



# **Tackling Efficiency Challenges and Exploring Greenhouse-Integrated Organic Photovoltaics**

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Abstract: Organic solar cells offer benefits such as transparent characteristics, affordability in manufacturing, and the ability to tailor light absorption properties according to specific needs. This review discusses challenges and recent strategies to enhance the power conversion efficiency of organic solar cells, such as bandgap tuning, molecular orbital alignment, active layer morphology engineering, electron-donating and -withdrawing group incorporation, side chain length engineering, a third additive's insertion, and control of the solubility of materials. The good transparency of organic solar cells makes them ideal for greenhouse-integrated photovoltaics applications. By efficiently absorbing sunlight for photosynthesis and clean energy production, transparent organic solar cells optimize light management, enhance energy efficiency, and minimize overheating risks, resulting in more sustainable and efficient greenhouse operations. This review also evaluates organic solar cell integration in the greenhouse. The implementation of the strategies explored in this review can significantly impact a wide range of performance parameters in organic solar cells. These parameters include the optoelectronic properties, absorption spectrum, open circuit voltage, exciton dissociation, charge transport, molecular packing, solubility, phase separation, crystallinity, nanoscale morphology, and device stability. An optimized organic solar cell design is particularly beneficial for greenhouseintegrated photovoltaics, as it ensures efficient energy conversion and energy management, which are crucial factors in maximizing the performance of the greenhouse.

**Keywords:** Polymer/Organic solar cells; energy band gap; Greenhouse-Integrated Photovoltaics (GIPV); power conversion efficiency

# 1. Introduction

Addressing global challenges such as the escalating need for food, triggered by the population surge, and mitigating the effects of global warming, resulting from fossil fuelbased energy generation, has become an urgent priority [1]. In recent years, solar energy has become an appealing option for the development of cleaner and more sustainable power sources [2]. Solar energy utilizes sunlight to produce electricity, offering a renewable and eco-friendly alternative to conventional energy sources. Photovoltaic (PV) cells, the key components of solar panels, convert sunlight into electricity [3]. Over time, various PV technologies have been developed, including silicon-based solar cells, perovskite photovoltaics, and organic photovoltaics or organic solar cells (OSCs), each with its unique advantages and challenges aimed at enhancing efficiency and reducing manufacturing costs [4]. Among the numerous PV technologies, OSCs are a promising option due to their unique features such as tunable optoelectronics, cost-effectiveness, lightweight, transparency, and flexible applications [5,6]. OSCs can be fabricated on lighter-weight substrates with high transparency and good flexibility, allowing for diverse applications. Transparent solar cells have gained tremendous interest in the last few decades because of the compatibility of the technology with many other applications (Figure 1), such as greenhouse-integrated



**Citation:** Ansari, M.A.; Ciampi, G.; Sibilio, S. Tackling Efficiency Challenges and Exploring Greenhouse-Integrated Organic Photovoltaics. *Energies* **2023**, *16*, 6076. https://doi.org/10.3390/en16166076

Academic Editors: Alessandro Ciocia and Antonio D'angola

Received: 22 July 2023 Revised: 8 August 2023 Accepted: 18 August 2023 Published: 20 August 2023



**Copyright:** © 2023 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (https:// creativecommons.org/licenses/by/ 4.0/). photovoltaics (GIPV) and building-integrated photovoltaics (BIPVs) [7–9]. A solar greenhouse allows the transmission of a selective wavelength needed for photosynthesis and absorbs the remaining solar radiation for electricity generation. Worldwide, approximately 9 million acres of agricultural land is used for better crop production in greenhouses. The same land can also be used for the conversion of solar energy into electricity to reduce the dependency on fossil fuel combustion if a transparent solar cell is integrated with the greenhouse. Similarly, transparent photovoltaic windows can be integrated with buildings. In this way, a building can convert solar energy into electricity.



Figure 1. Integrated photovoltaics applications [7–13].

The role of optoelectronic materials is crucial in defining solar cell efficiency, stability, transparency, processability, and cost. Solar cells based on different materials are summarized in Figure 2 with different parameters for comparison. There are several components of sunlight, including ultraviolet (UV), visible, and near-infrared (IR) or Long wavelength Infrared (LWIR) radiation. Optically active materials should have high visible spectrum transparency and high UV or near-IR spectra absorptivity for integrated photovoltaics applications.

Organic photovoltaics (OPVs), which consists of organic polymers and small molecules (SM), is a better photovoltaic technology compared to silicon solar cells due to several benefits [14]. Organic materials are abundant, optically modifiable, and their synthesis is relatively low-cost, making OSCs an attractive option for large-scale deployment and integration with many other technologies [15]. OSCs are easy to fabricate by the roll-to-roll method of printing, which enables large-scale high-speed manufacturing on flexible and transparent substrates with good mechanical resilience, rendering them suitable for integration into diverse environments and applications [6,16,17]. The absorption properties of OSCs can be easily tailored for targeted applications by modifying the molecular structure of organic materials, resulting in enhanced light-harvesting capabilities and unique utilization with other technologies, such as smart greenhouses and the smart windows of a building [18].

Transparency is a crucial factor for GIPV. Transparent OSCs can transmit selective wavelengths necessary for photosynthesis while absorbing the remaining solar radiation for electricity generation [8,19]. The solar spectrum, shown in Figure 3, encompasses various radiation types, including ultraviolet (UV), visible, and infrared (IR) radiation [16,20]. Infrared absorption profiles contribute 52% of the total energy in the solar spectrum, making IR-absorbing donors ideal for agricultural applications of transparent OSCs [21]. The optimization of OSCs is vital for GIPV applications, as it enables optimized light management, improved energy efficiency, enhanced space utilization, reduced overheating risks, and customizable transparency to cater to diverse requirements [18,21–23].



High temperature (>500 °C): 1





**Figure 3.** Solar radiation spectrum ranges from ultraviolet (UV) to infrared (IR) wavelengths, with visible light in between [20].

# 1.1. Evolution of Organic Solar Cell (OSC)

As described by Brabec et al. [24], the early stages of OSC development were mainly focused on understanding the fundamental principles, exploring suitable materials, and optimizing device architectures. The progress made during this period laid the foundation for subsequent research and advancements in the field of OSCs. There are three types of OSCs based on the active layer architectures.

 Single-Layer OSC → In this layer of the OSC, a thin layer of organic semiconductor material is placed between two conducting layers called electrodes, with one layer that can allow the radiation to transmit. There are two types of active materials in the organic layer, such as an electron donor and electron acceptor. The organic layer serves both as an electron-donating and an electron-accepting layer. Single-layer OSCs typically exhibit low PCE because of their small exciton diffusion length and inefficient charge separation. In 1986, Tang et al. presented the first single-layer system using copper phthalocyanine as the active material [25].

