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Review Article

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The Role of Carbon Nanotubes in the Performance of Perovskite Solar Cells

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Abstract: Carbon nanotubes (CNTs) offer promising advantages for improving the performance, efficiency, and stability of perovskite solar cells (PSCs). These nanostructures help address key challenges in solar cell technology, such as fabrication complexity, limited operational stability, and inefficient charge transport. This review explores the integration of CNTs into PSCs, with a focus on their role in charge carrier movement, interface modification, and overall device architecture. The interaction of CNTs with other nanomaterials is also discussed, highlighting their combined effects in enhancing device functionality. CNTs, known for their excellent electrical conductivity, enable faster and more effective charge transfer—an essential feature for improving energy conversion. Additionally, their strong mechanical properties support the physical robustness of PSCs, which is vital for long-term durability. By summarizing recent advancements and identifying current research gaps, this study aims to support further progress in CNT-based PSC development. The inclusion of CNTs represents an important step toward more reliable and sustainable solar technologies.

Keywords: CNT, Perovskite, Solar Cell, Nanomaterials

1. Introduction

The global shift towards sustainable energy has intensified the focus on renewable sources, with solar photovoltaics (PVs) emerging as a key solution to address climate change and the depletion of fossil fuels.[1-3] Among various PV technologies, perovskite solar cells (PSCs) have garnered significant attention due to their high power conversion efficiency (PCE) and cost-effective fabrication processes [4]. Despite these advantages, PSCs face challenges related to charge carrier transport, scalability for large-scale production, and environmental stability, necessitating the exploration of new materials and techniques to enhance their performance and longevity. Carbon nanotubes (CNTs), known for their exceptional mechanical strength, chemical stability and electrical conductivity, have emerged as promising materials to improve PSC performance. Incorporating CNTs into PSCs can enhance charge mobility, device efficiency and structural stability, leading to improved long-term operational stability [5, 6].

Perovskite materials are characterized by high absorption coefficients, long carrier diffusion lengths, and tunable bandgaps, making them suitable for efficient light harvesting and charge transport in solar cells [7]. However, PSCs often suffer from efficiency losses due to accelerated degradation and material instability when exposed to environmental factors such as temperature, humidity, and ultraviolet light [8] CNTs, with their large aspect ratio and exceptional electrical conductivity, can promote charge transfer and reduce recombination losses, thereby enhancing device stability and performance [9-11].

Integrating CNTs into PSCs requires careful consideration to ensure even distribution within the solar cell layers and to prevent adverse effects on the device's optical properties and structural integrity. Advancements in CNT composite preparation and nanomaterial processing have been adopted to improve PSC performance. Surface functionalization and surfactant-assisted dispersion techniques enable uniform integration of CNTs, while hybrid nanostructures combining CNTs with other materials further enhance device efficiency [12-14]. This review discusses the primary role of CNTs in PSCs, focusing on their fundamental characteristics essential for solar energy applications. It also addresses the challenges and potential solutions associated with incorporating CNTs into PSCs, examining their impact on device structure, stability, and photovoltaic performance, as well as their synergy with other nanomaterials. Future research directions are suggested to advance PSC technology towards commercial applications.

2. Methods of Incorporating CNTS into PSCS

Carbon nanotubes (CNTs) have garnered attention for their unique properties that enhance charge transfer, stability, and overall power conversion efficiency in perovskite solar cells (PSCs). Research efforts focus on integrating CNTs into various PSC layers to improve alignment, dispersion and functional performance within the device [15].

Three primary techniques are employed to incorporate CNTs into PSCs: direct blending into the perovskite layer, solution deposition, and sequential stacking (figure 1). The chosen method significantly influences the efficiency and structural viability of the solar cell. Strong interfacial interaction between CNTs and the perovskite material is crucial, as poor compatibility may lead to charge recombination or structural defects. Optimizing these techniques is essential to achieve highly efficient and durable PSCs.

2.1 Direct blending with perovskite precursors

One approach to enhance PSCs involves directly incorporating CNTs into the perovskite precursor solution before solidification.10 This method achieves uniform dispersion of CNTs within the perovskite structure, improving both structural and electrical properties. CNTs facilitate smoother electron flow and reduce charge recombination losses, thereby increasing the electrical conductivity of the perovskite layer. Studies have shown that adding a small amount of CNTs, typically 0.1–0.5 weight percent, can boost PCE by 10–15% compared to PSCs without CNTs [16, 17] Additionally, CNTs influence the crystallization process, leading to films with fewer structural flaws such as pinholes and grain boundaries. The enhanced microstructure minimizes nonradiative recombination and improves charge transportation, contributing to increased device lifetime and overall efficiency [18]

2.2 Incorporation into charge transport layers

CNTs can also be integrated into the charge transport layers of PSCs, which include the electron transport layer (ETL) and hole transport layer (HTL). Due to their superior mechanical stability, electrical conductivity and ability to facilitate rapid charge transfer, CNTs are well-suited for this application. Strengthening these critical layers with CNTs enhances charge transfer and extraction efficiency, improving overall PSC performance. However, proper incorporation of CNTs into charge transport layers is essential. Uneven distribution can lead to improper conductivity and reduced device performance. Therefore, controlling CNT concentration, surface modification, and deposition methodology is crucial. Achieving a homogeneous distribution of CNTs in ETLs and HTLs is vital for device stability and efficiency in advancing solar cell technology [19]

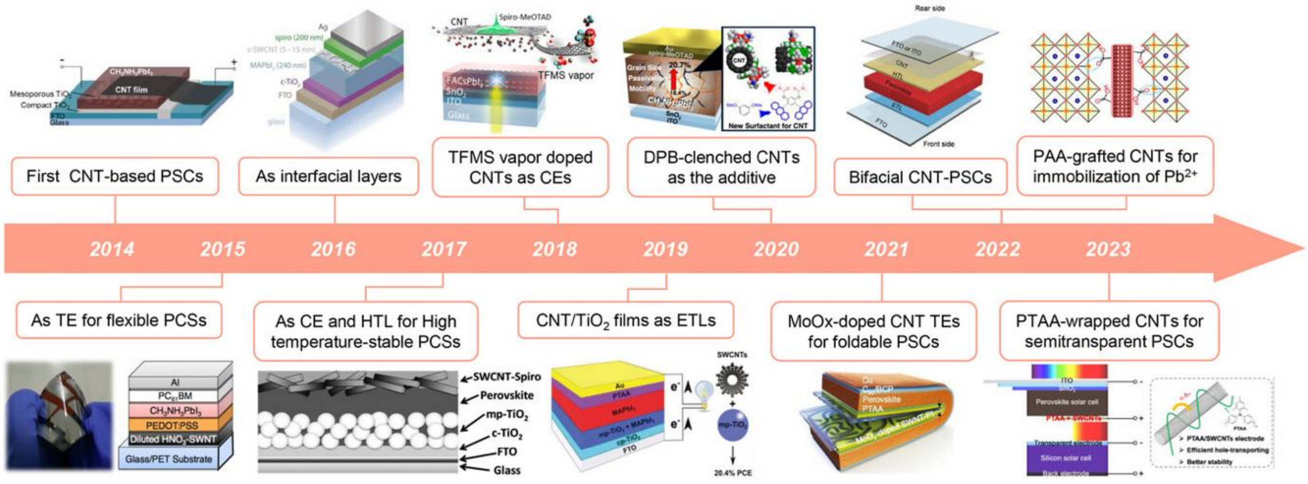

Figure 1. Brief chronology of the development of carbon nanotubes (CNTs) in perovskite solar cells (PSCs) [5]

2.2.1 Electron transport layer (ETL)

Incorporating CNTs into the ETL, responsible for collecting electrons from the perovskite absorber and transferring them to the electrode, is essential for enhancing PSC stability and efficiency. Traditional ETLs often suffer from low conductivity and limited charge mobility, affecting device performance. CNTs, with their high electrical conductivity, form a conductive network within the ETL, reducing recombination losses and enabling rapid electron movement. This network also provides mechanical stability to withstand temperature variations, improving PCE and device performance [20].

