

A New Horizon in Renewable Energy: Materials and Advances in Plastic Solar Cells

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Abstract. With the background of global energy demand escalating and environmental repercussions, the discovery of renewable energy alternatives is urgent. Over recent decades, plastic solar cells have showcased their remarkable characteristics compared to traditional materials, indicating great potential to the quest for efficient, sustainable energy. This paper is dedicated to consolidating the latest research findings, primarily focusing on cutting-edge materials and advancements within the field of plastic solar cells. It includes a comprehensive analysis of environmental impacts, production methodologies, and the emergence of novel materials such as P3HT, polyaniline, and perovskite. The ensuing discussions provide a detailed evaluation of critical materials, notably conductive polymers and small molecule organic semiconductors. These materials are characterized by their superior electrical conductivity, environmental and thermal resilience, and versatility of modification. Nevertheless, the complexity of assessing the environmental performance of photovoltaic systems and the necessity for enhancing efficiency and stability are shown by industrial and academic insights. Inkjet printing, spin-coating, and slot die coating are triple common production methods that align with different needs. However, the technique's application is currently hampered by limitations in achieving high efficiency and stability, which restricts its upscaling adoption. Besides, the integration of OPV technology into wearable devices and building materials exemplifies the versatility of photovoltaics to meet diverse energy demands. In conclusion, further exploration of sustainable, eco-friendly materials and techniques is required to achieve better practical viability in the field of PSCs.

Keywords: Plastic solar cells (PSCs); PSC efficiency; PSC stability; environmental solution.

1. Introduction

PSCs, leveraging organic materials such as polymers for sunlight absorption and electricity generation, represent a significant innovation in photovoltaic technology. These cells are distinguished by their flexibility, lightweight nature, and reduced manufacturing expenses in comparison to conventional solar cells made of silicon. The significance of PSCs in the industrial and academic domains has been emphasized by the swift growth of the solar industry and the increasing need for sustainable energy sources. Notably, their scalability on various substrates facilitates cost-effective roll-to-roll manufacturing processes, enhancing their appeal for renewable energy production.

Over recent decades, PSCs have undergone remarkable evolution, achieving power conversion efficiencies (PCEs) exceeding 17%. This milestone, primarily attributed to the creation of effective photoactive compounds conjugated with π , marks a significant leap towards commercial viability, surpassing the previously established 15% efficiency threshold considered critical for PSC commercialization [1]. Despite these advancements, PSCs face persistent challenges that necessitate ongoing research and development. Among these is the imperative to improve the long-term reliability of PSC devices, addressing issues of degradation and performance decline during operation. Furthermore, the environmental impact of toxic solvents used in PSC fabrication processes calls for a reevaluation of materials and methods, promoting sustainability and environmental safety in PSC production [1].

The quest for efficient renewable energy solutions positions solar cells as pivotal in addressing global energy demands. Among various innovations, Intermediate Band Solar Cells (IBSCs) have come to the fore, offering improved energy conversion efficiencies through quantum dot

nanostructures and semiconductor alloys. Additionally, BJBC solar cells are widely recognized for their superior efficiency, which is attributed to minimized shading and reduced recombination losses. The exploration of III-V solar cells, Dye-Sensitized Solar Cells (DSSCs), PSCs, and organic solar cells continues, with the aim of optimizing energy conversion. To date, the highest recorded conversion efficiencies include 27.6% for silicon, 25.2% for perovskite, 12.3% for DSSCs, 53.8% for III-V solar cells, 15.38% for flexible solar cells, 18.05% for quantum dot cells, and 13.76% for organic solar cells [2].

In conclusion, while PSCs and other solar technologies have demonstrated significant potential for meeting global energy needs, addressing the challenges of stability, environmental impact, and efficiency remains crucial for the advancement and widespread adoption of these renewable energy solutions. Thus, in this paper, it gives a comprehensive description of the advancements, challenges, and future prospects of PSCs, emphasizing their role in the broader context of renewable energy technologies. The key materials and emerging technologies enhancing their efficiency are explored, and the paper discusses innovative production methods and applications.