- 2. Bilayer OSC → Bilayer OSCs were developed to address the limitations of single-layer OSCs. These devices consist of double organic layers: one electron-donating material and one electron-accepting material stacked in a planar hetero-junction configuration [3]. This arrangement allows for the better separation of charges at the donor-acceptor interface, leading to higher efficiency than in single-layer OSCs. However, the diffusion length is still a restricting factor for the performance of these devices [25]. Bilayer OSCs demonstrate improved charge separation compared to single-layer devices but still suffer from limited exciton diffusion and sub-optimal donor-acceptor interfaces [26].
- 3. Bulk Heterojunction (BHJ) OSC → A BHJ OSC is produced from the blending of electron-donating and electron-accepting materials, which creates an inter-penetrating network in the active layer. This network gives a greater interfacial region between the electron-donating material and electron-accepting material, facilitating good exciton dissociation and the separation of charges. In 1995, the idea of BHJ OSCs was first described by Yu et al., who used [6,6]-phenyl-C61-butyric acid methyl ester (PCBM) as an electron acceptor and poly(3-hexylthiophene) (P3HT) as an electron donor [27]. BHJ OSCs have become the most widely researched and promising OSC architectures due to their superior performance and potential for further optimization [28].

The operation mechanism (Figure 4) of OSCs involves several critical steps, such as the absorption of radiation, the generation and diffusion of excitons, separation, and the collection of charges [24]. In particular, it is possible to schematize the operation mechanism as four steps.



Figure 4. Operation mechanism of OSC.

- Radiation absorption → when light is incident on the OSC, optical absorption is caused by the active material layer, which comprises donor and acceptor materials (for example, a P3HT and PCBM, respectively) [14]. Upon absorbing a specific wavelength of light compatible with the bandgap of the donor, an electron excites from one molecular energy level (such as HOMO) to another molecular energy level (such as LUMO) of the donor material, generating an excited state with excitons (pairs of holes and electrons) [18]
- Exciton generation and diffusion → excitons are bound pairs of electron-holes created upon light absorption [29]. They are mobile and can diffuse through the donor material. Generally, the exciton diffusion length in organic materials is approximately 10–20 nm, limiting the active layer's thickness [30]. The morphology of the active materials has a vital role in facilitating the diffusion of excitons and charge separation [31].
- Charge separation → Due to an energy offset between the acceptor's LUMO and donor's LUMO, excitons undergo migration across the donor-acceptor interface [32]. This process, called exciton dissociation, separates the electron and hole, generating free-charge carriers [33].
- 4. Charge collection → following charge separation, the excitons migrate through the active materials, to their corresponding electrodes [34]. The charge transport efficiency depends on factors such as the charge carrier's mobility, the active layer's morphology, and the presence of charge traps [35]. After the pairs of electrons and holes have migrated toward their respective electrodes, they are collected, generating an external current [36].

## 1.2. Objectives and Structure of the Research

This review addresses efficiency challenges and examines different topics related to photovoltaic cells. To summarize, the objectives of this study can be outlined as follows:

- to discuss the dependency of the PCE on several parameters, such as the fill factor (FF), short circuit current density (Jsc), and open circuit voltage (Voc);
- to discuss the recent strategies to enhance the PCE, such as bandgap tuning, molecular orbital alignment, active layer morphology engineering, electron-donating and -withdrawing group incorporation, side chain length engineering, a third additive's insertion, and control of the solubility of materials;
- to discuss recent advances in GIPV.

In this paper, Section 2 discusses the various factors that affect the performance of photovoltaic cells. Section 3 discusses the challenges and methods involved in improving the efficiency of organic solar cells. Section 4 explores the application of GIPV. Section 5 discusses the Internation green initiatives. Section 6 summarized the discussion of this review. Finally, Section 7 presents the conclusions of the study and provides insights into future possibilities.

# 2. Power Conversion Efficiency (PCE)

This section describes the key parameters for the determination of the performance of photovoltaic cells. These parameters are related to the PCE of a photovoltaic cell, which measures how effectively the device converts sunlight into electricity. These parameters include  $V_{OC}$ , J<sub>SC</sub>, and FF. The PCE can be calculated by using Equation (1):

$$PCE = \frac{V_{OC} \cdot J_{SC} \cdot FF}{P_{IN}}$$
(1)

where P<sub>in</sub> is the incident light power.

## 2.1. Open Circuit Voltage (V<sub>OC</sub>)

The open circuit voltage is the voltage generated by a solar cell when it is not connected to a load, i.e., when zero current passes through the device.  $V_{OC}$  is primarily influenced by the gap in the energy level between the donor's HOMO and acceptor's LUMO in the OSC and the inherent potential [37]. This process is influenced by the difference in the work functions of both respective electrodes [31]. The maximum achievable  $V_{OC}$  equals the energy offset between the HOMO of the donor and the LUMO of the acceptor, minus the energy losses due to charge recombination [38].  $V_{OC}$  is mostly calculated by Equation (2) for conjugated polymer donors and fullerene-based OSCs.

$$V_{OC} = (1/e)(|^{HOMO}E_{Donor}| - |^{LUMO}E_{PCBM}|) - 0.3 V$$
 (2)

where "e" is a unit charge equivalent to  $1.602 \times 10^{-19}$  coulombs.

#### 2.2. Short Circuit Current Density $(J_{SC})$

The short circuit current density refers to the current density produced by a solar cell under conditions of a short circuit—that is, when there is no voltage difference across the cell [29]. Several factors, including the optical absorption properties of the active materials, the thickness of the active layer, and the charge carrier mobility, influence the J<sub>SC</sub>.

# 2.3. Fill Factor (FF)

The fill factor is used to quantify the "squareness" exhibited by the current–voltage curve of a photovoltaic cell, which indicates how well the device performs under actual operating conditions. It is described as the quotient of the solar cell's maximum power output relative to the product of Voc and Jsc. A higher FF indicates a more efficient solar cell. FF is dependent on the series and shunt resistances of the photovoltaic cell, as well as the charge recombination processes and the built-in electric field [18]. The PCE of a photovoltaic device is also determined by Equation (3).

$$PCE = \frac{V_{max} \cdot J_{max}}{V_{OC} \cdot J_{SC}}$$
(3)

# 2.4. J-V Curve

The performance of a photovoltaic device is represented through a plot known as the current density–voltage (J-V) curve, under different voltage conditions [39]. It provides valuable information about the key parameters ( $V_{OC}$ ,  $J_{SC}$ , and FF). Below is a brief description of the J-V curve's main components.