Integrating CNTs benefits conventional ETL materials like titanium dioxide (TiO_2) and tin dioxide (SnO_2) by enhancing electron transmission and balancing energy levels between the perovskite absorber and the ETL. This alignment ensures efficient charge transfer without energy loss during transmission. Improved charge extraction enhances photovoltaic performance, increasing parameters such as fill factor (FF) and open-circuit voltage (Voc) [21]. Thus, CNTs contribute to advancing PSC technology by improving electron mobility and device stability.

2.2.2 Hole Transport Layer (HTL)

Adding CNTs to the HTL, which facilitates hole transport from the perovskite absorber to the electrode, can enhance the overall efficiency and long-term stability of PSCs. Organic HTL materials like Spiro-OMeTAD often exhibit poor conductivity and limited stability, affecting device performance and lifespan [22]. Incorporating CNTs enhances hole transport and reduces losses, optimizing PCE by increasing the HTL's resistance to environmental degradation.

The conductivity of common HTL materials such as Spiro-OMeTAD and PEDOT:PSS has been significantly improved by adding CNTs. This enhancement increases the short-circuit current density (Jsc), decreases series resistance, and strengthens the HTL against environmental factors like chemical exposure and temperature variations [23]. While achieving long-term stability in PSCs is challenging, incorporating CNTs adds mechanical stability and durability.

Incorporating CNTs into both the HTL and ETL reduces recombination losses and facilitates complete charge extraction, improving electrical transport. However, improper distribution or excessive CNT loading can affect the HTL's optical properties, impacting performance. Therefore, careful optimization is necessary to ensure that CNT integration leads to stable, efficient, and cost-effective PSCs.

2.3 Surface Modifications

To enhance the overall efficiency of PSCs, hybrid materials such as composite layers made of CNTs and metal oxides or conductive polymers are employed as suitable interfacial layers. These composites improve light absorption, charge transfer, and material strength against environmental conditions, addressing challenges related to interfacial characteristics and charge loss [24].

Interfaces between distinct layers in PSCs are critical for charge transfer but can also lead to energy loss due to misaligned energy levels or trap states. CNT-based composites help overcome these shortcomings by enhancing charge transmission efficiency. Modifying the perovskite's electronic structures minimizes traps and boosts overall device efficiency. Combining CNTs with conductive polymers like poly(3-hexylthiophene) (P3HT) or metal oxides improves stability by reducing hysteresis in PSCs. The high aspect ratio and excellent light absorption properties of CNTs increase short-circuit current density (Jsc), PCE, and charge carrier photogeneration [25].

Maintaining device integrity and ensuring long-term operational lifetime in PSCs necessitates careful regulation of CNT composite concentration, dispersion, and compatibility with other materials. Balancing optical and electrical enhancements is crucial to avoid undesirable effects such as excessive light absorption or changes in refractive index. High-precision manufacturing techniques can significantly enhance PSC performance, making CNT-based films more suitable for commercial solar energy applications [26]

Functionalizing CNTs with oxygen-containing groups like hydroxyl (-OH) and carboxyl (-COOH) improves their adherence to perovskite films and solubility in polar solvents. This is typically achieved through oxidation treatments using sulfuric acid (H_2SO_4) and nitric acid or nitric acid alone. Alternatively, oxygen plasma treatment introduces carboxyl and hydroxyl groups on CNT surfaces, enhancing wetting properties and enabling uniform distribution in transport layers. Functionalized CNTs effectively reduce interface defects and suppress non-radiative recombination, leading to better charge extraction and increased fill factor (FF) and open-circuit voltage (Voc) in PSCs [27].

The primary challenge of using carbon nanotubes is their tendency to aggregate due to strong van der Waals forces [28]. To overcome this, researchers have investigated polymer functionalization processes. CNTs coated with organic polymers, such as polyvinylpyrrolidone (PVP), disperse more effectively in perovskite precursor solutions and integrate more easily with the perovskite matrix. Additionally, conductive polymers like P3HT enhance charge transmission and offer mechanical stability. Polymer-functionalized CNTs have been demonstrated to enhance Jsc and PCE in PSCs [29].

Metal oxide coating represents another effective technique for promoting electron transport by coating carbon nanotubes (CNTs) with zinc oxide (ZnO) and titanium dioxide (TiO_2). ZnO-coated CNTs, which have ZnO nanoparticles deposited on their surface, enable better energy level matching with the perovskite layer. This increases electron mobility and prevents interfacial recombination. TiO_2, frequently used in electron transport layers (ETLs), improves electron transfer efficiency and adds environmental stability. These modifications create smoother charge transport pathways, which reduces recombination losses and further enhances PSC performance [30].

2.4 Post Treatment Methods

Post-treatment procedures are required for perovskite solar cells (PSCs) to inhibit degradation and enhance overall performance. Spin coating, spray coating, and chemical vapor deposition are techniques used to apply CNTs on the PSC surface. Surface passivation, charge transfer, and environmental stability are essential factors that are significantly influenced by the addition of CNTs to the post-treatment procedure.

One of the major benefits of CNT post-treatment is surface passivation, in which surface imperfections are reduced by CNTs and non-radiative recombination is prevented, which reduces energy losses and improves device effectiveness. CNT coatings raise open-circuit voltage (Voc) by reducing recombination losses and optimizing charge transport, which eventually improves power conversion efficiency (PCE) [31]. CNTs protect perovskites from environmental degradation while maintaining structural stability of the device [32].

The deposition of homogeneous layers is possible with the spin coating method in terms of film thickness and homogeneity, making it suitable for large-area applications. CVD offers perfect integration through the direct development of CNTs on the PSC surface [33] Spray coating enables uniform large-area deposition, while spin coating provides acceptable thickness control. Stabilization of the device and improved lifetime can be achieved by CNT coatings that maintain cross-layer interactions. Improved charge transport in the PSC layers is made possible by doping and surface modification enhancement [14]. CNT adhesion and dispersion can be improved through compatibility with the perovskite material via plasma surface treatment. Defects are removed by laser ablation techniques, improving the structural and electrical conductivity of CNTs by maximizing charge transfer efficiency and reducing charge recombination. The bond between CNTs and PSC materials can be strengthened with improved perovskite layer crystallinity through thermal annealing methods [14]. CNT-based PSCs with large-area scalability for mass production, power conversion efficiency, and stability can be achieved through post-treatment methods with improved advanced techniques.

