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Review Article

Advances in Organic Photovoltaics: A Review of Materials, Devices, and Stability Challenges

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Abstract

Organic photovoltaics (OPVs) have gained significant attention as lightweight, flexible, and low-cost alternatives to silicon solar cells. The development of non-fullerene acceptors, ternary blends, and tandem device architectures has driven power conversion efficiencies above 19%. However, widespread commercialization remains limited due to challenges in long-term operational stability, scalable processing, and material degradation under environmental stress. Understanding the interplay between material design, device physics, and degradation mechanisms is critical for advancing OPVs toward viable renewable energy applications. This review aimed at critically examining recent advances in OPV materials, device structures, and strategies addressing stability challenges for commercial deployment. Recent progress in donor-acceptor material design, particularly Y-series non-fullerene acceptors, has enabled higher efficiencies and broader spectral absorption through optimized energy levels and morphology. Ternary and tandem architectures further improve photocurrent and voltage by broadening absorption and reducing recombination losses. Advances in interfacial layers and electrode materials have enhanced charge extraction and reduced device resistance. Regarding stability, encapsulation, UV-filtering, and molecular engineering have mitigated photo-oxidation, morphological instability, and burn-in degradation. Studies show that device lifetime can exceed 1000 hours under ISOS protocols when using intrinsically stable polymers and cross-linked acceptors. Scalable fabrication techniques such as slot-die coating and blade coating demonstrate potential for roll-to-roll manufacturing. However, efficiency-stability trade-offs persist, and standardized testing remains inconsistent. Machine learning and high-throughput screening are emerging to accelerate material discovery and predict degradation pathways. OPVs show strong potential for niche and large-area applications due to material and device innovations. Overcoming stability and scalability barriers through robust materials, better encapsulation, and standardized testing will be key to translating lab efficiencies into commercially viable, durable organic solar technologies.

Keywords: Organic photovoltaics, Bulk-heterojunction, Non-fullerene acceptors, Stability, Power conversion efficiency, and Scalable fabrication

Introduction

Growth in the world population and rapid industrialization has been a cause of rising demands for energy resources to unprecedented levels (Leandro et al., 2024; Xue et al., 2025). Global infrastructure has been using fossil fuels as an energy resource for many years now, and this use has been causing higher greenhouse gas emissions, environment degradation, and global climate changes (AlZohbi, 2024; Kiskira, 2024). In order to tackle these challenges, the international community needs to adopt systematic change towards the use of renewable energy resources and the building of corresponding low-carbon infrastructures. Among such energy sources is solar radiation, which can be considered one of the most

abundant energy sources that deliver more raw energy to the surface of our planet during one hour than consumed by the whole human population in one year (Ansari et al., 2024; Solak & Irmak, 2023). Solar energy technology history can be generally considered through the following three different technological generations, beginning with the first generation of photovoltaic cells based on crystalline silicon wafer-based technologies (AlZohbi, 2024; Dallaev, 2025). Even though silicon has been dominating on the commercial market due to its great material stability and efficiency of conversion, it requires quite energy-intensive production process involving high-temperature and high material purity requirements that increase the payback period of the modules (Hassan, 2024; Kiskira, 2025). The second generation of thin-film solar cells, namely CdTe and CIGS, has managed to decrease the volume of materials and cost of manufacturing, but suffer from the issues of the structure shortage of these materials and their toxicity (AlZohbi, 2024; Kiskira, 2024).

This structural limitation led to the development of the third generation of photovoltaics, a new range of innovative thin film designs that are capable of offering high levels of mechanical flexibility, low processing costs, and minimal environmental footprint (Dallaev, 2025; Khan & Jarząbek, 2024). In particular, among the innovations that emerged within the third-generation category, the organic photovoltaic cells (OPVs) seem very promising due to their specific operation mechanism and flexible structure (Bernardo et al., 2021; Leandro et al., 2024). The fundamental principle behind organic solar energy transformation saw a significant modification by introducing the bulk heterojunction (BHJ) configuration as the alternative to single-layer ineffective designs.

This limitation resulted in creating the third generation of solar cells, which are represented by the variety of innovative thin-film types which can provide such features as mechanical flexibility, low costs of manufacturing, and low environmental impact (Dallaev, 2025; Khan & Jarząbek, 2024). In this respect, the innovations that were developed in the third generation include such solar cells as OPVs which can be considered promising owing to their working principle and flexibility (Bernardo et al., 2021; Leandro et al., 2024). The main working principle of organic solar energy conversion was changed through introduction of the bulk heterojunction (BHJ) structure as an alternative to ineffective single-layer structures. Nevertheless, there are still major challenges before such commercial exploitation could be achieved. Scaling up such thin films into modules often results in loss of performance as a consequence of the sheet resistance increase for large transparent electrodes as well as film thickness uniformity issues within large active areas (Bernardo et al., 2021; Angulo-Preckler et al., 2024). Moreover, the lifetime of such materials is currently constrained by their environmental sensitivity, since ambient humidity, oxygen, and heat usually interfere with the sensitive active layer structure (Duan et al., 2024; Oliveira et al., 2024; Upama et al., 2024)

In order to solve these pressing problems, this comprehensive review offers a detailed insight into the materials, engineering and stabilization aspects of OPVs that form the present status quo of OPV technology. The development in the field is monitored through the donor-acceptor chemistry evolution from classical fullerenes to current non-fullerene acceptors (NFAs), which have driven the technology to achieve unprecedented performances. Moreover, the degradation mechanisms due to optical, thermal and environmental conditions are discussed, as well as current efforts in interface engineering and encapsulation towards improved lifetimes. Finally, the mechanical and geometrical issues related to scale-up fabrication from lab to industrial printing processes will be addressed, providing a clear insight on how OPVs can become a commercial renewable energy technology.