2. Environmental Benefits of Plastic Solar Cells

A comprehensive assessment of photovoltaic (PV) systems, focusing on their efficiency and environmental impact, has been conducted, encompassing an analysis of system components and building materials. Life cycle analysis shows that PV systems are not considered zero-emission technologies due to the potential negative impact on land development, air quality, water resource utilization, and the presence of risky materials, as well as the possibility of ocular and sound pollution. However, studies indicate that the adoption of innovative technologies, for instance, hybrid and floating PV systems, can enhance PV performance while minimizing land use. When compared to conventional power generation methods, PV systems exhibit substantially lower environmental impacts, particularly concerning air quality and climate change. Nonetheless, addressing the environmental consequences that come with using hazardous materials in PV fabrication remains a significant challenge, compounded by the difficulty of recycling these materials due to their diversity and complex processing requirements. In terms of carbon footprint, PV solar systems are much more efficient than gas (607.6 grams), oil (742.1 grams), and coal (975.3 grams) power plants due to their average range of 14 to 73 grams of CO₂-equivalent per kilowatt-hour. Advancements in material science and the recycling of silicon materials hold the potential to reduce greenhouse gas emissions by up to 50% [3].

In a separate study focusing on the environmental payback time (PBTI) of PV systems—a metric assessing the duration required for the environmental impact of a PV system's lifecycle to be offset by the environmental benefits derived from solar power—researchers have highlighted the variability of PBTI across different impact categories, such as global warming, marine poisoning, society harm, fossil fuel depletion, and metal wastage. This variability is influenced by the specific technologies used in coal electricity generation. The findings suggest that the overall environmental payback time for PV systems can range from 0.0331 to 34.48 years, indicating a significant variance in the time it takes for the environmental benefits of solar energy to outweigh the considerable environmental harm caused by the manufacture of PV systems [4]. These revelations highlight how difficult it is to assess PV systems' green credentials and the necessity for ongoing innovation and strategic approaches to mitigate their ecological footprint while maximizing their efficiency and sustainability.

3. Key Materials in Plastic Solar Cells

3.1. Conductive Polymers

The conductive polymer known as poly(3-hexylthiophene) (P3HT) has gained extensive attention due to its use in a variety of electrical and optoelectronic technologies, such as solar cells, organic light-emitting diodes (OLEDs), organic field-effect transistors (FETs), and chemical detection

devices. Characterized by its low optic bandgap, strong energy accessibility, excellent conductivity, and volatility in a variety of organic substances, P3HT serves as crucial application to a wide array of technological applications. Despite the relatively modest PCE of P3HT-based solar cells, these cells have achieved significant prominence within the domain of organic photovoltaics. This is explained by their substantial absorbance index ($\sim 105 \text{ cm}^{-1}$), which allows around 95% of the electromagnetic spectrum of the sun to be absorbed in the visible wavelengths. Significant progress has been achieved in addressing the low PCE problem via the creation of mass hetero junctions photovoltaic devices. The combination of P3HT with fullerene derivatives, including [6,6]-phenyl-C61-butyric-acid-methyl-ester (PCBM), are employed in the energetic component of these devices, thereby enhancing their efficiency [5].

A research conducted stability tests on devices featuring active layers composed of various materials, including P3HT: SF (DPPB)₄, P3HT: ICxA, and P3HT: PCBM, by subjecting them to continuous light exposure over several days. Initial findings indicate a rapid degradation of the devices during the initial 'burn-in' stage, followed by a deceleration in the degradation rate, leading to a more predictable degradation pattern. The duration of the burn-in stage, as influenced by the composition of the active layer, was observed to range between 3 to 7 days. Among the tested configurations, devices incorporating P3HT: PCBM active layers demonstrated superior stability under constant illumination, exhibiting the least proficiency loss during the burning-in period. Figure 1 shows the current-voltage (I-V) characteristics as time passes as well as the standardized deterioration graphs for each of the three distinct kinds of gadgets.

