111] prepared an effective electron transport layer (ETL) for inverted structure organic solar cells by altering commercially obtainable SnO_2 nanoparticles using a simple molecule 2-(3-(dimethylamino)propyl)-1,3-dioxo-2,3-dihydro-1*H*-benzo[*de*]isoquinoline-6,7-dicarboxylic acid (NMA). Tin oxide has gained considerable interest as an electron transport layer due to its superior electron mobility, ultraviolet resistance, reduced photocatalytic activity and remarkable chemical stability when compared to ZnO. The surface alteration successfully eradicates the light soaking problem found in devices featuring uncoated SnO_2. Moreover, it greatly improved the efficiency and stability of the solar power devices. Using the hybrid electron transport layer, the PM6:L8-BO device attains an exceptional power conversion efficiency of 18.33%, a fill factor of 78.62%, an open circuit voltage of 0.882 V and a short circuit current of 26.4 mA/cm^2. Significantly, this device demonstrates remarkable shelves, thermal and photostabilities. It preserved 99.7% and 87.1% of its initial efficiency during storage in nitrogen and thermal stress at 65 ºC for 1000 h, respectively. Under constant sunlight with maximum power point tracking for 800 h, the device maintained 86.6% of its original efficiency. The device featuring NMA molecule showed an improved EQE response throughout almost the entire absorption spectrum. The integrated short circuit current values derived from the EQE curves were 25.12, 24.65 and 26.74 mA/cm^2 for the uncoated SnO_2 prior to and after light soaking, as well as for the NMA modified devices, respectively.

Challenges and future prospects of solar cells: Crystalline silicon photovoltaics accounted for approximately 90% of total production, followed by thin-film technologies, which contributed around 6% to the overall manufacturing output. That decrease in cost-per-watt of photovoltaic module as a function of cumulative production was evident. Therefore, the photovoltaic technologies that consume relatively small amounts of less expensive, less pure feedstock become increasingly favorable. Multiple low-cost inorganic thin-film solar cells are now available, which have the possibility to achieve high efficiency with high stability. Among them, chalcogenide thin films are highly appealing, in particular Cu(In,Ga)Se_2 whose efficiency turned out to be 23% at the laboratory scale. Although there are benefits of Cu(In,Ga)Se_2 technology, the production of CIGS solar cells may have to be limited due to the absence of indium and gallium in end. Kesterite photovoltaics are the leading candidates for alternative to the chalcopyrite absorbers, by replacing the indium and gallium with much more abundant and cheaper zinc and tin. Standard fabrication of kesterite based solar cells include vacuum processes although solution methods have been used for the most performing Cu_2ZnSnS_4 devices.

After organic solar cells have been rapidly developed over the past years, it is still the two main obstacles that currently impedes commercialization of organic solar cells: scalability and long-term stability. Sure, they said, the current efficiencies attained have some potential to compete with other technologies when scaled up properly. Now the synthetic complexity of materials is not a significant focus, nor are scalable deposition methods, these are likely to become hot topics in the future along with more green compatible solvent systems. The long-term stability of organic solar cells has always turned out to be cumbersome, mainly due to damages caused by moisture and oxygen pressure. A variety of intrinsic (*e.g.* phase separation and interlayer chemical reaction) and extrinsic factors (*e.g.* moisture, oxygen, temperature and light) influence the stability of organic photovoltaic (OMPV). Developments in this area are anticipated as our understanding of non-fullerene acceptors advances, as this material has shown promising prospects in long-term stability.

As the case of dye-sensitized solar cells, photoanodes have been acknowledged to be one of the most important parts of efficiency of cells. Some of the obstacles related to the development of semiconductor materials are improving of the efficiency, electron mobility, electron injection from dye to anode, light absorption capacity and the dye loading and at the same time reducing the recombination rate. The major factors which influence the solar cell efficiency are the surface area, porosity, morphology, size of photoanodes, photo-induced charge separation, the amount of dye loading, light scattering ability and the interfacial charge separation. Charge recombination is a major issue facing solar cells, which contributes to their low power conversion efficiencies. The recombination generally occurs at (i) the dye/electrolyte/metal oxide interface, (ii) the metal oxide/electrolyte interface, and (iii) the FTO substrate/electrolyte interface. One of the factors controlling transport of electrons across a solar cell is recombination, which can be minimized to increase the power conversion efficiency of solar cells. For large-scale production, long-term stability under outdoor conditions has still to be met. The most disadvantage is the poor stability due to the volatility and instability of liquid redox electrolyte at different temperatures. The liquid electrolyte can freeze and expand at low and high temperatures, causing the solar cells to degrade. Furthermore, perovskite-based solar cells have shown remarkable progress in recent years, with efficiency gains surpassing those of conventional silicon cells. Their high power conversion efficiency, low production costs, and fabrication flexibility make them strong contenders for next-generation solar energy technologies. Scalable manufacturing methods such as solution processing and vacuum deposition, which enable cost-effective, large-scale production. Moreover, their versatility in size and shape allows integration into a wide range of applications, from portable devices to large-area solar panels. Despite ongoing challenges related to stability and scalability, continuous advancements in research are steadily improving their commercial viability.

Conclusion

Significant advancements have been made in organic, dye sensitized, perovskite and thin-film solar cells through novel fabrication methods and semiconducting materials. Enhancing both efficiency and stability while reducing material and production costs remains critical for wider adoption. Thin-film solar cells are attractive for their low material use and growing efficiencies, but long-term reliability and economic viability especially for applications like building-integrated photovoltaics require further development. Perovskite solar cells show great promise but face challenges related to charge separation, transport, and collection losses, where interface engineering plays a key role. Dye-sensitized solar cells would be benefited from detailed modeling to optimize semiconductor, dye and electrolyte combinations, reducing experimental demands. Meanwhile, organic solar cells have improved significantly due to a variety of efficient donor and acceptor materials, including polymers, small molecules and fullerenes, which define their classification based on material combinations.

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CONFLICT OF INTEREST

The authors declare that there is no conflict of interests regarding the publication of this article.

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