Organic Photovoltaic Materials

Active Layer Materials

The development of high-performance organic photovoltaics (OPVs) relies fundamentally on optimizing the nanoscale morphology and chemical composition of the photoactive layer. Within a typical bulk-heterojunction (BHJ) matrix, light absorption and subsequent electrical power generation are facilitated by an interpenetrating network composed of specialized electron-donating and electron-accepting materials (Chung *et al*., 2024). This structural architecture decouples optical harvesting from charge transport, enabling efficient exciton dissociation and carrier extraction (Rafiq, 2026). Donor polymers constitute the backbone of the photoactive layer by harvesting incident photons and initiating charge transport. Early OPV devices relied on poly(3-hexylthiophene) (P3HT), which served as a benchmark material despite its relatively narrow absorption range (Dallaev, 2025). To improve device performance, contemporary polymer engineering emphasizes donor–acceptor (D–A) architectures that combine electron-rich and electron-deficient building blocks to fine-tune molecular orbital energy levels and broaden light absorption (Essid, 2024). This strategy has led to the emergence of high-performance conjugated polymers such as PM6 and its derivatives, while further molecular engineering, including alternating A1–A2 donor chains, has enhanced energy-level alignment and increased device operating efficiency (Ruduss, 2025; Li *et al*., 2025). As illustrated in Figure 1**,** incident photons generate excitons within the donor phase, which subsequently diffuse toward donor–acceptor interfaces where charge separation occurs. The resulting electrons and holes are transported through continuous acceptor and donor pathways, respectively, minimizing recombination losses and maximizing photocurrent generation (Chung *et al*., 2024; Rafiq, 2026).

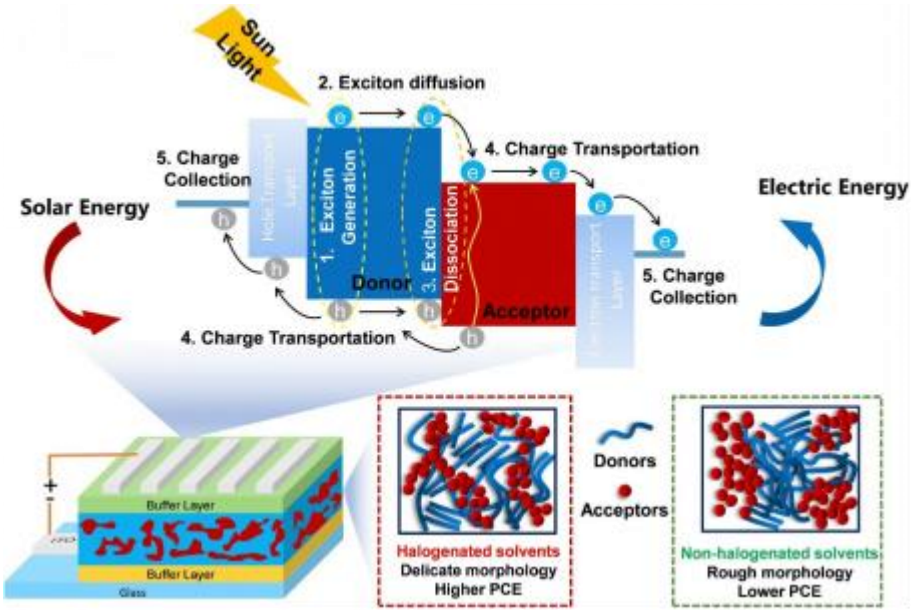

Figure 1. Schematic illustration of the bulk-heterojunction (BHJ) active layer architecture in organic photovoltaics showing photon absorption, exciton generation, exciton diffusion, charge separation at donor–acceptor interfaces, and electron/hole transport pathways. Source: Adapted from Chung *et al.* (2024)

Electron acceptor materials have undergone remarkable evolution over the past decade. Fullerene derivatives, particularly $PC_{61}BM$ and $PC_{71}BM$, initially dominated bulk-heterojunction (BHJ) active layers because of their high electron affinity and isotropic charge transport properties (Khan & Jarząbek, 2024). However, their limited visible-light absorption and poor morphological stability restricted further improvements in device performance (Chung *et al*., 2024). These limitations stimulated the development of non-fullerene acceptors (NFAs), with fused-ring electron acceptors such as the Y6 family and BTP-eC9 significantly extending light harvesting into the near-infrared region (900–1000 nm) while improving energy-level matching with donor polymers (Hassan, 2024; Rafiq, 2026). Their acceptor–donor–acceptor (A–D–A) molecular architecture also provides greater flexibility for tailoring molecular packing, charge transport, and exciton dissociation.

Table 1. Representative donor and acceptor materials employed in organic photovoltaic active layers and their engineering significance

Material Class	Representative Materials	Key Structural Characteristics	Primary Engineering Advantages	References
Polymer Donors	P3HT	Semicrystalline conjugated polymer	Good processability; benchmark donor material	Dallaev (2025)
High-Performance Polymer Donors	PM6 and derivatives	Donor–acceptor (D–A) conjugated backbone	Broad absorption, efficient charge transport, high PCE	Ruduss (2025); Li *et al*. (2025)
Fullerene Acceptors	$PC_{61}BM$, $PC_{71}BM$	Spherical fullerene derivatives	High electron mobility and isotropic electron transport	Khan & Jarząbek (2024)
Non-Fullerene Acceptors (NFAs)	Y6, BTP-eC9	Fused-ring acceptor–donor–acceptor (A–D–A) molecules	Near-infrared absorption, tunable energy levels, reduced voltage loss	Hassan (2024); Rafiq (2026)
Morphology Engineering Additives	Solvent additives and volatile solid additives	Controlled nanoscale phase separation	Improved molecular packing, charge transport, and film morphology	Khan (2024)
Advanced BHJ Architectures	Pseudo-bilayer BHJ	Vertical donor–acceptor phase segregation	Enhanced charge extraction and reduced recombination	Cao & Xu (2025)

Current material engineering strategies increasingly focus on optimizing BHJ morphology through additive engineering, solvent selection, and processing control. Volatile solid additives and high-boiling-point solvents regulate nanoscale phase separation and molecular packing during film formation, producing more favorable charge transport pathways (Khan, 2024). Likewise, pseudo-bilayer BHJ architectures fabricated using environmentally friendly orthogonal solvents improve vertical phase segregation, facilitating efficient charge extraction and reducing recombination losses (Cao & Xu, 2025).