On the *y*-axis, the current density (J) is denoted, measured in milliamperes per square centimeter  $(mA/cm^2)$ , while the *x*-axis represents the voltage in volts (V); see Figure 5.

The curve starts from the J<sub>SC</sub> point on the *y*-axis, where the voltage is zero and the solar cell produces its maximum current. The curve then progresses toward the V<sub>OC</sub> point on the *x*-axis, where the current is zero and the solar cell produces its maximum voltage. The point on the J-V curve where the product J × V achieves its maximum value is referred to as the maximum power point (MPP). This point shows the maximum power that the photovoltaic cell may deliver under specific illumination conditions. The fill factor (FF), which is shown by the grey area in the Figure 5, is defined as the proportion of the highest power output (at the MPP) to the product of the J<sub>SC</sub> and the V<sub>OC</sub>. The ratio of the MMP to the product of J<sub>SC</sub> and V<sub>OC</sub> is the FF. It represents the J-V curve's "squareness", indicating the performance of the solar cell under actual operating conditions [40].



Figure 5. The current density-voltage (J-V) curve of OSC [39].

# 3. Challenges and Strategies to Improve Efficiency

This section illustrates challenges and strategies to improve the efficiency of OSCs. Several limitations, such as poor stability, low PCE, complex material synthesis, and significant sensitivity to processing conditions, where even variations in thickness during fabrication can lead to a substantial decline in their overall performance [41], currently hinder OSCs' widespread adoption and commercialization [42]. Due to several factors, OSCs often have shorter operational lifetimes and lower PCE compared to silicon-based solar cells. The lifetime of a silicon-based solar cell is approximately 10 years, while the lifetime of an OSC is usually less than 1 year [13]. Environmental conditions such as oxygen, moisture, and temperature can significantly impact the performance of OSCs, which can reduce their performance and operational lifetimes [43]. For example, an OSC was integrated with a greenhouse in real environmental conditions and it was found that peeling or separation layers, known as delamination, were a frequently encountered issue, irrespective of the device architecture. Delamination in these modules contributed to a 10 to 20% drop in the active area of the OSC and the overall performance, depending on the photoactive layer choice. Data monitoring of temperature and humidity indicated that intense stress cycles, naturally occurring during diurnal/nocturnal periods within a greenhouse, served to hasten the degradation rate of the agrivoltaic modules [44].

The lifetime or operational stability of OSCs has been a major challenge, limiting their commercial viability. Several strategies have been explored for the improvement of stability, including a molecular design and the choice of active materials, device architecture, and encapsulation [45]. In the molecular design of donor and acceptor materials, the side-chain/end-group engineering of donor and/or acceptor materials is performed, which can optimize the stability of the materials and hence the lifetime of the device as well [46,47]. In the device architecture, the inverted device structure is more stable compared to the conventional architecture of the device. In a conventional OSC design, the low-work-function cathode on the exposed surface is vulnerable to damage from oxygen and moisture. The inverted device structure overcomes this issue by swapping the positions of the anode

and the cathode, hence shielding the cathode from direct exposure to these environmental conditions [48]. This results in improved air stability and potentially longer lifetimes for OSCs. It has been found recently that the side penetration of oxygen and moisture into the photoactive layer can initiate chemical reactions, leading to the degradation of the device. To mitigate these issues, a prevalent strategy is the encapsulation of OSC devices, which serves to inhibit the permeation of moisture and oxygen from the surrounding environment [49].

Several factors, such as optoelectronic processes and the types of materials, affect the performance of OSCs. The process of radiation absorption by the active material leads to the creation of excitons, which are pairs of electrons and holes that are bound together. The binding energy of excitons in organic active materials is typically higher than that of inorganic materials, making it more difficult to dissociate excitons as free charge carriers and thereby reduce the PCE [50]. Organic materials have lower charge carrier mobility than inorganic materials, resulting in the slower transport of electrons and holes. This can increase recombination rates and reduce the charge collection efficiency, ultimately lowering the PCE [31]. The efficiency of OSCs also depends on the interfacial properties and the active layer's morphology. Achieving an ideal morphology for faster charge separation and transport may be challenging, as it requires a delicate balance between phase separation and the intermixing of donor and acceptor materials [51,52]. Each organic material has a relatively narrow absorption range; therefore, it cannot effectively harvest the full solar spectrum. This limitation results in lower photocurrent generation and reduced PCE; however, the use of multiple organic materials in a single device can overcome this limitation [10,53]. In recent years, research has been actively performed to improve the stability and PCE of OSCs [54,55]. Figure 6 presents the development of the PCE of different solar cells with respect to time, published by the National Renewable Energy Laboratory (NREL), from February 1976 to April 2023. To date, the PCE of OSCs has been recorded to reach as high as 20.2% [56].



Figure 6. Solar cell efficiency chart with respect to time [57].

The bandgap tuning of active materials is a good strategy to control the PCE of OSCs. The bandgap tunning of the donor material and acceptor material affects the optical spectrum,  $V_{OC}$ , and overall device efficiency. There are some key aspects of bandgap tuning. Tailoring the energy bandgap of the active material can help to achieve a broad and complementary absorption spectrum, which is essential in maximizing photocurrent