The strategy for synthesizing and depositing carbon nanotubes (CNTs) plays a significant role in determining their efficiency in perovskite solar cells (PSCs). Techniques like chemical vapor deposition (CVD) and arc discharge are utilized to synthesize CNTs of high structural quality and defined size, thereby making them compatible for use in optoelectronics. The deposition technique, such as spin coating, spray coating, or direct incorporation, affects the CNT distribution within the PSC layers. Spray coating is most suitable for uniform coating of large areas, while spin coating is applied when precision in thickness is required. These processes need to be optimized for uniform integration of CNTs and efficient scaling up of PSC production.

Post-treatment processes further refine CNT performance in PSCs. Surface doping and chemical treatment improve electrical properties and interfacial adhesion with adjacent materials. Halogen or alkali metal doping introduces additional charge carriers, improving conductivity and facilitating charge transfer between layers. Plasma functionalization improves the surface characteristics of CNTs to enhance dispersion and adhesion in PSC devices [14]. This treatment also facilitates surface chemistry tuning with reduced effort, improving material compatibility.^19^ Laser ablation is also an effective approach that removes structural flaws from CNTs, making them more electrically conductive and mechanically stable. Both properties are crucial for device stability. Device efficiency and charge mobility are directly impacted by these improvements [14].

Thermal annealing has also proven effective. It reduces the likelihood of charge recombination by orienting CNTs in the PSC architecture to improve unidirectional (anisotropic) charge transfer. Additionally, it enhances the crystallinity of perovskite films, facilitating improved layer-to-layer integration. Over time, all of these enhancements lead to higher power conversion efficiency (PCE).7 CVD not only enables the synthesis of high-quality CNTs but also their uniform deposition on device surfaces. Uniform electrical contact and efficient charge transportation are ensured by controlled deposition of functionalized CNTs using this method. These novel post-processing methods collectively enhance the PCE, device lifetime, and enable large-area fabrication to make it commercially viable.

3. Impact of CNTs on Device Architecture

The inclusion of CNTs in PSCs offers several benefits such as enhanced charge transport, mechanical stability, and overall performance enhancement in PSC architecture.

3.1 Traditional PSC Architectures

In traditional perovskite solar cells, a light-absorbing perovskite film is positioned between an electron transport layer (ETL) and a hole transport layer (HTL) along with conductive metal or polymer electrodes, resulting in remarkable advancements in power conversion efficiency (PCE) over the years. Difficulties such as interface compatibility, long-term stability, and misalignment at the perovskite-transport layer interface result in high recombination losses and reduced efficiency. Mass production challenges arise due to poor conductivity that inhibits charge transport and destabilizes the perovskite layer due to the presence of moisture and oxygen [34].

3.2 CNT-Enhanced PSC Architectures

The incorporation of carbon nanotubes into PSCs enhances electrical conductivity with high charge carrier mobility, reducing recombination losses and increasing overall PCE. The potential to create lightweight and adaptable PSCs is another significant benefit of CNT integration, which enhances PSCs' mechanical stability and prolongs their operational life. Compared to traditional designs, CNTs allow for the manufacturing of flexible and portable solar cells, promising their application in wearable technology and space-based solar energy harvesting in the future for commercial adoption of CNT-based PSCs.

3.3 Successful Integration of CNTs in PSCs

It is notable that perovskite solar cells show tremendous stability and high efficiency through adding carbon nanotubes in a range of device topologies. Bulowski *et al.* (2024) reported that the TiO_2 electron transport layer showed improved electron mobility along with low series resistance through the inclusion of CNTs using a spin coating process [35]. A 15% rise in power conversion efficiency was also observed, showing improvement in charge transmission and reduced energy loss at the surface contact compared to standard PSCs. Through the process of solution blending, Spiro-OMeTAD hole transport layer with the inclusion of CNTs leads to increased hole mobility and reduced series resistance, giving enhanced open-circuit voltage (Voc) and short-circuit current density (Jsc), resulting in efficient performance enhancement. Incorporation of CNTs in PSCs with enhanced HTLs shows an 82% increase in PCE with longevity and good stability compared to normal HTLs [36].

Mixing CNTs with ZnO composites acts as a buffer layer between the ETL and perovskite structures, leading to remarkable light absorption and high charge transfer efficiency [37]. This results in a 20% increase in PCE with good stability under environmental degradation conditions. Hence, CNTs show promising potential to overcome various technological challenges in PSCs like stability, charge transport constraints, and environmental durability, thus proving effective in increasing PSC efficiency with advancements in solar energy versatility and endurance.

3.4 Comparative Analysis

A comparative study of CNT-doped and traditional PSCs is listed in Table 1. There is an overall increase in performance, improvement in mechanical stability, and environmental longevity with the inclusion of CNTs in perovskite solar cells.

Table 1. Comparative Analysis of traditional and CNT enhanced PSC.

Metric	Traditional PSCs	CNT enhanced PSCs
Power Conversion Efficiency (PCE)	Typically range from 15% to 22%	Improved PCE, oftenexceeding 25% due toenhanced chargetransport and reduced recombination losses.
Stability	Prone to degradation under moisture, oxygen, and UV exposure. Requires encapsulation for longevity.	Enhanced stability dueto improved filmmorphology, surface passivation, andenvironmentalresilience provided by CNTs
Charge Transport	Limited by the conductivity of ETL/HTL materials. Potential for recombination losses.	Superior charge transport due to high conductivity of CNTs, leading to reduced recombination and higher fill factors.
Flexibility	Rigid architecture, often limited flexibility.	Improved flexibility with CNTs integrated into the PSC layers, making them suitable for flexible and wearable applications
Scalability and Fabrication	Scalability can be challenging due to complex layern deposition processes.	CNT integration offers potential for scalable, solution-processable techniques, enhancing the scalability of PSCs

In addition, it helps overcome issues with increased interfacial properties, reduced energy losses, and high charge mobility, resulting in a tremendous improvement in power conversion efficiency of about 15% when used in the perovskite, hole transport layer, or electron transport layer due to enhanced charge transfer and reduced recombination losses [38].

Sensitive environmental factors like variation in temperature, moisture, and oxygen affect the long-term stability of PSCs, with less than 60% of initial power conversion efficiency retained, whereas CNT-coated PSCs act as a barrier in composite films or coatings, helping to overcome these challenges while retaining approximately 90% PCE. This increases the lifespan of the device operational system with improved stability, making it suitable for real-world applications.

In the demand for lightweight and flexible solar cells for wearable electronics and portable energy harvesting, mechanical flexibility presents a significant challenge. The brittle nature of traditional PSCs makes them incompatible with flexible substrates. Inclusion of CNTs in PSCs helps the device withstand bending and deformation without loss of performance by enhancing the mechanical strength of composite layers, HTLs, and ETLs, making them suitable for greater flexibility, longevity of photovoltaics, high power conversion efficiency, and shielding from environmental degradation compared to standard PSCs. These properties make CNTs a more suitable candidate as a prominent next-generation photovoltaic device, leading to advancement in solar cell technology.

The comparative research highlights how incorporating CNTs into PSC architecture provides significant advantages. Comparing CNT-enhanced PSCs to conventional PSCs, the former offer advantages in mechanical flexibility, stability under environmental conditions, and PCE. These developments demonstrate the potential application to address important issues in solar cell technology and help create solar energy solutions that are more effective, long-lasting, and adaptable.