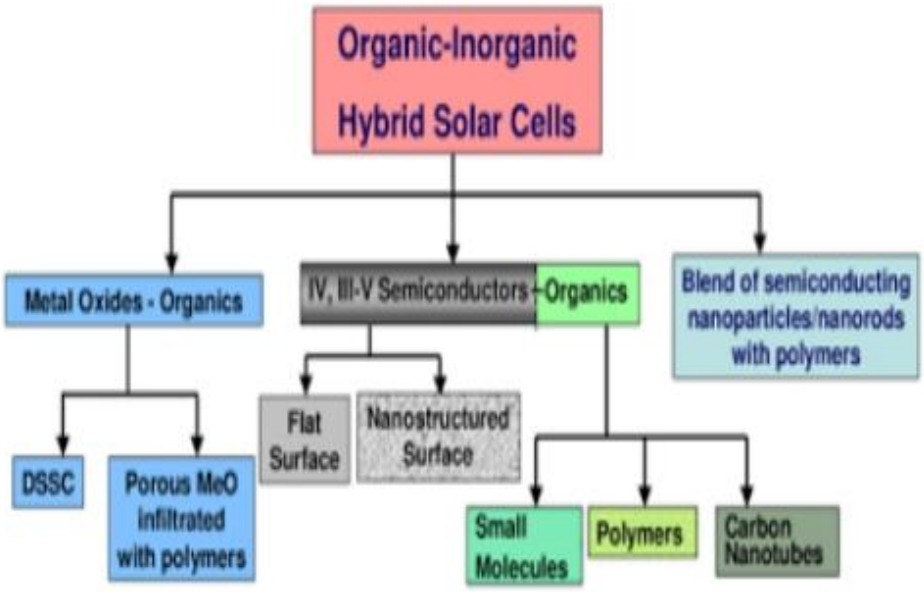

Figure 2. Classification of organic-inorganic hybrid solar cells Source: Ansari *et al*. (2024)

As illustrated in Figure 2, organic photovoltaic materials can be broadly classified into several categories, including metal oxide–organic hybrid systems, IV–VI semiconductor–organic composites, and polymer-based nanocomposites incorporating semiconducting nanoparticles or carbon nanotubes. Within OPV devices, conjugated polymers and small-molecule semiconductors constitute the principal photoactive materials responsible for light harvesting and charge generation. Their selection directly determines the nanoscale morphology of the active layer and consequently influences photon absorption, exciton dissociation, charge transport, and overall power conversion efficiency (PCE) (Ansari *et al*., 2024).

Complementary donor–acceptor materials with appropriate energy-level alignment maximize solar energy harvesting across the ultraviolet, visible, and near-infrared regions. Following exciton generation, efficient charge separation and transport depend on a well-optimized bulk-heterojunction morphology. Poor material compatibility or inappropriate donor–acceptor ratios may produce isolated domains and trap states that increase charge recombination and reduce the fill factor (FF) (Ullah *et al*., 2024). Consequently, selecting materials with compatible frontier molecular orbital energy levels, balanced carrier mobility, and controlled nanoscale phase separation remains essential for achieving high-performance organic photovoltaic devices (Solak & Irmak, 2023).

Optoelectronic Properties

The conversion of sunlight into electrical energy within an organic photovoltaic (OPV) device relies on the precise optimization of its optoelectronic properties. A fundamental aspect of this process is bandgap engineering, in which the energy difference between the highest occupied molecular orbital (HOMO) and the lowest unoccupied molecular orbital (LUMO) is tailored to maximize solar light absorption while maintaining efficient charge separation (Hassan, 2024). Simultaneously, appropriate energy-level alignment between donor and acceptor materials is required to generate a sufficient driving force for exciton dissociation without causing excessive voltage losses. As illustrated in Figure 2, incident photons generate tightly bound excitons within the donor phase, which subsequently migrate to the donor–acceptor interface where the LUMO energy offset promotes electron transfer to the acceptor while holes remain within the donor. This interfacial charge separation governs the maximum attainable open-circuit voltage (VOC) and plays a critical role in minimizing non-radiative recombination losses (Solak & Irmak, 2023; Cui *et al*., 2019).

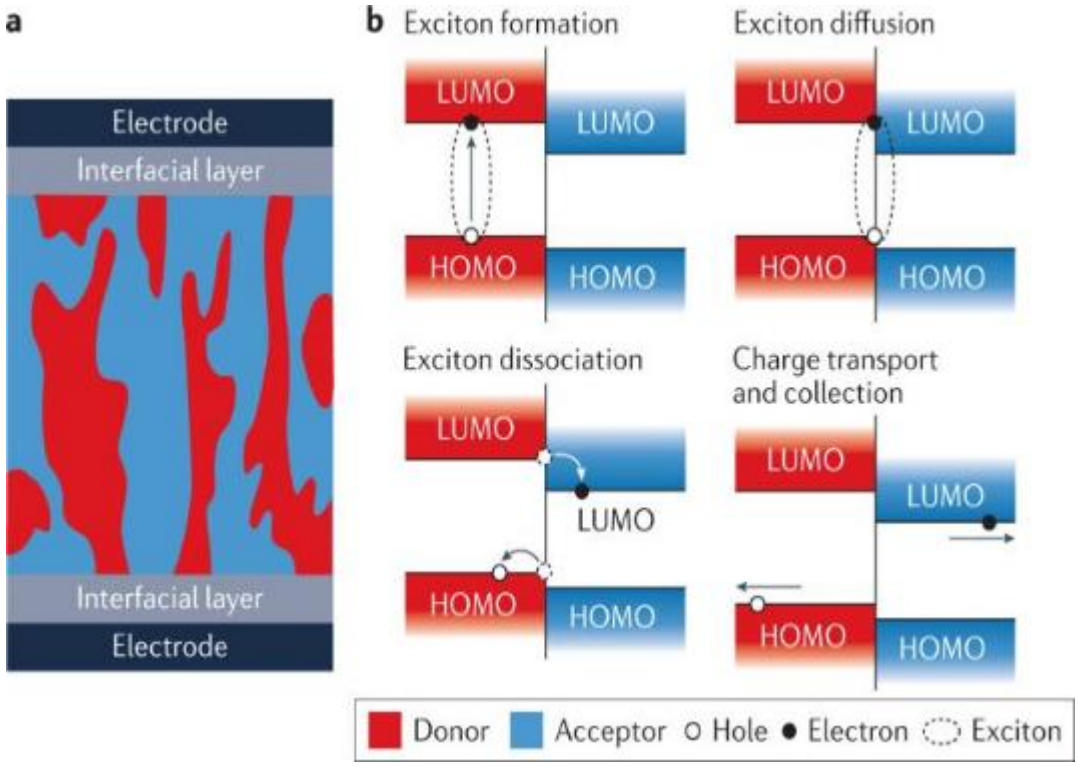

Figure 3. Energy-level alignment and charge generation mechanism in a bulk-heterojunction organic photovoltaic device
Source: Cui *et al.* (2019)

Light absorption constitutes the first stage of photovoltaic energy conversion. Owing to the high absorption coefficients of conjugated organic semiconductors, photoactive layers with thicknesses of approximately 100 nm can absorb a comparable number of photons to substantially thicker crystalline silicon

absorbers (AlZohbi, 2024). However, photon absorption initially produces electrically neutral excitons rather than free charge carriers. Because exciton diffusion lengths are typically limited to 5–20 nm, the donor and acceptor phases must form an optimally phase-separated bulk-heterojunction morphology that enables excitons to reach an interface before recombination occurs (Chung *et al*., 2024). As shown in Figure 3, this nanoscale morphology is essential for efficient exciton diffusion, charge separation, and suppression of radiative decay.