generation. Zhou et al. [58] tuned the energy levels (HOMO-LUMO) and bandgap of benzothiadiazole (conjugated polymeric material) by incorporating two strong electronwithdrawing fluoro groups. Designing materials with narrower bandgaps allows the OSCs to absorb a more significant portion of sunlight, such as IR radiation, resulting in an increased J<sub>SC</sub> and overall PCE [58]. The process of  $\pi$ -extension in the end capping groups of non-fullerene acceptors (NFAs) appears to be a noteworthy methodology to enhance electronic delocalization. This enhancement potentially paves the way for red shifting in the optical absorption, which plays a significant role in the optimal performance of OSCs. The shift in the optical absorption spectrum to longer wavelengths can enhance the overlap with the solar spectrum and thus increase the number of photons that can be absorbed and converted into electricity. Furthermore, halogenation, particularly the incorporation of end-group halogen atoms, is another valuable strategy in modulating the electronic properties of NFAs. Halogen atoms such as chlorine, when introduced into the molecular framework, tend to modify the HOMO and LUMO energy levels. This adjustment is crucial in achieving the desired energy offsets between the donor and acceptor materials in OSCs. Such offsets ensure efficient charge transfer at the donor-acceptor interface, subsequently offering enhanced OSC performance. The work by Su et al. [59] provides a concrete example of this methodology, wherein they incorporated chloro groups into an NFA akin to Y6 but with an extended  $\pi$  system via naphthalene. The chloro groups not only served the purpose of energy level tuning but also seemed to offer additional benefits. Chlorine's higher electrophilic nature and its availability of 3d orbitals lead to stronger intermolecular interactions. These interactions particularly arise between chlorine atoms and lone pairs of electrons on sulfur atoms, as well as the  $\pi$  electrons of the conjugated system. Such interactions can be considered beneficial in promoting crystallinity, which can significantly affect the morphology and thus the charge transport properties of the active layer in OSCs. Since the fluorine atom density strongly affects OSC performance, the introduction of direct fluorination on a benzothiazole (BT) skeleton-based NFA led to a reduced bandgap and enhanced intermolecular charge transportation [60]. Another study indicated that incorporating fluorine atoms and expanding the  $\pi$  -conjugation on the Y5 acceptor caused a noticeable shift toward the red end of the optical spectrum. These modifications enhanced the crystallinity, optimized the film structures, and boosted the carrier mobility [61]. Due to its high electronegativity, fluorine introduces a more pronounced intramolecular electron push–pull effect in NFAs without imposing spatial constraints. As a result, NFAs containing fluorine tend to shift their optical absorption toward longer wavelengths. This shift is an effective strategy in optimizing the bandgap for specific applications, such as GIPVs. For this application, the optical spectrum of active materials should fall within a spectral range that plants do not utilize for photosynthesis. The bandgap of a conjugated polymeric material can also be contracted by incorporating alternating donor-acceptor polymers during copolymerization. This occurs because the energy levels of the electron donor of the copolymer interact with the levels of energy of the electron acceptor of the copolymer, leading to an elevated HOMO and a downshifted LUMO within the donor part of the copolymer [62]. As an illustration, Ding et al. [63] designed a copolymer using D18 as a donor, which is based on DTBT (a fused ring acceptor unit), known for its high hole mobility. The solar cells employing D18:Y6 resulted in PCE equal to 18.22% (Figure 7). The OSC system D18:Y6 was also compared with the OSC system D16:Y6 (PCE 16.72%). Zhou et al. [58] developed a donor-acceptor PBnDT-DTffBT copolymer by introducing two strong electron-withdrawing fluoro groups in place of two hydrogens. A bandgap of 1.7 eV was found for this copolymer by cyclic voltammetry. It was observed that the PCE increased from 5 to 7.2% after this slight modification. It proves that slight modifications in the molecular structure might affect the PCE of OSCs due to changes in the HOMO-LUMO energy levels, bandgap, molecular plane, and hole mobility.

![](_page_9_Figure_1.jpeg)

**Figure 7.** High-efficiency DTBT-based donor polymer: (**a**) the molecular structure for D16, D18, and Y6; (**b**) absorption spectra of D18 solution, D18 film, and Y6 film; (**c**) energy level diagram. Republished with permission, [63], 2020, Elsevier.

The active material's bandgap influences the energy offsets between the electron donor's HOMO and the electron acceptor's LUMO, which in turn determines the  $V_{OC}$  of the OSC. A more significant energy level offset generally results in a higher V<sub>OC</sub>; however, it may also limit the absorption spectrum and photocurrent generation. Therefore, finding an optimal balance between the bandgap and energy level offsets is crucial in maximizing the PCE [64]. Enlarging the extent of conjugation along the polymer backbone may also narrow the bandgap by increasing the delocalization of  $\pi$  electrons [65,66]. This can be achieved by incorporating larger  $\pi$ -conjugated units or by a higher degree of polymerization in conjugated polymers. The bandgap of the active material also affects the exciton dissociation and charge transport properties. Materials with narrow bandgaps typically have a longer length of exciton diffusion, which can facilitate the dissociation of excitons at the interfacial junction of the electron donor and electron acceptor [67]. However, a low bandgap may also reduce the charge transport properties, negatively impacting the device's performance. The bandgap of the materials can also influence the stability of the OSCs. Materials with low bandgaps tend to have a higher density of states and a higher tendency for charge recombination, which can lead to reduced device stability and lifetimes [68]. Bandgap tailoring is a critical aspect of OSC design, as it influences the absorption spectrum,  $V_{OC}$ , the dissociation of the excitons, charge transport, and the stability of the device. Achieving an optimal balance between these factors is crucial in maximizing the PCE of OSCs.

The alignment of the HOMO–LUMO levels of energy of the electron donor and electron acceptor materials in OSCs significantly influences the PCE of the devices. Markus et al. [64] suggested a correlation between the PCE of a BHJ organic photovoltaic cell, the bandgap, and the donor's LUMO level. A shift in the donor's bandgap by 0.65 eV only resulted in a fluctuation of 1% in the PCE of the device. However, a similar shift of 0.65 eV in the LUMO level of the conjugated polymer had a significant effect, causing the PCE to vary between 3.5

and 8%, contingent on the original donor bandgap. The energy offsets between the HOMO of the donor material and the LUMO of the acceptor material directly impact the  $V_{OC}$  of OSCs. A larger energy level offset typically results in a higher V<sub>OC</sub>. However, an excessively large offset may limit the absorption spectrum and photocurrent generation, so finding an optimal balance is crucial in maximizing the PCE [64]. Markus et al. derived the direct relationship (Figure 7) between the oxidation onset potential and  $V_{OC}$  for different devices, which could be used for the improvement of the device's efficiency [64]. The positioning of the HOMO and LUMO at the junction between the electron donor and electron acceptor materials is crucial in promoting effective charge transfer and the dissociation of excitons. Efficient charge transfer requires a suitable energy level difference between the energy levels of the active materials. Proper alignment of the energy levels promotes interfacial exciton dissociation and enhances the overall device performance [69]. The HOMO and LUMO alignments also influence the charge recombination rate in OSCs. A smaller energy level difference between the acceptor's HOMO and the donor's LUMO can help to reduce the recombination of the charge and optimize the device's performance. However, a very small offset may lead to inefficient charge transfer and exciton dissociation [70]. The arrangement of energy levels also significantly affects the durability and operational lifespans of OSCs. Proper energy level alignment can help to minimize the trap states of the density, minimize charge recombination, and improve device stability [68]. The HOMO-LUMO levels' alignment at the donor-acceptor junction is essential in studying the underlying principles of OSCs. In a conjugated polymeric donor material with fullerene derivatives as acceptors, an energy difference greater than 0.3 eV is commonly reported in high-performance OSCs [71]. This energy difference is considered to facilitate improved charge separation by providing the required driving force. Zhang et al. discovered that lowering the HOMO offset results in a slower transfer rate of holes. Maximizing the benefits of the acceptor materials is possible when the HOMO level difference between the donor and acceptor materials is reduced, provided that the active layers exhibit both a high absorption coefficient and optimized structure [72].