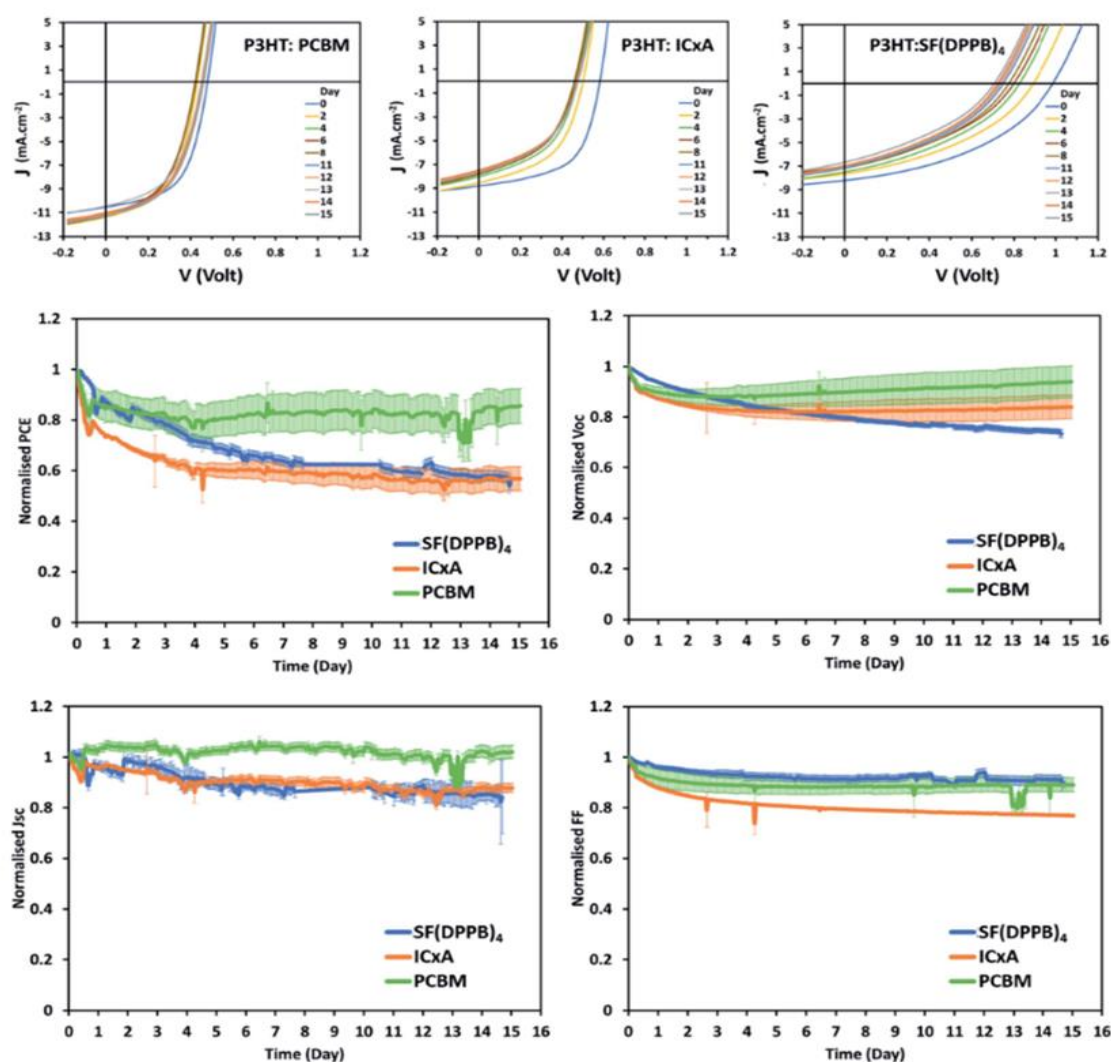


Fig 1. I-V graphs for various active layer devices (P3HT: PCBM, P3HT: ICxA and P3HT: SF (DPPB)₄) [5].

Numerous studies have focused on evaluating new donor and acceptor materials for organic photovoltaics (OPV) based on individual parameters: material performance, stability, and cost. Despite the critical importance of these factors, comprehensive assessments that consider all three parameters concurrently are notably scarce in the literature. This gap in research methodology presents a significant challenge to the broader application and development of OPV technology, as there is often a trade-off among these parameters that must be navigated. For example, the widely utilized donor polymer, P3HT, is known for its affordability and relative stability, yet it only achieves moderate power conversion efficiencies, approximately 3-4%, when paired with phenyl-C61-butyric-acid-methyl-ester (PCBM).