Following exciton dissociation, the transport and collection of electrons and holes depend on the charge mobility within their respective transport pathways (Leandro *et al*., 2024). Balanced electron and hole mobilities minimize space-charge accumulation and trap-assisted recombination, thereby improving the short-circuit current density (JSC) and overall device efficiency (Rahman, 2025). Furthermore, solution-processed interfacial layers at the cathode and anode optimize energy-level matching, reduce contact resistance, and suppress carrier recombination (Ullah *et al*., 2024). Despite these advances, maintaining uniform optoelectronic properties over large active areas remains a major challenge for commercial-scale manufacturing. Life-cycle and techno-economic assessments indicate that slight variations in nanoscale morphology can substantially influence module efficiency, production cost, and long-term operational stability during scale-up (Kiskira, 2024, 2025). Consequently, precise control of molecular energy levels, donor–acceptor morphology, and interfacial engineering remains fundamental to improving internal quantum efficiency and the commercial viability of next-generation organic photovoltaic technologies (Bernardo *et al*., 2021).

Device Architectures and Operating Mechanisms

Operating Principle of Organic Solar Cells

The conversion of light into electrical energy within an organic photovoltaic (OPV) cell follows a coordinated sequence of optoelectronic processes governed by the unique properties of organic semiconductors. Unlike inorganic silicon, where photon absorption directly generates free charge carriers, the relatively low dielectric constant of conjugated organic materials ($\varepsilon r \approx 3–4$) results in the formation of strongly bound electron–hole pairs known as excitons following light absorption (Rafiq, 2026). Consequently,

efficient photovoltaic operation depends on a series of interconnected events, including photon absorption, exciton generation, exciton diffusion, charge separation, charge transport, and charge collection, each of which contributes to the overall power conversion efficiency of the device. As illustrated in Figure 4, incident photons with energies equal to or greater than the optical bandgap are absorbed by the photoactive layer, promoting electrons from the highest occupied molecular orbital (HOMO) to the lowest unoccupied molecular orbital (LUMO) and generating tightly bound excitons through Coulombic attraction (AlZohbi, 2024; Dallaev, 2025).