The active layer morphology in the OSC significantly impacts the PCE of the device [73]. The active layer's nanoscale morphology, particularly in BHJ OSCs, affects exciton dissociation and charge transport. For example, Kangkang et al. [74] proposed that employing polymer fibril networks could be a promising strategy to enhance the PCE. There are some important viewpoints about morphologies and their impacts on the PCE. The interface's morphology influences the exciton dissociation efficiency. A larger interfacial area between the donor and acceptor can result in efficient exciton dissociation, as it offers an expanded surface area that facilitates the migration of excitons toward the junction at the donor and acceptor boundary, promoting their separation into free charge carriers [74,75]. The active layer morphology significantly impacts the charge transport in the OSCs [76]. The ideal morphology should offer uninterrupted routes for both electrons and holes to traverse via their specific electron donor and electron acceptor phases, consequently reducing charge carrier recombination and facilitating improved electrode charge collection [77]. The domain size and phase separation between the donor material and acceptor material in the active layer are crucial in achieving high PCE. An optimal domain size enables efficient exciton dissociation while allowing charge carriers to reach the electrodes with minimal recombination. A balance between phase separation and mixing is essential in creating efficient charge transport pathways and maintaining a large area at the interface for exciton dissociation [78]. Control of the active layer's morphology can be achieved through various processing techniques, such as solvent annealing, thermal annealing, or using solvent additives. These techniques can influence the phase separation, crystallinity, and nanoscale morphology, improving device performance [28]. For instance, Yoo et al. studied the impact of incorporating an additive, specifically  $p-DTS(FBTTh_2)_2$ , into an OSC system consisting of PTB7-Th (donor) and IEICO-4F (acceptor). The study revealed that the enrichment of the additive led to enhanced crystallinity, which in turn improved the PCE from 9.8 to 10.9% [79].

A research work conducted by Lu at el. also unveiled an efficient method, namely an organic-inorganic hybrid electron transport layer (ETL), to optimize the performance of inverted structured OSCs. The incorporation of benzyl viologen dichloride (BV-2Cl) into ZnO for an ETL led to a significant enhancement in the OSCs' efficiency, underpinned by improved charge transport, exciton dissociation, and a reduced work function. With this strategy, a 16.5% rise in PCE was observed [80]. The blended morphology in BHJs is critical for the effective operation of OSCs. It was reported recently by Wang et al. [81] that by introducing a block copolymer (such as PS-b-PAA) into the OSC system (such as PM6:IT-4F), there is a noticeable refinement in the BHJ structure. Such morphological improvements play a pivotal role in facilitating better charge transport within the device. A well-organized and interconnected pathway for both electrons and holes ensures that these charge carriers reach their respective electrodes efficiently, leading to higher photocurrents. Moreover, the reduced bimolecular, monomolecular, and trap-assisted recombination processes further improve the device's performance. Recombination processes are often the primary reason behind energy losses in organic photovoltaic devices. By minimizing these processes, more charge carriers can contribute to the photocurrent, leading to higher PCE. The reduction in these recombination pathways can be attributed to the better phase separation and optimal domain sizes achieved by incorporating PS-b-PAA, ensuring that charges can move freely without encountering as many obstacles or traps. Incorporating metallic nanoparticles (such as  $Ag@SiO_2$ ) into the active layer is also a notable strategy to optimize OSC devices [82]. Due to the localized surface plasmon resonance (LSPR) effect exhibited by these nanoparticles, there is an enhancement in light absorption within the active layer. This improved absorption translates into increased exciton generation and, consequently, a potential rise in the PCE of the OSCs. Thus, optimizing the morphology of the active layer is crucial in enhancing the overall efficiency of OSCs.

Chemical modification by inserting the electron-donating group and electron- withdrawing group in the donor and acceptor may also significantly impact the PCE of OSCs. These groups influence the energy levels (HOMO–LUMO), absorption properties, and molecular packing, which in turn affect the photovoltaic performance of OSCs. Therefore, the modification of the energy levels makes optimizing the V<sub>OC</sub> and improving charge transfer at the donor–acceptor interfacial region possible, which can lead to improved PCE [83]. Functional group introduction (such as electron-donating/-withdrawing groups) can affect the absorption spectra of the electron donor material and electron acceptor material. By tuning the absorption properties, it is possible to broaden the absorption range, allowing OSCs to harvest more sunlight and generate a higher photocurrent. In this way, the J<sub>SC</sub> may increase and the PCE can be improved [84,85]. The inclusion of electron-donating or electron-withdrawing groups in the donor material or acceptor material can impact the molecular arrangement and structure of the active layer within OSCs. By optimizing the molecular packing and optimizing the layer's morphology, charge transport and exciton separation can be enhanced, and charge recombination can be decreased, which ultimately leads to an increase in PCE [86]. Electron-donating and -withdrawing groups can also impact the stability and lifetimes of OSCs by influencing the molecular packing and energy level alignment. Properly designed donor and acceptor materials with suitable side groups can improve device stability and offer longer operational lifetimes [34]. Over 16% PCE was attained by incorporating a potent electron-withdrawing cyano group on a polythiophene donor. Enhanced efficiency was realized because of the reduction in the HOMO level and the optimized crystal structure of the polymeric material [87,88]. Electron-donating and electron-withdrawing groups can improve OSCs' PCE by influencing the energy levels, absorption characteristics, molecular packing, and stability. The careful design and incorporation of these groups in donor and/or acceptor materials may improve solar cell performance.