The necessity for a holistic approach in the study and evaluation of OPV materials cannot be overstated. It is imperative for the advancement of OPV technology that researchers undertake a comprehensive assessment of materials, weighing performance, stability, and cost simultaneously. Such an approach is essential for identifying the optimal balance among these parameters, thereby facilitating the enhanced adoption and optimization of plastic solar cell technology. Only through such integrated evaluations can the full potential of OPV materials be realized, paving the way for significant advancements in the field of renewable energy.

Further, polyaniline, another typical typed conductive polymer, exhibits distinct properties based on its degree of oxidation, manifesting in three primary categories: part-way (partly oxidized) emeraldine, completely oxidized (per) nigraniline, and thoroughly decreased leucoemeraldine. Polyaniline demonstrates a broad spectrum of electrical conductivity, with values ranging from 30 to 200 $\text{S}\cdot\text{cm}^{-1}$. The application of polyaniline in fabrication processes offers significant economic advantages due to its cost-effectiveness and straightforward synthesis. Moreover, it is distinguished by its exceptional environmental stability and is recognized as the most thermally stable among conductive polymers. Similarly, polythiophene, another conductive polymer, presents a conductivity range from 10 to $10^3 \text{ S}\cdot\text{cm}^{-1}$, showcasing its considerable potential within the realm of conductive materials. A notable attribute of polythiophene is its outstanding stability, which facilitates ease of modification and processing without necessitating additional substances. The deployment of 1D nanostructures based on conductive polymers, or incorporating them as additives, has proven to be immensely beneficial across a variety of applications. These applications span supercapacitors, lithium-ion cells, filtrating screen, gas sensors, and aqueous processing solutions. The unique properties of conductive polymers, including their electrical conductivity, environmental and thermal stability, and ease of modification, underscore their significant value and versatility in advancing technological and environmental solutions [6].

3.2. Small Molecule Organic Semiconductors

3.2.1. Fullerenes

Fullerenes, a distinct class of carbon molecules, are characterized by their unique spherical or cylindrical arrangements of interconnected carbon atoms. Among these, C60, commonly referred to as a 'buckyball,' is notably recognized for its exceptional electronic and optical properties. These properties render fullerenes particularly intriguing for scientific research, especially in their role as electron acceptors in organic OPV. Initially, the application of C60 as an acceptor material in OPVs was limited by its poor solubility, which hindered advanced processing techniques. This challenge was overcome in 1995 with the introduction of a soluble fullerene derivative, PCBM. PCBM has significantly advanced the field by facilitating the production of mass heterojunction OPV technologies via solution processing techniques. The cost-effective and scalable production of organic solar batteries is marked by a pivotal development in the cost-effective and scalable production of natural photovoltaic cells due to the combination of PCBM with conjugated components, including MEH-PPV (poly(2-methoxy-5-(2-ethylhexyloxy)-1,4-phenylenevinylene)).

The proficiency of charge extraction in OPV devices is influenced by various factors, including electron mobility, film structure, and the spatial arrangement of fullerene derivatives. Research conducted by Jen and colleagues has demonstrated the critical role of electron mobility within

fullerene-based layers on solar cell performance. Their findings indicate that devices incorporating fullerene derivatives such as IC60BA, PCBM, and C60 exhibit PCE of 8.06%, 13.37%, and 15.44%, separately. These results underscore the correlation between enhanced electron flexibility in the specific fullerene layer and improved photovoltaic performance.

Beyond OPV applications, pristine fullerene derivatives find utility as layers or additives in perovskite photovoltaic batteries and as channel layers in natural field-effect transistors. In these contexts, the index of the lowest unoccupied molecular orbital (LUMO), charge mobility, molecular packing order, as well as film structure are pivotal factors determining device performance [7].

3.2.2. Non-Fullerene Acceptors

In the nascent stages of OPV development, fullerene derivatives such as PC61BM and PC71BM emerged as the predominant electron-acceptor materials, favored for their high electron mobility ($103 \text{ cm}^2/\text{V}\cdot\text{s}$), isotropic charge transportation behavior, and high electron affinities. Despite the pivotal role of fullerene components in the rapid advancement of OSCs, their application is marred by several limitations, including weak inherent absorption, significant voltage losses (V_{loss}), morphological instabilities, and inflexibility of energy levels. Exploring innovative materials has become imperative for enhancing the photovoltaic efficiency of OSCs especially by utilizing non-fullerene acceptors (NFAs).