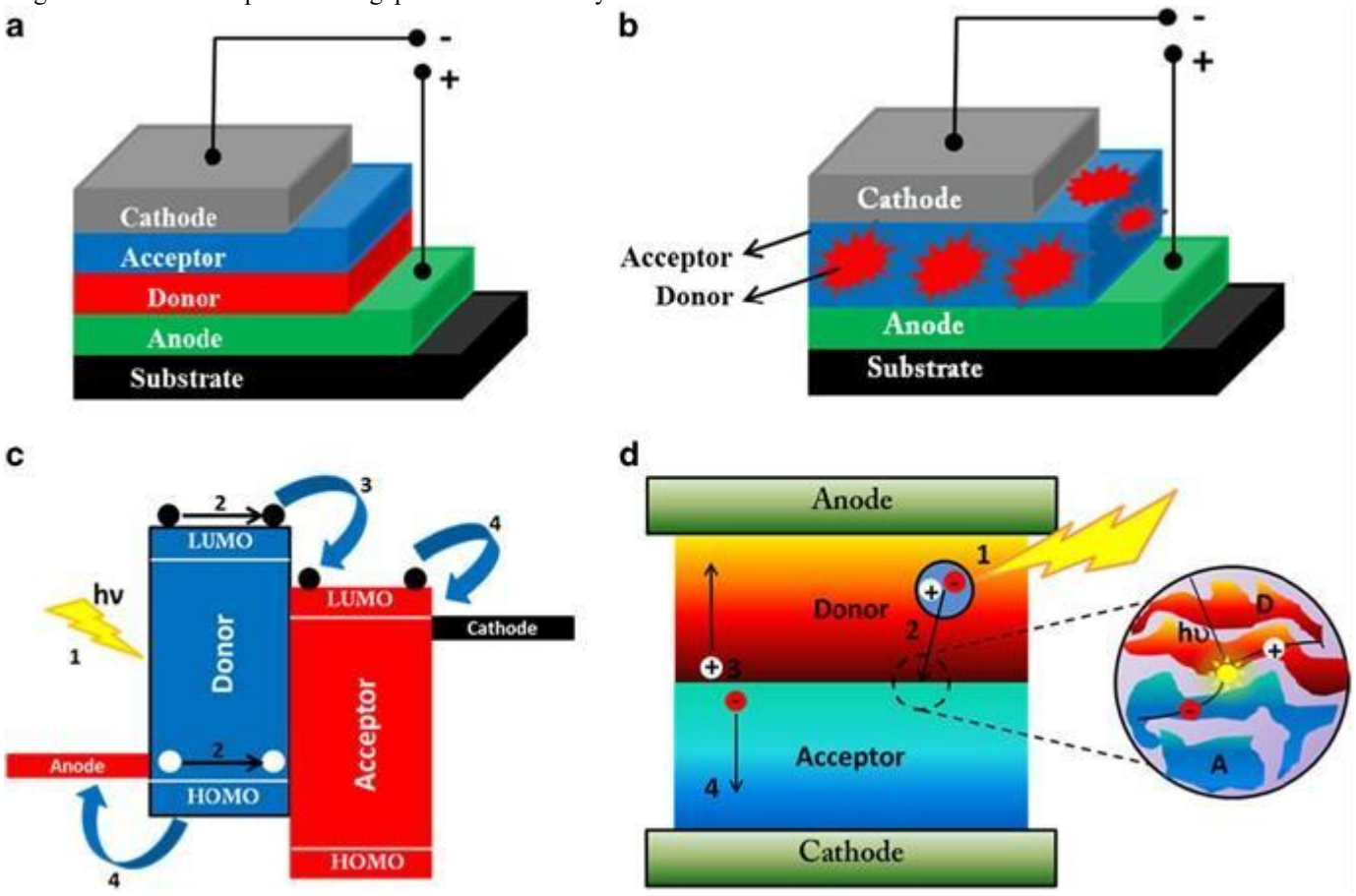

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Figure 4. Schematic representation of the photovoltaic energy conversion mechanism in an organic photovoltaic (OPV) device. Following photon absorption, excitons are generated within the donor material and diffuse toward the donor–acceptor interface, where charge separation occurs. The resulting electrons and holes are transported through acceptor and donor pathways, respectively, before being collected at the cathode and anode to produce electrical current.
Source: Chung *et al*. (2024)

Because excitons in organic semiconductors possess diffusion lengths of only approximately 5–20 nm, the photoactive layer must exhibit a finely controlled bulk-heterojunction morphology that enables excitons to reach the donor–acceptor interface before undergoing radiative or non-radiative recombination (Chung *et al*., 2024). At this interface, energy-level offsets between the donor and acceptor materials provide the thermodynamic driving force required to overcome exciton binding energy, producing an intermediate charge-transfer state that subsequently dissociates into free electrons within the acceptor phase and free holes within the donor phase (Rafiq, 2026). As shown in Figure 4, this interfacial charge separation represents the pivotal step linking light absorption to electrical power generation.

Following charge separation, electrons and holes migrate through their respective transport pathways under the influence of the built-in electric field established by the electrodes. Electrons are transported through the acceptor network toward the cathode, whereas holes move through the donor matrix toward the anode, where both carriers are collected to generate an external electrical current (Rahman, 2025; Ullah *et al*., 2024). Efficient carrier transport depends on continuous percolation pathways, balanced charge mobility, and minimal trap-assisted recombination, emphasizing the importance of nanoscale morphology control in maximizing current density, fill factor, and overall device performance.

This operational flow highlights the physical steps required to transform incident light into usable electricity, illustrating how thin-film organic blends manage charge generation and collection. The efficiency of this complete photovoltaic process depends on optimizing each individual step. Any mismatch in the nanoscale morphology of the bulk-heterojunction can disrupt this sequence. For example, if the domain sizes exceed the exciton diffusion length, a large

fraction of the generated excitons will recombine before reaching an interface, lowering the short-circuit current density (Jsc) (Chung *et al*., 2024). Similarly, poor interconnectivity within the donor or acceptor domains can trap free carriers during transport, increasing bimolecular recombination and lowering the device's fill factor (FF) (Rafiq, 2026). Consequently, maximizing the power conversion efficiency requires balancing material energy level alignments with precise nanoscale morphology control to ensure efficient charge separation and collection (Solak & Irmak, 2023).

Device Architectures

To improve charge generation, carrier transport, and overall device efficiency, several organic photovoltaic (OPV) architectures have been developed. The major configurations include single-junction, bulk-heterojunction (BHJ), and tandem devices, each differing in structural complexity and photovoltaic performance. As illustrated in Figure 5, the evolution from conventional single-junction cells to tandem architectures reflects continuous efforts to maximize light harvesting while minimizing charge recombination and energy losses. Single-junction OPVs consist of a single photoactive layer positioned between two electrodes and may adopt either a conventional or inverted configuration, with inverted devices generally exhibiting improved environmental stability (Khan & Jarząbek, 2024). The BHJ architecture, now the dominant single-junction design, blends donor and acceptor materials into an interpenetrating nanoscale network that provides a large donor–acceptor interfacial area, thereby facilitating efficient exciton dissociation within the limited exciton diffusion length (Chung *et al*., 2024).

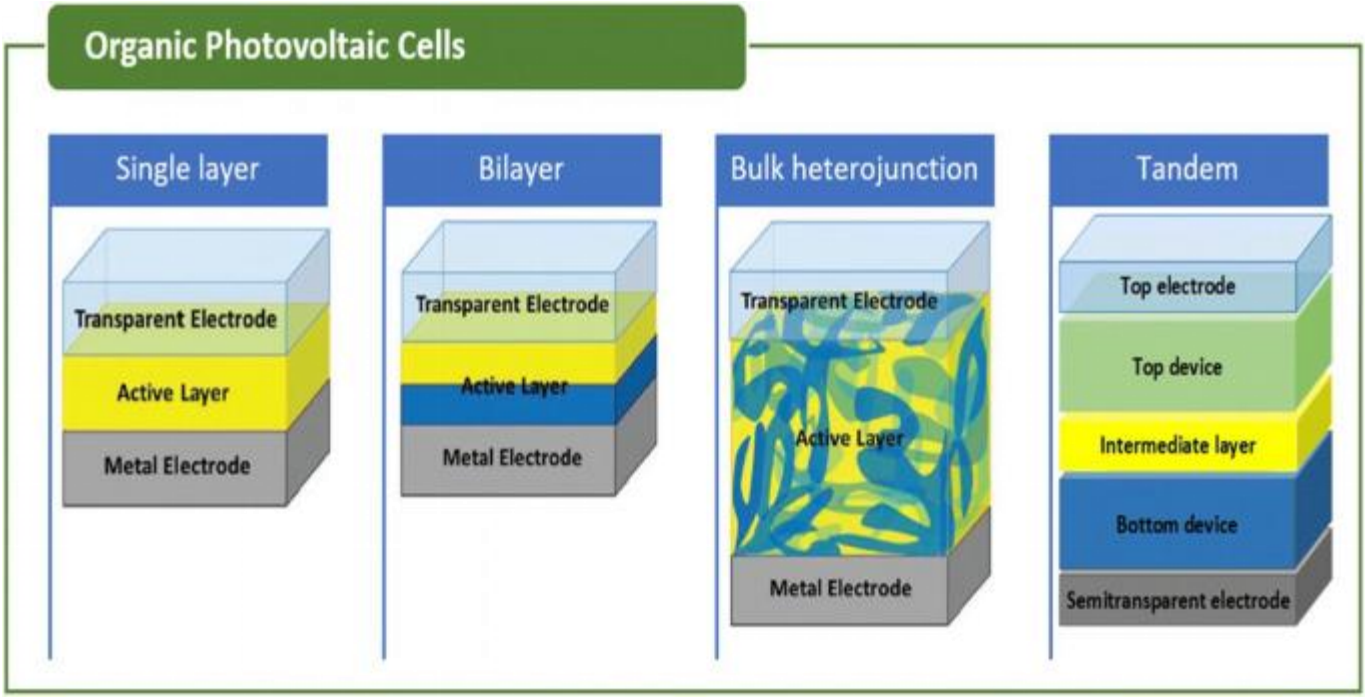

Figure 5. Representative architectures of organic photovoltaic devices showing conventional single-junction, bulk-heterojunction (BHJ), and tandem configurations. The progressive structural evolution enhances exciton dissociation, charge transport, and solar spectrum utilization, resulting in improved power conversion efficiency.
Source: Khan and Jarząbek (2024)