The side chain length of the donor material and acceptor material in OSCs can significantly impact the PCE of the devices. The side chain length influences factors such as the molecular packing, solubility, film formation, and active layer morphology, which can affect the photovoltaic efficiency of OSCs. There are some key aspects of the side chain length and its impact on OSCs' PCE. The side chain length can affect the molecular packing of the active layer materials. Proper molecular packing is essential for efficient charge transport and exciton dissociation. Longer side chains may lead to looser packing, which might have a detrimental influence on how well the OSC performs [89]. The side chain length affects the miscibility of the materials in organic solvents, which is crucial for the solution processing of materials during the fabrication of the device. By tuning the side chain length, it is possible to optimize the film-forming properties, resulting in a better film morphology and improved device performance [90]. The side chain length can also impact the phase separation and active layer morphology at the nanoscale. An optimal morphology, characterized by interconnected donor and acceptor domains, is essential for efficient charge transport and exciton dissociation. The proper selection of the side chain length can help to achieve the desired morphology, leading to higher PCE [91]. The side chain length can also impact charge carrier mobility in OSCs. Longer side chains may increase the distance between adjacent  $\pi$ -conjugated backbones, reducing the charge transport efficiency and potentially leading to lower PCE. Optimizing the side chain length can help to maintain efficient charge transport and improve overall device performance [18]. For instance, Sun et al. identified the impact of side chains on the donor (BDT unit) and acceptor (BDTDO unit). They discovered that the longer alkyl group on the BDTDO unit could result in significant steric hindrance and produce a distorted molecular structure. Consequently, a moderately bulky alkyl chain on the BDTDO unit demonstrated optimal solar cell efficiency, yielding high PCE [92]. Li et al. [93] studied the impact of side chains on small-molecule donors containing a benzodithiophene (BDT) moiety. The study revealed that varying alkylthio side chains could influence the molecular stacking and crystallinity. A shorter alkylthio group displayed a strong inclination toward crystallization, while a longer alkylthio group exhibited diminished crystallinity. Ge et al. [94] also optimized the molecular stacking by 2-ethylhexyl alkyl chains in a series of donor materials. It has been demonstrated that the side chain length can significantly affect the PCE of OSCs. This is due to its impact on aspects such as molecular packing, solubility, the formation of films, and the active layer morphology. The careful design and optimization of the side chain length in the electron donor and electron acceptor materials can lead to improved solar cell efficiency [93,95].

The addition of a third additive or a ternary component in the active layer of OSCs has been found to enhance their PCE by influencing various photovoltaic parameters, such as absorption, morphology, and charge transport [96]. Lu and colleagues reported that introducing a third additive, specifically a small-molecule NFA, into the active layer of a BHJ OSC composed of a wide-bandgap donor polymer and a fullerene acceptor could improve the device performance. The presence of the third additive resulted in a broadened absorption spectrum, enabling the OSC to harvest more sunlight and generate a higher photocurrent. Additionally, the optimized morphology and phase separation within the active layer facilitated efficient charge transport and exciton dissociation, ultimately contributing to the enhancement of the device's PCE [97]. Moreover, research by Liu et al. [98] highlighted the potential of integrating a ternary component, TBFCl50-BDD, into a PM6:IT-4F-based OSC. By incorporating 20% (by weight) of this specific ternary component, a significant enhancement in the PCE of the OSCs was observed. This boost in efficiency was attributed to two primary factors: the more efficient movement of charge carriers and a good reduction in charge recombination. Moreover, the ternary blend outperformed binary OSCs in terms of exciton diffusion speed. This faster diffusion ensured that more excitons were successfully dissociated, thereby enhancing key performance metrics such as the FF and the JSC of the devices.

The solubility of the electron donor and electron acceptor in OSCs is an important factor that can influence the PCE of the device [99]. Solubility affects the materials' processability, film formation, and the active layer morphology, which in turn impact the photovoltaic efficiency of OSCs. Hou and colleagues investigated the role of solubility in

the OSCs' performance by systematically varying the side chains in the backbone donorconjugated polymers in the active layer [90]. They found that the solubility of the donor materials in organic solvents is crucial for solution-based processing, such as spin coating, which is commonly used for the fabrication of OSC devices. Proper solubility ensures good film formation and uniformity, improving device performance.

Additionally, solubility is related to the active layer's morphology, which facilitates charge transport, exciton dissociation, and charge recombination. By optimizing the active materials' solubility, the authors achieved a better active layer morphology, which in turn led to the improvement of the device's PCE. The miscibility of the donor material and acceptor material in OSCs can impact the PCE by influencing factors such as processability, film formation, and the active layer morphology. The careful design and choice of materials with suitable solubility, as demonstrated in the referenced study, can result in higher-performance OSCs [100,101].

The utilization of the strategies (Figure 8) discussed in this review profoundly influences various parameters in terms of improving the efficiency of OSCs. These parameters encompass optoelectronic properties, absorption spectra,  $V_{oc}$ , exciton dissociation, charge transport, molecular packing, solubility, phase separation, crystallinity, nanoscale morphology, and device stability. The optimization of OSCs is crucial for integrated photovoltaics applications. The use of OSCs in GIPV applications is primarily enabled by their tunable absorption properties, allowing them to selectively absorb specific wavelengths of the solar spectrum while remaining transparent in the visible region. This unique feature makes OSCs an ideal candidate for GIPV, where transparency and energy generation are critical factors [102].

![](_page_13_Figure_4.jpeg)

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Figure 8. Summary of strategies to improve PCE.

#### 4. Greenhouse-Integrated Photovoltaics (GIPV)

This section showcases the application of the integration of photovoltaics into greenhouses. Sustainable agriculture necessitates the attainment of high crop yields within the confines of limited agricultural land while reducing the reliance on non-renewable energy sources [103]. Greenhouse farming offers advantages such as reduced water consumption and controlled temperatures, irrespective of external conditions [104]. Although greenhouse-based farming can enhance crop production compared to conventional agriculture, it requires electricity [105]. The system cannot be deemed sustainable if the electricity source is non-renewable. The necessity of sustainable agriculture and renewable energy source utilization has driven rapid advancements in GIPV [2].

PCE of 15–16% for some OSC systems for greenhouse applications has been achieved [7]. This efficiency is low compared to silicon (Si)-based solar cells, but transparency is the key feature in the integration of OSCs with greenhouses. Numerous combinations of active materials have been described in scientific papers for the integration of OSCs with greenhouses. Liu et al. first reported the greenhouse application of a flexible OSC based on infrared (IR) active acceptors (such as F8IC, IEICO-4F, and FOIC) combined with PTB7-Th as the donating material, reaching good PCE (9.26, 10.03, and 8.92%, respectively) [106]. The growth of mung bean plants over a thirteen-day period in a greenhouse powered by PTB7-Th:IEICO-4F OSCs was found to be similar to growth under normal sunlight conditions (Figure 9).