3.5 Integration of CNTs in PSCs

Research findings show that adding carbon nanotubes (CNTs) to perovskite solar cells has numerous benefits, including enhancement in charge carrier mobility, device stability, and high performance efficiency. The inclusion of carbon nanotubes in PSCs through their usage in composite structures, hole transport layers (HTLs), and electron transport layers (ETLs) are discussed in this section.

3.5.1 CNTs in Hole Transport Layers

The Spiro-OMeTAD-based HTL of PSCs with the addition of carbon nanotubes was analyzed by Lou *et al*. (2021). An increase in overall power conversion efficiency with improved short-circuit current density (Jsc) was observed by reducing series resistance and significantly increasing hole mobility [39]. The CNT-coated PSCs showed 21% enhancement in PCE. A longer operating lifetime in the device with HTL was also noted, with better chemical stability under continuous thermal and light stress.

3.5.2 CNTs in Electron Transport Layers

The hybrid ETLs showed improved electron mobility and energy level alignment with the perovskite layer. TiO_2 combined with CNTs to form a composite electron transport layer (ETL) was analyzed by Fatima et al. (2024) [40]. There was an increase in the fill factor and the power conversion efficiency reached 25.2%. Inclusion of CNTs in the ETL showed good device stabilization with longevity, showing 90% of initial efficiency after 1000 hours of continuous operation [41].

3.5.3 CNT-Composite Layers

The charge transfer mechanism and light absorption have been greatly increased by carbon nanotube-coated ZnO composite, which is positioned between the perovskite absorber and the ETL, resulting in a 20% rise in power conversion efficiency [42]. It supports device stability and reduces hysteresis under a range of environmental conditions. CNT composites support the design of next-generation solar cells by effectively addressing various aspects of PSC performance.

3.5.4 Post-Treatment with CNTs

The usage of carbon nanotubes on the perovskite surface allows for defect passivation and non-radiative recombination reduction, leading to Voc improvement and power conversion efficiency (PCE) enhancement [43]. CNTs also act as a protective layer against moisture, withstanding environmental degradation of PSCs and showing increased durability and enhanced functionality over time. Spin or spray coatings were used for optimizing CNT dispersion throughout the perovskite surface. CNT coatings help improve charge mobility by enhancing energy levels and forming efficient conduction channels. Efficient charge transfer is possible through highly controlled CNT dispersion using spray coating methods.15 Charge carrier mobility and mechanical flexibility are sustained in CNT-coated PSCs in wearable electronics applications due to the homogeneity and flexibility of the device.

Post-treatment techniques with carbon nanotubes (CNTs) have shown great promise for improved photovoltaic efficiency. CNT films inhibit non-radiative recombination by passivating defects at the surface level, which directly leads to greater open-circuit voltage (Voc) and efficient energy conversion.40 When uniformly deposited, CNTs create smooth conductive channels that allow for efficient charge transport. Advanced methods such as spin and spray coating enable such conformal deposition, matching energy levels between layers and increasing charge mobility.

These deposition processes also play a protective role by introducing a barrier against environmental factors like oxygen and humidity, which otherwise destabilize the perovskite structure. Spray coating ensures proper control over the distribution of CNTs along with coverage and consistent interfacial contact. This leads to improved charge separation and transfer across different layers [15]. In addition, these approaches provide mechanical flexibility, making CNT-treated PSCs more suitable for application in portable and wearable electronics. Overall, CNT post-treatment processes both structurally enhance the lifetime and improve electrical quality. This addition enhances charge extraction efficiency and extends PSCs' lifespan, thereby making the utilization of CNTs extremely valuable in next-generation solar cells.

3.5.5 Flexible PSCs with CNTs

CNT integration has also been crucial in increasing the flexibility of PSCs. Yoon et al. demonstrated that incorporating CNTs into the perovskite and charge transport layers rendered the PSC flexible with improved mechanical stability [44]. The device exhibited a high PCE value of 23.8% even after more than 10,000 bending cycles, making it appropriate for wearable and flexible devices. The study on CNT-enhanced PSCs demonstrates the remarkable potential that results from adding CNTs to various layers. Such studies demonstrate that CNTs can greatly increase mechanical robustness, stability, and efficiency, thereby resolving important issues in solar cell technology. CNTs have been successfully positioned to maximize charge transport, prevent deterioration, and improve overall performance in a variety of device topologies [36]. More innovation in using CNTs is anticipated to propel the creation of more effective, durable, and flexible solar cells as research progresses. Future research and the large-scale commercial production of high-performance CNT PSCs will likely be based on cost-effective and scalable CNT deposition processes.

4. Enhancement in Photovoltaic performance

The integration of carbon nanotubes (CNTs) into perovskite solar cells (PSCs) has been the subject of intense research due to its potential to significantly improve photovoltaic performance. This section presents the precise gains in charge collection efficiency, light absorption, and power conversion efficiency (PCE) that can be attributed to carbon nanotubes (CNTs), as demonstrated by quantitative data from recent studies. It also discusses the difficulties in incorporating CNTs and offers a fair assessment of how they affect PSCs.

4.1 Quantitative Evidence of performance Gain

The potential for improved overall photovoltaic performance has made the integration of carbon nanotubes (CNTs) with perovskite solar cells (PSCs) a key subject of interest. Recent findings show that the inclusion of CNTs helps in enhancing power conversion efficiency, light absorption, and charge transfer efficiency. This section discusses the impact of CNT integration on PSC technology.

4.1.1 Power Conversion Efficiency (PCE)

Nakka *et al.* (2022) analyzed in their research that adding carbon nanotubes to the Spiro-OMeTAD hole transport layer (HTL) increases the power conversion efficiency from 20.1% to 23.9% (Figure 2) [45]. This enhancement leads to high hole mobility and reduced series resistance due to the incorporation of CNTs. A more versatile device is formed with improved charge carrier mobility where the hole transport layer can extract charges efficiently from the perovskite layer.

Zhao *et al.* (2024) examined the inclusion of carbon nanotubes in the electron transport layer (ETL) of TiO_2, resulting in an increase of power conversion efficiency from 22.3% to 25.5% compared to traditional PSCs [46]. This considerable improvement is due to increased electron mobility and reduced interfacial recombination, leading to optimization of charge collection and mobilization. Hence, it is found that carbon nanotubes play a predominant role in optimizing both the HTL and ETL, paving the way for the development of high-efficiency PSC technology.

4.1.2 Light Absorption

To lengthen the optical path with enhanced photon-active layer interaction, carbon nanotubes play a major role in the ability to absorb light in the perovskite layer, as investigated by Qamar et al. (2024) [47]. The inclusion of CNTs improves light absorption by 12% in the 400–700 nm visible range spectrum. The short-circuit current density (Jsc) was drastically improved from 22.8 mA/cm² to 25.6 mA/cm², contributing to the improvement of overall power conversion efficiency through enhanced light harvesting in the system [36].