Tandem OPVs further improve device performance by stacking two or more sub-cells with complementary absorption bandgaps that are connected through an interconnecting layer (ICL) (Lee *et al*., 2026). In these devices, the front sub-cell absorbs high-energy ultraviolet and visible photons, while the rear sub-cell harvests lower-energy near-infrared light, enabling broader solar spectrum utilization and reduced thermalization losses (Rangreez *et al*., 2026). Consequently, tandem architectures can surpass the theoretical efficiency limits of single-junction devices, with recent multi-junction OPVs achieving power conversion efficiencies exceeding 21% under laboratory conditions (Lee *et al*., 2026). Despite their superior performance, tandem devices present greater fabrication challenges than single-junction counterparts. Efficient operation requires optically transparent and electrically balanced interconnecting layers that maintain current matching between sub-cells while minimizing parasitic

optical reflection and voltage losses (Rangreez *et al*., 2026). Nevertheless, advances in interfacial engineering, material compatibility, and device fabrication continue to position tandem OPVs as one of the most promising strategies for next-generation high-efficiency organic photovoltaic technologies.

Fabrication Techniques and Performance Enhancement

The commercialization of organic photovoltaics (OPVs) requires scalable fabrication techniques capable of producing uniform active layers while preserving the nanoscale morphology essential for efficient charge generation and transport (Ghasemi *et al*., 2024). Although spin coating remains the standard laboratory deposition method because of its excellent film uniformity and thickness control, its high material loss and batch-processing nature limit industrial-scale production (Ghasemi *et al*., 2024; Lanzetta *et al*., 2024). Consequently, scalable deposition technologies, including slot-die coating, blade coating, roll-to-roll (R2R) printing, and inkjet printing, have been developed to improve manufacturing efficiency, reduce material waste, and facilitate large-area flexible OPV production (Angulo-Preckler *et al*., 2024; Lanzetta *et al*., 2024; Xie *et al*., 2025).

Table 2. Comparison of scalable fabrication techniques for organic photovoltaic devices

Fabrication Technique	Key Feature	Main Advantage	Reference
Spin coating	Centrifugal deposition on rotating substrate	Excellent film uniformity for laboratory devices	Ghasemi *et al*. (2024); Lanzetta *et al*. (2024)
Slot-die coating	Continuous metered coating	High material utilization and industrial scalability	Angulo-Preckler *et al*. (2024)
Blade coating	Ink spread using a moving blade	Simple, low-cost fabrication for large-area films	Lanzetta *et al*. (2024)
Roll-to-Roll (R2R) printing	Continuous web-based printing	High-throughput production of flexible OPV modules	Xie *et al*. (2025)
Inkjet printing	Digital droplet deposition	Mask-free patterning with minimal material waste	Ghasemi *et al*. (2024)

The choice of processing method directly governs thin-film nucleation dynamics and the resulting nanoscale domain morphology. During fast spin coating, rapid solvent evaporation freezes the polymer–acceptor blend into a highly mixed state. In contrast, scalable techniques such as slot-die and blade coating involve longer drying times, which can promote uncontrolled aggregation if solvent evaporation is not carefully regulated (Angulo-Preckler *et al*., 2024). Variations in shear forces during industrial printing further influence the crystalline orientation of non-fullerene acceptors, directly affecting out-of-plane charge mobility and device performance (Xie *et al*., 2025). Consequently, maintaining high efficiency across large-area printed modules requires careful optimization of ink viscosity, coating speed, and drying conditions to reproduce the nanoscale phase-separated morphology achieved in laboratory devices (Lanzetta *et al*., 2024). As illustrated in Figure 6, scalable roll-to-roll manufacturing integrates sequential deposition of the transparent electrode, printed photoactive layer, and primary electrode on a flexible substrate, enabling continuous fabrication of lightweight OPV modules while preserving the multilayer architecture required for efficient light absorption, charge separation, and current collection.