O'Connor et al. [10] reported on the electricity distribution generated from a GIPV with a combination of two active layers (FTAZ:IT-M and PTB7-Th: IEICO-4F). This system achieved PCE of 12.8%. Interestingly, only 50% of the electricity generated in this system was consumed by the greenhouse (for lettuce cultivation) in hot climate conditions, leaving the remaining 50% of electricity available for storage. Additionally, it was observed that in mixed humid weather conditions, energy consumption by the greenhouse was higher, yet the produced energy remained in surplus [10,11,107].

O'Connor et al. [11] also showcased an OSC featuring an active material layer with absorption properties that complemented the absorption of chlorophyll in red leaf lettuce. The fresh and dry weights of red leaf lettuce cultivated under semitransparent OSCs were comparable to those of the control treatment. OSC filters (shown in Figure 10), integrated with a greenhouse, were composed of three BHJ layers, namely FTAZ:IT-M, FTAZ:PC71BM, and PTB7-TH:IEICO-4F. They exhibited average visible transmittance (AVT) in the spectrum of photosynthetically active radiation (PAR) at 29, 31, and 38% and PCE of 11, 6, and 12%, respectively.

Hu et al. [108] reported on the development of semitransparent ternary materials (BDT-Th: IT-4F and IEICO-4F as the alloyed acceptor) in solar cells that displayed both high PCE of 9.40% and AVT of 24.6% [106,109]. Li et al. [110] also developed an innovative OSC for integration in a greenhouse using a non-halogenated green solvent. This OSC was based on a potent polymer donor (PM6). Acceptor materials (such as A-2ThCl and A-4Cl) were combined with PM6 donors by the strategical alignment of the HOMO–LUMO energy levels. It was observed that there were high offsets of energy of approximately 0.2 eV ( $\Delta$ HOMO) and 0.35 eV ( $\Delta$ LUMO) between the donor (PM6) and A-4Cl near-IR acceptor. After the mixing of another near-IR acceptor, A-2ThCl with A-4Cl showed single oxidation potential (-5.70 eV) and reduction potential (-3.98 eV) on a cyclic voltammogram that proved that they had good miscibility. The combination of these two miscible acceptors and a fullerene acceptor ( $PC_{71}BM$ ) with donor PM6 resulted in a unique electricitygenerating light filtering system for greenhouse integration. These OSCs reached PCE of 13.08%, along with a growth factor of 24.7% for plants. The study focused on mung bean sprouts, which were observed to thrive under the OSC-filtered light. After 90 h, the sprouts grown under the OSC-filtered light reached a height of approximately 7.6 cm, demonstrating growth characteristics similar to those grown under traditional glass in the context of height, branching, and leaf development [110]. In a study by C. Zisis et al., a photoactive layer of P3HT:PCBM, featuring transparency of 19.4% in the region of PAR,

was implemented in a greenhouse. Notably, better plant growth was observed beneath the integrated photovoltaic covering on the greenhouse [111]. Cao et al. [111] designed a J52:IEICO-4F:PC71BM ternary blend OSC for greenhouse integration application. They observed 7.75% PCE for the OSC, with a 24.8% crop growth factor [112]. An OSC composed of a P3HT donor and naphthobisthiadiazole-based acceptor showed good performance for energy generation and strawberry plant growth [113]. An OSC composed of donor D2 and acceptor A26 exhibited PCE of 9.3 with AVT of 31%, resulting in the comparable growth of mung bean under both natural sunlight and an OSC covering [106]. The use of OSCs in greenhouses not only supports environmentally friendly agricultural practices but also offers substantial financial benefits. An experiment performed by O'Connor et al. [12] revealed that the net present value (NPV) of OSC-integrated greenhouses can be increased by up to  $\frac{320}{m^2}$ , particularly for tomato production at latitudes below  $35^\circ$ , compared to traditional greenhouses. In colder climates, OSCs have been found to offset up to 65% of the greenhouse energy demand, significantly reducing energy consumption and the associated costs. Additionally, OSC-integrated greenhouses provide optimal lighting conditions for plant growth. The selective transmission of light through the OSCs allows for the absorption of wavelengths most conducive to photosynthesis, thereby promoting enhanced crop growth [12]. The adoption of an optimized design for OSCs brings particular advantages, especially in the context of GIPV, as it guarantees efficient energy conversion and effective energy management. These factors are vital in maximizing the overall efficiency and productivity of greenhouse systems.

![](_page_15_Figure_3.jpeg)

**Figure 9.** (a) Integration of OSC in a greenhouse; (b) molecular structures of IEICO-4F, F8IC, and FOIC; (c) absorption spectra of donor and acceptor materials. Reproduced with permission, [106], 2019, Elsevier.

![](_page_16_Picture_2.jpeg)

![](_page_16_Figure_3.jpeg)

![](_page_16_Figure_4.jpeg)

FTAZ

![](_page_16_Figure_6.jpeg)

**Figure 10.** Experimental setup of plant growth and chemical structures for photovoltaic systems FTAZ:IT-M, FTAZ:PC71BM, and PTB7-TH:IEICO-4F. Reproduced with permission, [11], 2021, Elsevier.

## 5. International Green Initiatives

This section focuses on international green initiatives. Amidst a surge in international efforts to combat climate change and advance sustainability, the convergence of pivotal initiatives has emerged, such as the United Nations' Sustainable Development Goals (SDGs) [114], the Paris Agreement [115], and the European Green Deal (EGD) [116]. The SDGs span a wide range of social, environmental, and economic directives. Among the 17 goals, SDG 7 focuses on ensuring access to affordable, reliable, sustainable, and modern energy for all. Meanwhile, SDG 13 targets overcoming climate change issues, which is achievable through a reduction in the dependence on fossil fuels. Notably, SDG 7 significantly dominates solar energy research at approximately 72%, followed by SDG 13 at approximately 11% [117]. Additionally, SDG 2 aims to eliminate hunger and promote sustainable agricultural practices. GIPV is at the intersection of these three SDGs, which clearly highlights the importance of this application. By merging energy generation with food production, GIPV can potentially enhance agricultural yields while ensuring that energy production does not come at the expense of valuable agricultural land. Similarly, the Paris Agreement is a landmark treaty under the United Nations Framework Convention on Climate Change (UNFCCC). It aims not only to limit the global temperature rise to below 2 °C, but also emphasizes the importance of adaptation and financial flows consistent with a path toward low greenhouse gas emissions. GIPV, in this context, serves a dual purpose. It can contribute to reducing CO<sub>2</sub> emissions by generating sustainable energy and, by being integrated with agriculture, it can also lead to climate-resilient agricultural practices.