4.1.3 Charge Collection Efficiency

Muchuweni *et al*. (2021) reported an increased charge collection efficiency from 85% to 93% due to the incorporation of CNTs into hole transport layers (HTL) [15]. Perovskite solar cells with high efficiency are achieved through CNT-based charge collection efficiency, decreased interfacial resistance, and enhanced charge transportation. Integration of CNTs raises the fill factor from 0.75 to 0.81, as reported by Hu *et al.* (2023). The high value of fill factor emphasizes better charge extraction and reduced energy loss, increasing the power conversion efficiency in PSCs and representing a promising factor for next-generation solar cells. Improved surface modification methods like functionalization and post-deposition treatment optimize carbon nanotube morphology for perfect integration with the perovskite layers. These optimizations enhance charge mobility for efficient power conversion efficiency and stability of PSCs.

The efficiency in charge collection of perovskite solar cells (PSCs) depends greatly on the chemical and structural characteristics of carbon nanotube (CNT) films. A planar and smooth CNT film reduces interfacial resistance, facilitates greater charge transfer, and minimizes energy loss during operation [4]. The doping of CNTs also enhances their compatibility with the surrounding layers by improving the surface chemistry of the CNTs. This leads to strong interfacial bonding and minimizes the probability of charge recombination.

Surface processing methods, including functionalization and post-deposition treatments, are crucial for optimizing CNT morphology.

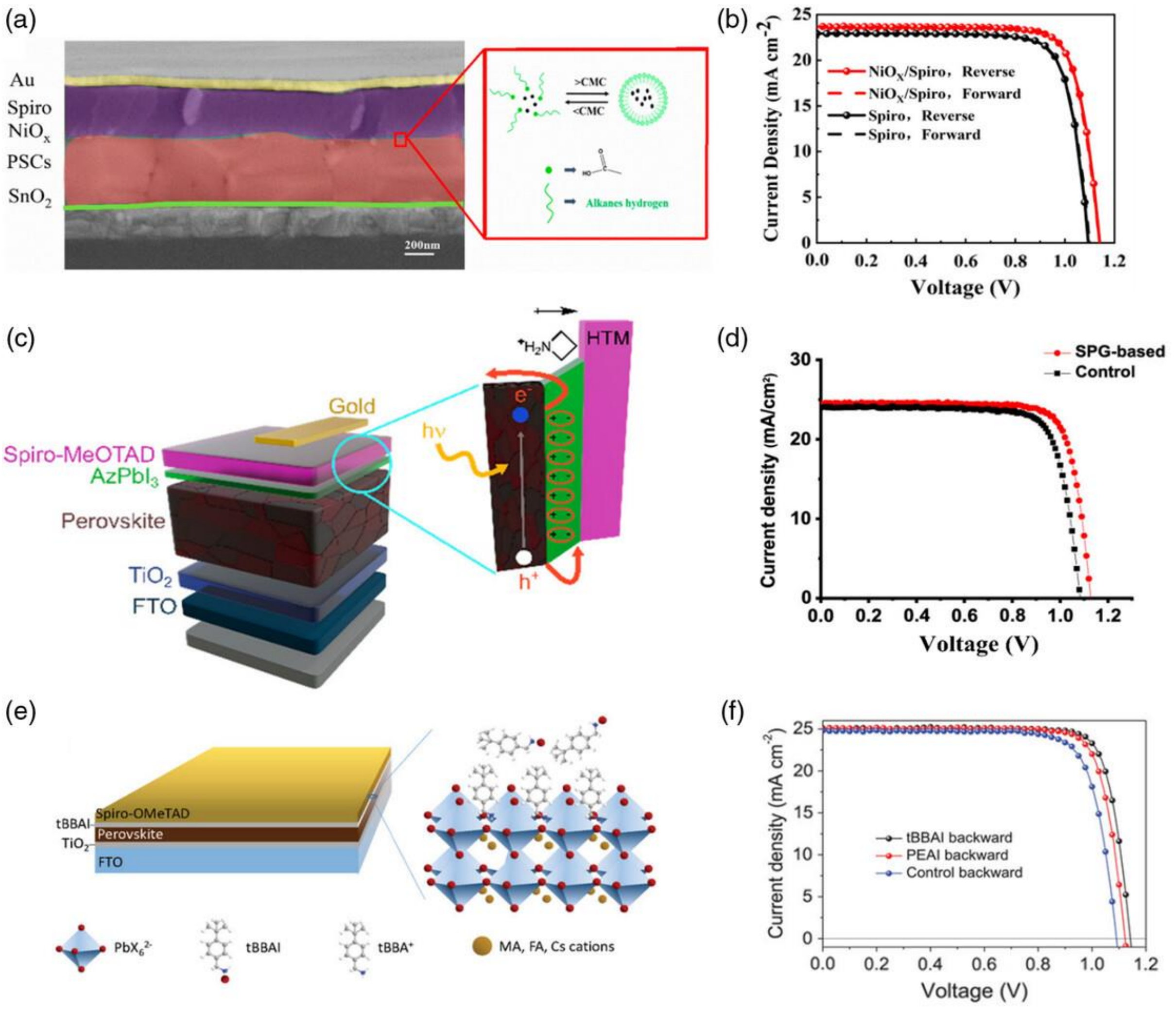

Figure 2. Device structures and J–V characteristics of PVSCs with interface modifiers [46]

These processes allow efficient CNT alignment in the PSC structure, enabling directional (anisotropic) charge transfer. As a result, charge carriers move more efficiently along the device, resulting in improved power conversion efficiency (PCE) and durability. Enabling charge collection through such measures is a necessary step toward high-performing, stable PSCs.

4.2 Addressing Potential Drawbacks and challenges

While adding CNTs to PSCs has many advantages, there are drawbacks that must be overcome to fully enjoy the benefits of CNT-enhanced PSCs. This section examines the main issues around fabrication difficulties, financial concerns, and potential detrimental effects on device attributes, as well as proposed fixes and current research initiatives.

4.2.1 Fabrication Difficulties

One of the primary challenges in using CNTs in PSCs is the nonuniform dispersion in the device due to strong van der Waals forces and a high aspect ratio. This uneven distribution increases charge recombination and affects overall efficiency [48]. Optimal performance in the device is achieved through uniform distribution of CNTs throughout the active layer for continuous charge transmission. Numerous methods, including chemical functionalization and surfactant-augmented dispersion, have been investigated by researchers to overcome this problem. Both of these methods have proven successful in preventing aggregation, but they increase production costs and process complexity. The development of low-cost, scalable dispersion technologies represents a vital and ongoing research endeavor.

4.2.2 Cost Considerations

The economic feasibility of CNT-based PSCs is overshadowed by CNT synthesis and processing expenses, particularly for single-walled carbon nanotubes (SWCNTs). While SWCNTs possess superior electrical and optical properties, they remain expensive to produce, making large-scale application unaffordable. Multi-walled carbon nanotubes (MWCNTs), while cheaper, do not necessarily offer the same level of performance efficiency as SWCNTs [49]. To push CNT-based PSCs closer to commercialization, researchers are exploring cost-effective fabrication techniques, including large-scale chemical vapor deposition (CVD) methods and alternative synthesis routes. At the same time, composite materials and architecturally modified CNTs are being developed to find a balance between cost and performance. The outcome of these efforts will determine the viability of integrating CNTs into the next generation of solar technology.