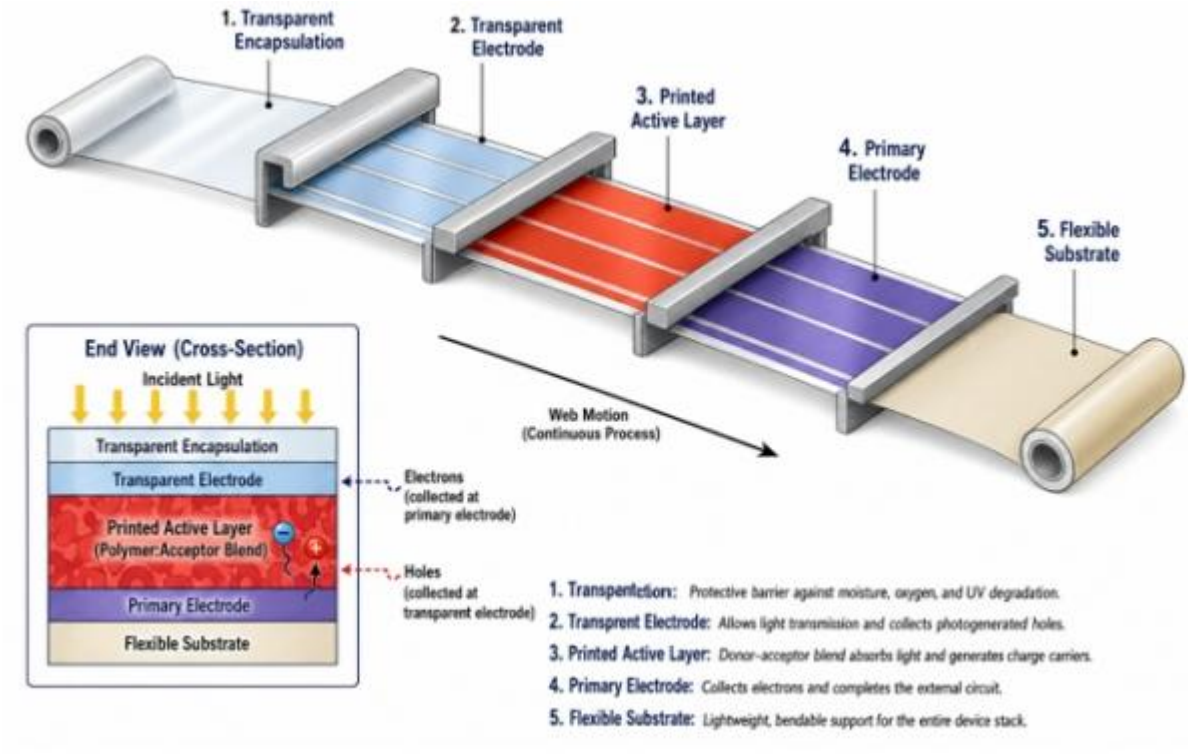

Figure 6. Roll-to-roll fabrication architecture of printed organic photovoltaic devices Source:Angulo-Preckler *et al.* (2024)

Strategies for Improving Device Efficiency

Improving the power conversion efficiency (PCE) of organic photovoltaic (OPV) devices requires coordinated optimization of molecular design, active-layer morphology, interfacial charge transport, and device architecture (Zhang *et al*., 2024). Strategies such as morphology control, interface engineering, solvent engineering, molecular engineering, and tandem device architectures collectively enhance light harvesting, exciton dissociation, charge transport, and carrier collection while minimizing recombination losses (Xie *et al*., 2025; Bi *et al*., 2024; Lanzetta *et al*., 2024). The principal efficiency enhancement strategies employed in modern OPVs are summarized in Table 3.

Table 3. Major strategies for improving the power conversion efficiency of organic photovoltaic devices

Strategy	Main Approach	Performance Benefit	Reference
Morphology control	Thermal annealing, solvent vapor treatment, multifunctional additives	Optimizes donor–acceptor phase separation and exciton dissociation	Xie *et al*. (2025)
Interface engineering	ZnO nanoparticles, self-assembled monolayers, transport layers	Improves energy-level alignment and suppresses carrier recombination	Bi *et al*. (2024)
Solvent engineering	Green solvents and controlled drying additives	Enhances molecular packing and active-layer crystallization	Lanzetta *et al*. (2024)
Molecular engineering	Side-chain modification, fluorination, donor–acceptor molecular design	Broadens light absorption and improves charge transport	Zhang *et al*. (2024)
Tandem architectures	Stacked wide- and narrow-bandgap sub-cells with interconnect layers	Increases spectral utilization and overall power conversion efficiency	Bi *et al*. (2024)

The multi-tiered optimization cascade outlined above tracks how deep structural alterations at the molecular level translate into optimized thin-film morphology and increased power output. The core mechanisms underlying these efficiency improvements focus on minimizing non-radiative voltage losses and suppressing charge carrier recombination. Precise molecular engineering optimizes the energy-level alignment between donor polymers and non-fullerene acceptors, thereby maximizing the open-circuit voltage and improving overall device performance (Zhang *et al*., 2024). Concurrently, solvent and morphology modifications optimize the interpenetrating network, ensuring that domain dimensions match the brief exciton lifespan to promote high internal quantum efficiencies (Xie *et al*., 2025).

At the device contacts, interface engineering introduces selective carrier layers that block opposing charges, preventing bimolecular and trap-assisted recombination at the metal boundaries (Bi *et al*., 2024). Stacking these optimized configurations into multi-junction tandem layouts minimizes thermalization losses by matching different regions of the solar spectrum to dedicated absorbing layers, allowing advanced organic solar modules to consistently push past previous efficiency limits (Bi *et al*., 2024).

Stability Challenges of Organic Photovoltaics

Despite remarkable improvements in power conversion efficiency (PCE), the long-term operational stability of organic photovoltaic (OPV) devices remains one of the greatest barriers to commercialization because organic semiconductors are highly susceptible to environmental degradation (Oliveira *et al*., 2024). Exposure to moisture, oxygen, ultraviolet radiation, elevated temperature, and repeated mechanical deformation progressively alters the chemical structure and morphology of the photoactive layer, resulting in reduced charge transport and device performance (Duan *et al*., 2024; Upama *et al*., 2024). Figure 7 summarizes the principal degradation pathways affecting modern OPV devices.