After the COVID-19 pandemic, the European Green Deal (EGD), while being a regional initiative, also provides a blueprint that can inspire global action. The EGD aims for net-zero greenhouse gas emissions by 2050, setting specific targets for 2030 while promoting energy self-sufficiency and economic progress. GIPV is being increasingly recognized in line with the EGD objectives, such as promoting sustainable energy and agriculture, ensuring food supplies, and boosting rural development. The potential of GIPV is vast. If only 1% of the EU's utilized agricultural area was covered with GIPV, it would yield an impressive 944 GW, assuming 0.6 MW/ha [118]. This is nearly half the output of conventional ground-mounted PV systems, which offer approximately 1809 GW. Thus, GIPV optimizes land usage and synergizes food production with clean energy generation, emphasizing their importance for the EU's usianable vision. In essence, GIPV is not merely a technological marvel but a vital instrument aligning with global objectives aimed at a sustainable future.

#### 6. Discussion

This section discusses the key development of OSCs and their agrivoltaic applications. The task of enhancing OSCs has taken center stage in the search for alternative renewable energy. However, these cells face operational stability and efficiency problems, especially when compared against their silicon-based counterparts. External factors such as environmental exposure, including oxygen, moisture, and temperature variations, further threaten the performance and longevity of OSCs. Researchers are tirelessly working to counter these issues through avenues such as molecular design changes, shifts in device architecture, and protective encapsulation mechanisms.

OSCs owe their efficiency and performance to several parameters, one of the most pivotal being the bandgap. Alterations such as introducing electron-withdrawing groups help to optimize the bandgap, affecting the PCE, among other parameters. Ensuring the alignment of the HOMO–LUMO energy levels in the donor and acceptor materials is equally important for effective charge transfer and stability. The morphology of the active layer in OSCs, which influences phenomena such as exciton dissociation and charge transport, has led researchers to probe into techniques such as solvent annealing. The exploration does not end here. Chemical modifications, notably introducing electron donating/withdrawing groups in donor and acceptor materials, have been identified as potential solutions, enhancing efficiency of OSCs. In this context, the length of the side chain in materials is also under scrutiny for its profound effect on PCE.

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Transitioning to applications, the distinct properties of OSCs, especially their tunable absorption capabilities, make them invaluable for integrated photovoltaics. Their potential is realized significantly in sustainable agriculture, particularly in greenhouse-integrated setups. It is evident from findings in the literature that despite their lower PCE than siliconbased solar cells, OSCs can efficiently run greenhouses without hampering plant growth. Numerous studies have underscored the successful integration of OSCs in greenhouses, further validating their efficacy. These advancements coincide with global green initiatives, such as the United Nations' SDGs, the Paris Agreement, and the EGD, reinforcing the importance of innovations such as GIPV in the larger quest for sustainability.

## 7. Conclusions and Outlook

This section addresses the concluding remarks and future perspectives. This comprehensive review emphasizes the promise of organic solar cells as a sustainable and versatile clean energy alternative, thanks to their light weight, transparency, and flexible characteristics. These features enable several applications, including greenhouse-integrated photovoltaics. To boost their power conversion efficiency, researchers have investigated numerous strategies, such as bandgap tuning, molecular orbital alignment, active layer morphology engineering, and material property manipulation. These approaches greatly influence key performance parameters, including the optoelectronic properties, absorption spectrum, open circuit voltage, exciton dissociation, charge transport, molecular packing, solubility, phase separation, crystallinity, nanoscale morphology, and device stability. The inherent transparency of organic solar cells makes them exceptionally suitable for greenhouse-integrated photovoltaics applications, as they optimize light management, enhance energy efficiency, and minimize overheating risks. Tailored organic solar cells cater to specific applications, such as near-IR radiation active devices for agrivoltaics, demonstrating their potential to play a role in shaping a future with greater sustainability and energy efficiency.

There are several implementation risks for stakeholders looking to upscale and commercialize GIPV. It is vital to invest in R&D to boost OSCs' durability against climatic challenges. With the integration of innovative technologies such as OSCs into agricultural frameworks, initial challenges from technology novelty to potential public skepticism are expected, underscoring the need for comprehensive pilot projects and transparent performance metrics. Agrivoltaic ventures demand significant initial investments, considering aspects such as equipment depreciation and diminishing photovoltaic component efficiency over time [119]. O'Connor et al. [12] have already highlighted the economic potential of GIPV, revealing a surge in NPV of up to \$320/m<sup>2</sup> with OSC-integrated greenhouses, providing a compelling case for the combination of organic photovoltaics and agriculture. However, many studies on GIPV are based on models with unvalidated assumptions, pointing to an existing knowledge gap due to insufficient data from real-world GIPV implementations. Future research must focus on detailed economic evaluations of GIPV setups across varying contexts to address this.

The evolution and enhancement of organic solar cells are pivotal in revolutionizing the future of sustainable energy sources. To optimize the PCE of OSCs, future studies must prioritize the advancement of durable materials that effectively harness the potential of the portion of the solar spectrum in the near-IR range [21]. This advancement will improve the efficiency of OSCs. While OSCs have achieved notable power conversion efficiency, ensuring longer durability continues to be a considerable obstacle [42]. When integrating organic solar cells with greenhouses, they must withstand the harsh environmental conditions often found at agricultural sites, such as high temperatures, humidity, air, dust, and light. Ensuring stability under these conditions is crucial for the market penetration and widespread adoption of this technology. As the demand for large-scale device fabrication is growing, there is a pressing need for materials that maintain consistent performance, regardless of thickness, due to industrial challenges to control the active layer thickness. Concurrently, the evolution of OSCs demands a balance of cost, simplicity, and efficiency,

emphasizing the importance of materials that enhance device efficiency without complex structures or processes. Finally, with traditional mechanisms approaching their theoretical limits in photovoltaic performance, breaking these conventions or ushering in novel design concepts is pivotal for substantial PCE advancements [41].

Author Contributions: Conceptualization, M.A.A. and G.C.; methodology, M.A.A., G.C. and S.S.; software, M.A.A. and G.C.; validation, M.A.A. and G.C.; formal analysis, M.A.A.; investigation, M.A.A. and G.C.; resources, M.A.A., G.C. and S.S.; data curation, M.A.A. and G.C.; writing—original draft preparation, M.A.A. and G.C.; writing—review and editing, M.A.A., G.C. and S.S.; visualization, M.A.A. and G.C.; supervision, G.C. and S.S.; project administration, M.A.A., G.C. and S.S.; funding acquisition, G.C. and S.S. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

**Data Availability Statement:** The review article includes all references. Additional data presented in this study are available on request from the corresponding author.

Conflicts of Interest: The authors declare no conflict of interest.

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