4.2.3 Potential Negative impacts on device properties

The addition of CNTs can influence several important physical characteristics of PSCs, including transparency and mechanical flexibility. CNTs, while enhancing conductivity, can reduce optical transparency at higher concentrations, thereby being undesirable in situations where light transmission needs to be extremely high, such as in tandem solar cells and transparent photovoltaics. Balancing the maintenance of transparency with optimizing charge transport remains a core design consideration. Mechanical flexibility is also a concern, particularly in wearable and flexible electronic devices. While CNTs can be used to add mechanical strength, excessive use or improper integration can bring brittleness, compromising the structural performance of the device [50] Researchers are working to improve CNT deposition techniques and investigate hybrid materials that boost flexibility without sacrificing electrical performance to overcome these difficulties. CNT-incorporated PSCs provide high light absorption with enhanced power conversion efficiency. Overcoming these difficulties will provide a promising pathway for the development of next-generation solar cells.

5. Mechanisms of Action

The incorporation of carbon nanotubes (CNTs) has led to substantial improvements in perovskite solar cell (PSC) performance through enhanced charge transfer mechanisms and sophisticated interface engineering approaches. These advancements are supported by comprehensive simulations and robust theoretical frameworks that elucidate the underlying enhancement mechanisms.

5.1 Charge Transport and Collection

Carbon nanotubes exhibit exceptional electrical conductivity, which significantly enhances the charge carrier extraction capabilities of perovskite solar cells while simultaneously reducing recombination losses. Efficient transport and collection of charge carriers represents a fundamental requirement for achieving optimal PSC performance. The molecular interactions between CNTs and perovskite materials play a crucial role in advancing both charge collection efficiency and carrier transportation mechanisms.

5.1.1 Molecular Interactions and Charge Transport

The integration of carbon nanotubes into either the electron transport layer (ETL) or hole transport layer (HTL) of PSCs substantially enhances overall device efficiency by improving charge extraction and carrier mobility [51] Single-walled carbon nanotubes possess an extensive π-electron network that facilitates high electron mobility, enabling rapid charge transport with minimal energy losses. When CNTs are incorporated into the ETL, strong π-π interactions emerge, creating favourable alignment with perovskite layer energy levels. This alignment effectively minimizes recombination processes while enhancing electron mobility toward the electrode, ensuring efficient charge flow by reducing carrier losses and improving both stability and power conversion efficiency.

Beyond electron transportation enhancement, CNTs also significantly improve hole extraction when incorporated into the hole transport layer. This modification enables rapid charge carrier movement from the perovskite layer to the electrode, resulting in increased hole mobility and enhanced network conductivity, which collectively improve charge collection by reducing overall resistance. Venkataraman *et al.* (2019) demonstrated that CNT incorporation in the hole transport layer reduces hole transport time from 12.5 nanoseconds to 7.3 nanoseconds while simultaneously reducing recombination losses, thereby improving overall device efficiency [52].

Chenebuah *et al.* (2024) utilized theoretical models, including Density Functional Theory (DFT) simulations, to demonstrate that carbon nanotubes reduce the activation energy required for charge transfer, thereby enhancing both electron and hole extraction efficiency [53] Through energy level optimization, recombination loss reduction, and charge extraction enhancement, CNT-integrated PSCs represent a promising pathway toward achieving superior power conversion efficiency and advancing perovskite solar technology.

5.1.2 Charge Collection Mechanisms

Carbon nanotube integration in perovskite solar cells significantly enhances charge collection through the development of conductive networks and electrode interface optimization, resulting in efficient electron and hole transport with reduced recombination losses that improve overall device performance. When CNTs are strategically positioned at interfaces between the perovskite layer and both electron and hole transport layers, charge extraction becomes further optimized. Proper junction alignment reduces energy barriers, facilitating charge carrier movement toward electrodes.

De *et al.* (2020) observed a 15% increase in charge collection efficiency when CNTs were incorporated into the ETL, resulting in notable improvements in PSC power conversion efficiency (PCE) [54]. Their transient photovoltaic measurements confirmed that CNT-modified ETLs suppress recombination while enhancing charge extraction. By regulating energy levels at critical interfaces and establishing high-efficiency channels for charge transport, CNTs significantly reduce carrier losses and improve extraction efficiency. These enhancements not only optimize PSC performance but also provide a scalable approach toward advancing next-generation solar cell design. Recent experimental evidence in the literature demonstrates the potential of CNT-based modifications for enhanced efficiency, representing a promising avenue for maximizing perovskite solar cell performance.

5.2 Interface Engineering

The quality of interactions between various layers in perovskite solar cells significantly influences both charge transfer efficiency and long-term stability. CNT incorporation in PSCs optimizes interfacial characteristics, thereby extending device lifetime. The utilization of CNTs for enhanced stability, effective energy level alignment, and molecular defect mitigation is extensively discussed [55].

5.2.2 Molecular Interface Engineering

Single-walled carbon nanotubes can modify the energy levels of perovskite materials, thereby improving charge mobility at interfaces. This modification minimizes energy barriers and interfacial losses while increasing charge extraction and overall efficiency. CNTs also effectively address perovskite layer defects that typically cause charge losses and reduce device efficiency. Gao *et al.* (2018) observed that carbon nanotube incorporation reduces surface trap state density by 40%, significantly improving device stability [56]. Guo *et al.* (2024) conducted molecular dynamics simulations demonstrating that carbon nanotubes enhance device stability by reducing recombination losses. Device longevity and stability are crucial for commercial applications, representing significant advancement in interface engineering [57].

5.2.3 Chemical Stability and Environmental Resilience

The addition of CNTs to perovskite silicon composites provides enhanced environmental stability and chemical durability, resulting in increased lifespan and improved efficiency. The unique intrinsic hydrophobic properties of CNTs prevent moisture infiltration, which is primarily responsible for perovskite material degradation. Carbon nanotubes extend device lifespan by forming moisture-blocking and oxygen-blocking barriers at principal junctions in PSCs, thereby reducing damage in humid environments. PSCs incorporating CNTs demonstrate 25% greater stability compared to devices without CNT inclusion. CNTs provide extended performance by resisting thermal variations and UV light exposure while reducing chemical degradation [58]

Beyond chemical protection, CNTs contribute to the mechanical stability of PSCs. Their strength and flexibility enhance adhesion between layers, preventing delamination and cracking issues that commonly occur in their absence. This property proves particularly beneficial for flexible solar cells, which must endure repeated bending and mechanical stress. Without proper reinforcement, these stresses lead to performance degradation. The effectiveness of CNTs in achieving enhanced mechanical stability has been well demonstrated. Que *et al.* (2021) reported that flexible PSCs with CNT content retained over 90% of their initial power conversion efficiency following 1,000 bending cycles [59]. When devices are subjected to mechanical stress, CNTs prevent microcack formation while maintaining structural integrity.

Additionally, CNTs protect PSCs from oxygen and water exposure, two critical factors for long-term stability, serving as an external barrier against environmental contaminants. Both theoretical and experimental research confirm the positive impact of carbon nanotubes on improving device robustness and efficiency. However, additional research is needed to fully optimize their utilization. Optimizing CNT integration and addressing remaining challenges will be essential for advancing the development of more robust and efficient solar energy systems.