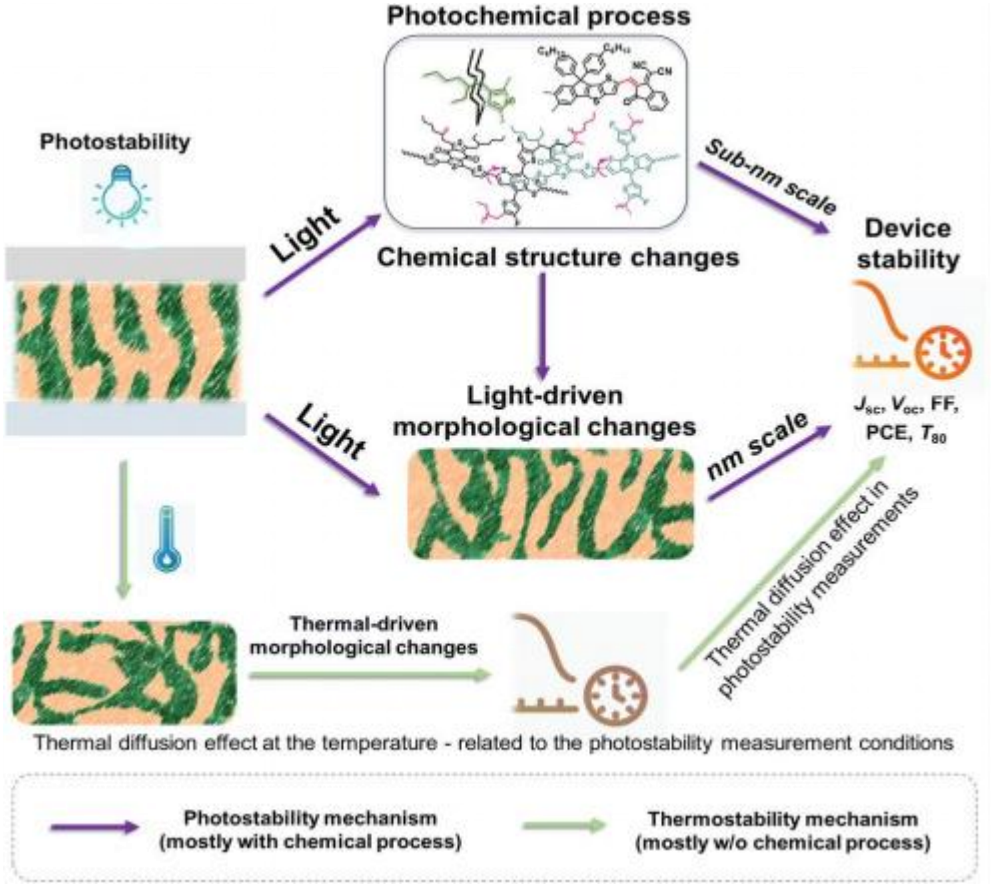

Figure 7. Major degradation pathways in organic photovoltaic devices Source: Adapted from Oliveira *et al.* (2024)

The figure illustrates the principal environmental degradation mechanisms affecting OPVs, including moisture and oxygen ingress, ultraviolet-induced photo-oxidation, thermal phase separation, and mechanical fatigue. These degradation pathways introduce defect states, disrupt donor–acceptor morphology, and reduce charge collection efficiency, ultimately decreasing device lifetime.

The combined effects of these degradation mechanisms reduce the fill factor (FF), short-circuit current density (Jsc), and open-circuit voltage (Voc) through increased charge recombination, morphological instability, and deterioration of interfacial charge transport (Duan *et al*., 2024; Upama *et al*., 2024; Grover *et al*., 2025).

Table 4. Major degradation mechanisms in organic photovoltaic devices

Stress Factor	Primary Effect	Device Impact	Reference
Moisture	Electrode oxidation and interfacial delamination	Reduced conductivity and lifetime	Oliveira *et al*. (2024)
Oxygen	Photo-oxidation of conjugated polymers	Formation of trap states and lower absorption	Duan *et al*. (2024)
UV radiation	Photochemical degradation of NFAs	Reduced electron-accepting capability	Grover *et al*. (2025)
Thermal stress	Phase separation and molecular aggregation	Lower exciton dissociation and charge transport	Upama *et al*. (2024)
Mechanical stress	Cracking of transparent electrodes	Delamination and electrical failure	Oliveira *et al*. (2024)

Strategies for Improving Stability

Improving OPV stability requires simultaneous optimization of material chemistry, interface engineering, encapsulation, and barrier technologies to minimize environmental degradation and preserve active-layer morphology during long-term operation (Upama *et al*., 2024). Material engineering enhances intrinsic resistance to thermal and photochemical degradation, while interface modification suppresses charge recombination and interfacial instability (Duan *et al*., 2024; Grover *et al*., 2025). Encapsulation and advanced multilayer barrier films further prevent moisture and oxygen ingress, significantly extending operational lifetime (Oliveira *et al*., 2024).

Table 5. Engineering strategies for improving OPV stability

Strategy	Function	Engineering Benefit	Reference
Encapsulation	Moisture and oxygen barrier	Extends operational lifetime	Oliveira *et al*. (2024)
Stable donor/acceptor materials	Improves intrinsic photochemical stability	Reduces thermal and UV degradation	Duan *et al*. (2024)
Interface engineering	Stabilizes charge transport layers	Lowers recombination losses	Grover *et al*. (2025)
Advanced barrier coatings	Flexible multilayer protection	Improves environmental durability	Upama *et al*. (2024)

Future Perspectives

Future research is expected to accelerate the commercialization of OPVs through advances in flexible device architectures, transparent photovoltaics, indoor energy harvesting, artificial intelligence (AI)-assisted materials discovery, and scalable green manufacturing (Spada *et al*., 2024; Xue *et al*., 2025). Flexible and semitransparent OPVs will broaden applications in wearable electronics and building-integrated photovoltaics (BIPV), whereas materials optimized for low-light environments are expected to power Internet-of-Things (IoT) devices efficiently under indoor illumination (Mainville *et al*., 2024). Simultaneously, AI-driven molecular design and high-throughput screening will shorten material development cycles, while roll-to-roll manufacturing and eco-friendly processing will facilitate cost-effective large-scale production (Spada *et al*., 2024; Xue *et al*., 2025).

Conclusion

Over the last decade, there have been substantial developments in the field of organic photovoltaics as a result of material science advances in design and thin film fabrication techniques. The shift away from traditional fullerenes acceptors to highly efficient non-fullerenes electronics materials has pushed the state-of-the-art single-junction laboratory efficiencies towards the 20% mark. The increased efficiency, coupled with the high optical absorption coefficients and adjustable bandgap, provides a solid platform for production of lightweight, flexible and semitransparent modules.

There are a number of significant engineering challenges that need to be addressed before large-scale industry deployment is possible. The lifetime of the devices is limited by moisture penetration and photo-oxidation effects. Moreover, scaling up from small lab devices, which are made using spin coating process, to industrial high-speed roll-to-roll fabrication leads to increased number of defects resulting in reduced fill factor of the devices. The future prospects of organic solar panels depend on focusing on markets of specialized applications that silicon-based alternatives cannot address. Organic solar cells'

ability to function well under artificial light makes them ideal candidates for powering IoT devices in office spaces, whereas their flexibility and variable transparency allow incorporating such panels into smart architectural surfaces. With the help of machine learning for material discovery, barrier technology, and environmentally friendly printing technologies, organic photovoltaics are likely to become a valuable part of future decentralized clean energy grids.

Authors' Contributions

The authors of this research have significantly contributed to the study's conception, data collection, and manuscript development. All authors were involved in writing the manuscript or critically reviewing it for its intellectual value. They have reviewed and approved the final version for submission and publication and accept full responsibility for the content and integrity of the work.

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Conflict of Interest

The authors declared that there are no conflicts of interest.

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