NFAs, in contrast to fullerenes, offer a broader absorption spectrum and molecular tunability, and can be synthesized through a relatively straightforward combination approach. These acceptors are generally categorized into two types: polymer acceptors and small-molecule acceptors (SMAs). A subset of SMAs called fused-ring electron acceptors (FREAs) have demonstrated a PCE that exceeds 18%, indicating their significant potential for future OSC advancements. FREAs' superior performance is enhanced by their structural configuration, which typically involves a fused-ring core that donates electrons and is flanked by potent electron-withdrawing terminal groups that are connected via a planar π -conjugated bridge. FREAs are currently the most significant acceptors in the ongoing advancement of OSCs, as they provide numerous advantages over traditional fullerene-based systems due to the two-dimensional molecular structure and robust intermolecular interactions provided by this arrangement [8].

3.3. Emerging Materials for Enhanced Efficiency

3.3.1. Perovskite Materials

The field of solar energy has witnessed remarkable advancements with the development of hybrid metal halide perovskite technology, which has seen a dramatic increase in PCE, from a modest 3.8% in 2009 to an officially certified 25.5% in 2020. This surge in efficiency positions perovskite materials as promising candidates for tandem solar cells, particularly when combined with organic layers. Perovskite materials' exceptional external radiative efficiency (ERE) compared to traditional silicon (Si) and CIGS photovoltaic battery techniques is a key attribute that makes them stand above the rest. Additionally, perovskites exhibit powerful optical absorption characteristics, allowing them to be fabricated as thin films through accessible solution processing techniques. Furthermore, the bandgap of perovskite materials can be conveniently tuned through compositional engineering, ranging from 1.20 to 2.3 eV, enhancing their applicability across a broad spectrum of solar cell applications [9].

To ensure longevity and maintain the high energy conversion efficiency of PSCs, it is imperative to address the degradation of all major layers within the devices. A myriad of techniques has been developed to mitigate environmental deterioration and improve equipment consistency. Among these, compositional and interfacial engineering stand out as pivotal strategies for the advancement of PSC performance. The material composition of all substantial layers and the metal electrode is optimized through compositional engineering, while interfacial engineering concentrates on passivating these layers in terms of lowering drawbacks and incorporate protective layers to prevent material degradation. These strategies have proven to be significantly effective in improving device stability and efficiency. However, despite these enhancements, achieving the industrial standard of a 25-year

operational lifespan for PSCs remains a challenge, necessitating further research and development efforts aimed at simultaneously achieving high efficiency and stability in PSCs [10].

3.3.2. Nanostructured Materials

Nanostructured materials also offer significant advantages in organic electronics, including enhanced charge transport and increased surface area, which lead to improved efficiency and performance of devices. Their unique properties enable the fine-tuning of electronic and optical behaviors, facilitating the advancement of highly efficient natural photovoltaics, luminous diodes, as well as transistors with superior functionality. Quantum dots (QDs) are nanoparticles characterized by their diminutive size, with diameters not exceeding 20 nm. These particles are subject to quantum confinement effects, which alter the band gap energy derived from the mass semiconductor component. This alteration is due to the relationship between the state distance in the k-space and the size of the QD, indicating that the electronic properties of QDs can be finely tuned by adjusting their size. Optoelectronic and photochemical devices are heavily relying on Nanowires (NWs), especially those configured as massive rows of nanowires (VANWs) that are vertically aligned with high aspect ratios. A novel approach to enhance charge transport and light absorption in organic photovoltaic cells (OPVs) can be achieved through the integration of quantum dots and nanowires, which leverages unique properties of both nanostructures to achieve superior device performance.