5.2.4 Surface Properties of CNT Coatings

The behaviour of carbon nanotubes in perovskite solar cells depends significantly on surface characteristics including structure, roughness, and composition. The orientation of CNT coatings critically influences the interaction between CNTs and perovskite layers as well as charge carrier materials. An orderly aligned and uniformly distributed CNT network ensures complete charge transportation without energy losses. However, CNT aggregation introduces defects that trap charge carriers and promote recombination, compromising device performance. Experimental evidence indicates that ordered CNT networks provide direct channels for charge transport with minimized resistance and maximized carrier mobility. Conversely, disordered CNT arrangements may increase charge recombination unless optimized through functionalization [60].

CNT film surface roughness also significantly controls charge recombination and injection processes. Rough surfaces increase interfacial area, which enhances charge extraction. However, excessive roughness creates non-uniform electric fields, leading to localized charge accumulation and recombination losses. Smooth and uniform CNT films offer better energy level alignment with perovskite films, minimizing recombination and increasing charge collection efficiency. Studies utilizing atomic force microscopy (AFM) and scanning electron microscopy (SEM) indicate that optimal CNT roughness leads to improved interfacial charge transfer and enhanced device stability [10].

The work function of CNT coatings depends on their chemical characteristics and energy level matching with PSCs. CNTs functionalized with appropriate surface chemistry can be tailored for enhanced charge extraction. For instance, oxygen-functionalized CNTs exhibit improved hole transport and better energy level matching with hole transport layers (HTLs). Doping CNTs with atoms such as nitrogen or boron also modifies their electronic properties, improving conductivity and charge transfer. Through precise surface engineering, researchers have achieved improvements in open-circuit voltage (Voc), fill factor (FF), and device stability. Future studies should focus on optimizing surface modification techniques to improve CNT integration and enhance both efficiency and lifespan of PSCs [61].

6.1 Potential Combinations and Their Impacts

The integration of carbon nanotubes into perovskite solar cells represents a revolutionary advancement in solar cell technology. However, CNT effectiveness can be further enhanced through combination with other nanomaterials, realizing synergistic effects that demonstrate improved performance, stability, and versatility. This section examines the integration of carbon nanotubes with other nanomaterials, addressing key challenges and their benefits in PSCs.

6.1.1 CNTs and Graphene

The efficiency and stability of PSCs can be significantly improved through the integration of carbon nanotubes with complementary nanomaterials [62]. These improvements are achieved because CNT counterparts complement their properties, such that when combined, they maximize various aspects of device performance.

Notable advancements in device performance have been observed with hybrid materials combining graphene (Figure 3). Ullah et al. (2022) demonstrated that incorporating a CNT-graphene hybrid material into the electron transport layer (ETL) increases PCE [63]. This enhancement was attributed to the hybrid material's higher charge mobility and decreased recombination losses. The synergistic pairing of graphene and CNTs represents a viable approach to improving PSC durability and performance. This hybrid solution addresses charge transport efficiency and mechanical stability, two major PSC technology concerns, by utilizing the enhanced electrical conductivity and mechanical robustness of these materials.

6.1.2 CNTs and Metal Oxide Nanoparticles

Both graphene and CNTs are widely recognized for their excellent electrical conductivity.

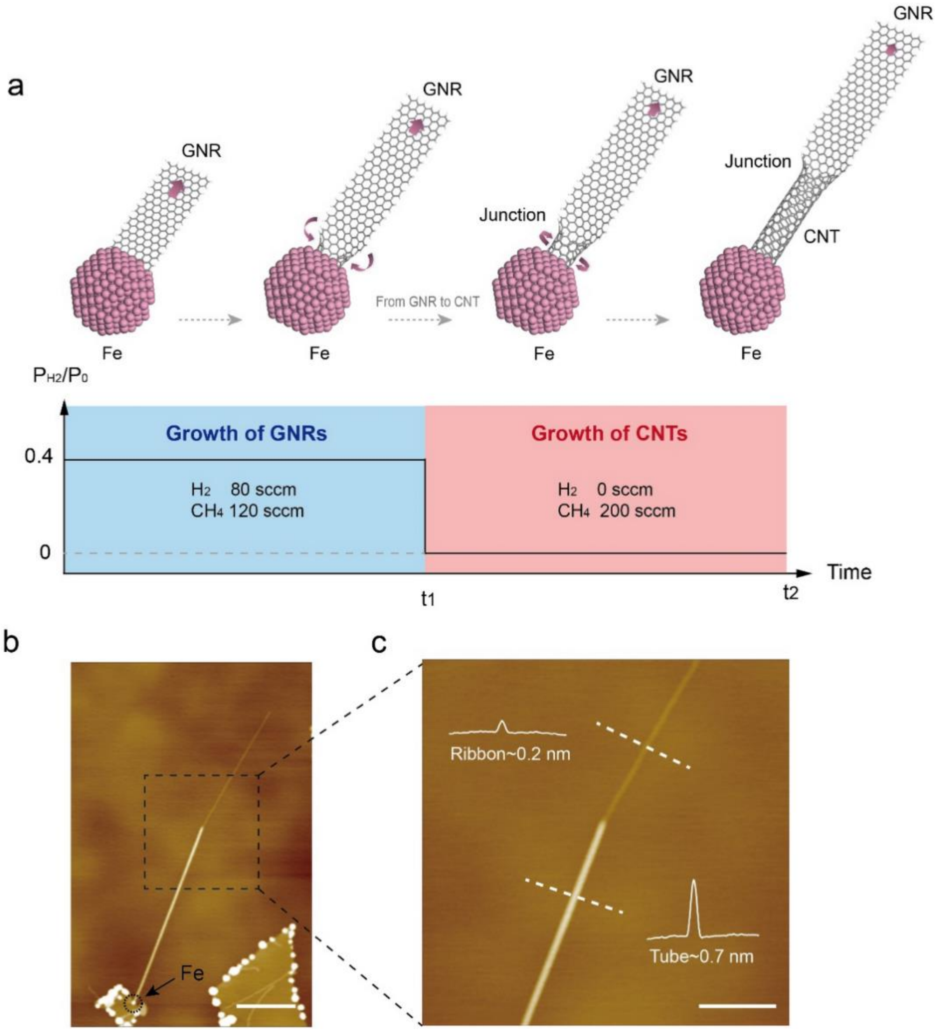

Figure 3. Growth of GNR/CNT junctions [66]

When integrated into PSCs, they provide long-range interconnected conductive channels that reduce resistive losses, leading to improved charge transportation and collection. CNT-graphene synergy significantly increases mechanical stability, which proves beneficial for flexible and wearable solar cells, in addition to electrical properties. The tensile strength of CNTs combined with the flexible nature of graphene provides structural support, preventing cracking and degradation during mechanical stress on devices, thereby extending PSC longevity and flexibility for practical applications. Figure 3 illustrates the utilization of CNT-graphene hybrids for efficient device performance. Ullah *et al.* (2022) reported that the combination of hybrid CNT-graphene materials results in increased power conversion efficiency [64].

6.1.3 CNTs and Quantum Dots

Metal oxide nanoparticles such as ZnO and TiO_2 in combination with carbon nanotubes significantly increase perovskite solar cell efficiency. The electron transport characteristics of metal oxides combined with CNTs enable simplified charge transport with reduced energy losses [65].

Carbon nanotube addition to PSC structures can eliminate metal oxide defects and provide protection from environmental degradation such as moisture and oxygen exposure. Liu *et al.* (2021) reported that TiO_2-based electron transport layers with CNTs increase device stability by 21% under continuous illumination. This improvement results from enhanced energy level alignment between the electron transport layer and perovskite layer, leading to improved charge carrier extraction and environmental stability for PSC effectiveness and longevity [66].

6.1.4 CNTs and Quantum Dots

Quantum dots (QDs) in combination with CNTs provide superior charge transport properties, enhanced light absorption across a wide range of wavelengths approaching infrared, and improved charge separation. The strong interfacial connection between carbon nanotubes and quantum dots facilitates electron-hole pair separation with reduced recombination losses.

Karimi *et al*. (2018) analyzed the inclusion of CdSe QDs with CNTs, finding dramatic improvements in power conversion efficiency, establishing new capability levels for PSCs [67].

6.2 Emerging Trends in Hybrid Nanomaterials

Research on hybrid nanomaterials advances PSC technology by improving performance, stability, and efficiency. The potential of hybrid nanomaterials for solar technology in combination with CNTs is discussed in this section.

6.2.1 Hybrid Perovskite-CNT Structures

Incorporating carbon nanotubes into perovskite films demonstrates significant increases in solar cell efficiency. Carbon nanotubes provide high charge transfer mechanisms with increased power conversion efficiency. Charge extraction and efficiency are enhanced through uniform distribution throughout the perovskite matrix, forming strong composite materials. Hossain *et al.* (2024) found a 15% increase in power conversion efficiency when carbon nanotubes were incorporated into perovskite layers for better charge transfer and reduced trap-assisted recombination [68] Zheng *et al.* (2023) analyzed that after 500 hours of prolonged light exposure, traditional perovskite solar cells lost 70% of their initial efficiency, whereas PSCs with carbon nanotube addition maintained 90% of their efficiency, demonstrating increased stability [69].

6.2.2 Hybrid Nanomaterial Combinations

Carbon nanotubes in combination with Metal-Organic Frameworks provide increased conductivity, improving device performance by enabling enhanced light absorption and charge separation processes with large surface areas and electronically tunable characteristics. Addition of CNTs to the electron transport layer with Metal-Organic Frameworks has increased power conversion efficiency by 20% [70] Inclusion of CNTs with Transition Metal Dichalcogenides (TMDs) such as MoS_2 represents another versatile strategy with superior optoelectronic qualities, providing high electron transport and increased environmental stability.

6.3 Future Directions and Research Opportunities

The development of perovskite solar cells, particularly with the utilization of carbon nanotubes and other nanomaterials, represents an area of significant research interest. Potential directions for improving power conversion efficiency, stability, and scalability of carbon nanotube-based PSCs are highlighted in this section.

6.3.1 Optimization of Material Composition

Understanding the molecular behavior of CNTs when coupled with other nanomaterials is essential for optimizing PSC performance. Physical characteristics such as diameter, aspect ratio, and single or multi-walled CNT structures influence charge carrier transport mechanisms when combined with perovskite films. Achieving homogeneous integration of carbon nanotubes in the PSC matrix is crucial for addressing current challenges. Additional investigations on CNT hybridization with other materials such as graphene oxide, metal-organic frameworks, and transition metal dichalcogenides are needed for improved performance [37]. Greater emphasis on hybridizing carbon nanotubes with lead-free perovskite formulations is required for the commercialization of PSC technology.

Future research must focus on developing hybrid material systems comprising carbon nanotubes and other nanomaterials with advanced properties. For example, integrating CNTs with two-dimensional materials such as graphene oxide has the potential to enhance both electrical conductivity and structural stability. Similarly, incorporating CNTs with materials like metal-organic frameworks (MOFs) or transition metal dichalcogenides (TMDs) can lead to synergistic effects in charge transport and device durability.[37] Another promising direction involves comparing applications of single-walled and multi-walled CNTs to determine their respective advantages for optimizing charge mobility and thermal stability. Concurrently, research must examine the interface between CNTs and new perovskite formulations, specifically non-toxic and lead-free variants. Understanding these interfaces is vital for increasing environmental sustainability and industrial scale-up of PSCs. These studies will not only help reduce ecological risks but also facilitate the development of next-generation solar technologies that are both high-efficiency and environmentally friendly.

6.3.2 Enhancing Fabrication Methods

Large-scale carbon nanotube-based PSC production requires scalable and cost-effective fabrication methods. Optimization of spray coating and inkjet printing techniques is needed for uniform CNT distribution over wide areas. Roll-to-roll fabrication methods represent one of the most promising approaches for producing flexible PSCs in large quantities with increased mechanical flexibility and durability. For creating high-performance PSC designs, printing methods are effectively utilized in patterning CNT layers for enhanced efficiency.[11] Atomic layer deposition (ALD) methods are highly recommended for device stability and effective charge transportation. Advancements in fabrication techniques are necessary for the commercialization of CNT-based perovskite solar cells.

6.3.3 Investigating Long-Term Stability

Long-term stability represents one of the most significant challenges facing carbon nanotube-integrated PSCs. Environmental degradation causes long-term deterioration through factors such as humidity, ultraviolet (UV) radiation, and thermal cycling. Advanced testing methods are required to identify failure mechanisms, including degradation pathways. For integration of carbon nanotube-based PSCs into large-scale energy applications, their long-term stability must be optimized.

6.3.4 Exploring New Combinations of Nanomaterials

Charge carrier transportation and light absorption properties can be further improved through hybridization of nanostructures with carbon nanotubes, incorporating organic-inorganic material elements such as graphene oxide or perovskite-quantum dot combinations to increase PSC effectiveness and performance. Photostability can be enhanced by hybridizing CNTs with perovskite layers. Creating next-generation PSCs with high performance capable of withstanding environmental degradation is highly sought after for solar energy technology development [36].

6.3.5 Improving Theoretical Models

Understanding the molecular behavior of carbon nanotubes in PSC design through computational modeling enables structural optimization. Comprehensive insights into CNT-perovskite interactions for designing optimized hybrid materials can be achieved through DFT calculations. Molecular dynamics simulations help predict how CNT inclusion affects device stability and charge carrier dynamics. Investigations of novel materials to identify intermolecular interactions in high-efficiency PSC structures can be conducted at low material costs using simulation approaches. Both experimental and computational analyses are required for establishing reliable frameworks in PSC optimization for future research scope.

7. Conclusion

Carbon nanotubes improve power conversion efficiency through effective charge transfer, reduced energy losses, and increased conductivity while providing structural flexibility in PSC architectures. CNT interactions with other nanomaterials such as metal oxides and graphene enhance light absorption and charge transfer mechanisms for more effective and durable PSC designs. Experimental validation combined with computer modeling provides greater insights into material behavior in device design for improved PSC efficiency. Carbon nanotube-modified PSCs have the potential to revolutionize solar energy and make substantial contributions to developing sustainable and scalable photovoltaic technology by enhancing device stability and environmental degradation resistance for high performance in future sustainable energy goals.

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E. Shobhana: Conceptualization, methodology, Investigation, Formal analysis, Writing Original Draft. R. Kannan: Writing, review and editing. N. Kripa: Writing, review and editing. All the authors read and approved the final version of the manuscript.

Does this article screened for similarity?

Yes

Conflict of interest

The Authors declares that there is no conflict of interest anywhere.

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