A notable example of this integration's potential is highlighted in a publication by Sandhu in Nature Nanotechnology, which reports a threefold increase in the PCE of photovoltaic cells incorporating ZnO VANWs in combination with PbSe QDs, in comparison to solar cells based on a simple thin-film ZnO structure. Further advancements have been achieved with the use of ZnO-based VANWs coupled with PbS QDs, culminating in a 35% increase in PCE. These significant enhancements are attributed to the synergistic effects of the ZnO NWs' aspect ratio and the density of the QDs [11]. This investigation into the use of quantum dots and nanowires in solar cells underscores how nanostructured materials can revolutionize the efficiency of photovoltaic devices. High-efficiency solar cells can be developed through the manipulation of the electronic properties of these nanostructures through size and structural configuration.

4. Production Methods and Applications

4.1. Production Methods

The fabrication of organic photovoltaics (OPVs) involves the application of multiple distinct layers, each requiring specific printing and coating methods to ensure optimal performance and efficiency. The complexity of OPVs, characterized by their multilayered structure, necessitates the selection of fabrication techniques that align with the unique properties of each layer. A critical factor in the practical application of OPVs is the achievement of high fabrication efficiency, especially given the lower stability of these devices during the manufacturing process. To address the industrial demand for scalable fabrication solutions, further research into roll-to-roll (R2R) processing techniques is essential.

Among the various methods available, inkjet printing stands out for its ability to create two-dimensional patterns, positioning it uniquely within both printing and coating categories. Its versatility and flexibility make it an attractive option for OPV manufacturing. However, the technique's application is currently hampered by limitations in achieving high printing speeds, which restricts its broader adoption. Historical analysis, spanning from 1998 to 2020, indicates that spin-coating has been the predominant method for processing OPVs, favored for its simplicity. Despite its widespread use, spin-coating is not without drawbacks, particularly when considering scalability. Due to its inherent inefficiencies, the method offers little regulation of film thickness and causes significant material loss during the coating procedure. In contrast, slot die coating emerges as a more efficient alternative, representing a laboratory-scale equivalent of R2R manufacturing. Large-scale production is more appropriate for this one-dimensional coating technology, which also reduces

material waste. The exploration of suitable printing and coating methods for OPVs is a critical area of research, with implications for the commercial viability and environmental impact of solar energy technologies. As the field progresses, the development and refinement of scalable, efficient fabrication techniques will play a pivotal role in advancing OPV technology and meeting the growing demand for renewable energy solutions [12].

4.2. Performance Applications of Plastic Solar Cells

OPV devices have emerged as innovative alternatives to conventional energy sources, distinguished by their flexible mechanical properties and high PCE. These attributes position OPVs as viable solutions for green, cost-effective, and portable electricity generation, aligning with the growing demand for sustainable energy solutions. By harnessing sunlight and converting it into usable energy, OPVs offer a promising avenue for a wide array of applications, including wearable photovoltaic devices that can seamlessly integrate into daily life. Furthermore, Building-Integrated Photovoltaics (BIPV) represent a significant advancement in the application of OPVs, enabling the incorporation of transparent and flexible solar panels into the architectural design of buildings. BIPVs not only facilitate the direct storage and utilization of solar energy but also contribute to the decarbonization of energy systems. The technology has the potential to completely change how energy is consumed in the built environment and provide a sustainable substitute for conventional energy sources, as demonstrated by a thorough analysis of the German BIPV market. The integration of OPV technology into wearable devices and building materials exemplifies the versatility and potential of photovoltaics to meet the diverse energy needs of modern society. OPVs are expected to be essential in the shift to more ecologically friendly and sustainable energy systems as long as research and development in this area continue to advance [13].

5. Conclusion

Over the course of past decades, PSCs have undergone a rapid and marvelous evolution, which shows significant progress and achieving a high PCE of over 17%. The primary contribution can be attributed to the upgradation and utilization of efficient π -conjugated photoactive materials, surpassing the threshold of 15% and being considered as a crucial milestone for the development of commercialization of PSCs. Nevertheless, despite these groundbreaking achievements, we still need to unveil the mystery of unsolved issues that acquire further attention and consecutive efforts. Enhancing the PSC devices' long-term stability is urgently needed, and doing so requires addressing the drawbacks of performance and degradation down the line. Additionally, it is crucial to reconsider the usage of toxic solvents in the fabrication processes of PSCs as it have negative and irreversible effects on the environment. By exploring sustainable, environmentally-friendly materials and technologies, PSCs will have better practical viability and become widespread across diverse fields.

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