Proceedings of the 5th International Conference on Materials Chemistry and Environmental Engineering
DOI: 10.54254/2755-2721/126/2025.20130

Advances in Blade-Coated Organic Photovoltaics

Mingfei Liu[1,a,*]

[1]*Department of Chemical Engineering and Applied Chemistry, University of Toronto, 200 College Street, Toronto, Ontario, M5S 3E5, Canada*
a. mingfei.liu@mail.utoronto.ca
**corresponding author*

Abstract: Organic photovoltaics (OPVs) are a type of solar cell technology that uses organic semiconducting materials to convert sunlight into electricity. Unlike traditional silicon-based solar cells, OPVs are lightweight, flexible, and can be fabricated using cost-effective solution-processing techniques such as blade coating, enabling large-area device fabrication and is compatible with roll-to-roll manufacturing, making it ideal for OPV production. However, key challenges for OPVs, such as achieving high efficiency and scalability, maintaining film uniformity, enhancing material stability, optimizing processing techniques, mitigating environmental and health impacts, improving charge transport and reducing recombination losses, and overcoming performance degradation in large-area production are still under investigation. Recent developments include high-efficiency copolymer donors, ternary additives for optimized morphology, and the integration of novel interlayers and electrodes. Scalable processes such as accelerated blade coating and green solvents like o-methylanisole are also explored, highlighting their role in enhancing efficiency, stability, and sustainability. Additionally, insights into nanoparticle additives, solvent engineering, and molecular design underscore the potential for blade-coated OPVs to achieve high performance while maintaining environmental compatibility. These advancements collectively address challenges in efficiency and scalability, paving the way for OPVs to meet industrial demands and contribute to a greener energy landscape.

Keywords: Organic Photovoltaics, Organic Solar Cells, Solution Casting, Blade Coating, Organic Semiconductor

1. Introduction

Organic Photovoltaics (OPVs) are an innovative and promising technology for sustainable energy generation, offering the advantages of lightweight, flexible, and low-cost solar cells. These features make OPVs particularly suitable for applications that require portable and lightweight energy solutions, such as wearable electronics and building-integrated photovoltaics. Additionally, their low manufacturing costs provide a competitive edge over other thin-film solar cell technologies, resulting in the shortest energy payback time and a relatively low global warming potential. Despite these advantages, further advancements in material selection and process optimization are crucial to overcoming existing challenges and unlocking the full potential of OPV technology in terms of performance, stability and scalability.

© 2025 The Authors. This is an open access article distributed under the terms of the Creative Commons Attribution License 4.0 (https://creativecommons.org/licenses/by/4.0/).

DOI: 10.54254/2755-2721/126/2025.20130

OPVs rely on donor-acceptor heterojunctions in active layers to facilitate charge separation and transport and harvest solar energy. Two main types of device architectures are “conventional” and “inverted”, as illustrated in Figure 1 (both designed for incident photons to enter from bottom glass side). The glass substrate provides structural support and allows light to enter the device. The electrodes (anode and cathode) extract charges generated in the active layer, with one collecting positive charges (holes) and the other collecting negative charges (electrons). The hole transport layer (HTL) selectively facilitates the movement of holes while blocking electrons, ensuring efficient charge separation. The bulk heterojunction (BHJ) layer is the active layer where light absorption occurs, generating electron-hole pairs that are then separated into free charges. The electron transport layer (ETL) enables the transport of electrons while blocking holes, further optimizing charge collection. Together, these layers work to efficiently convert light into electrical energy[1].

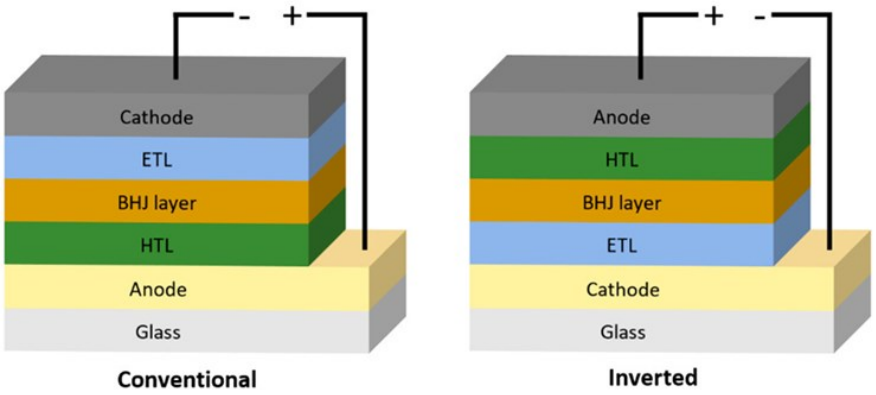


Figure 1: Schematic of conventional (left) and inverted (right) OPV architectures [1]

Deposition of layers of thin films onto the substrate in sequential order is required for OPV fabrication, and unlike conventional silicon photovoltaics, OPVs offer the advantage of solution processability, enabling large-scale production using coating and printing techniques, such as blade coating, slot-die coating, spray coating, inkjet printing and pad printing. Such technology can, in OPV fabrication processes, reduce or even eliminate the use of the energy-intensive process of physical vapor deposition which requires to be carried out under high vacuum. Among these, blade coating has gained significant attention as a scalable meniscus-guided fabrication technique, compatible with roll-to-roll processing and suitable for large-area device production.

This review discusses the advances made in blade coating for OPVs, explores the challenges faced in achieving high efficiencies, stability and scalability, and highlights emerging opportunities for future research and industrial application.

2. Fundamental Principles of Blade Coating for OPVs

Blade coating is a meniscus-guided coating technique in which a blade is used to spread a thin layer of a solution-based material across a substrate (Figure 2), known for its minimal ink waste and compatibility with roll-to-roll processing. The accumulation of ink on one side of the blade creates a meniscus, with the film thickness and uniformity determined by parameters such as blade height, blade velocity, solution viscosity, solution surface tension, and surface temperature. These parameters must be carefully optimized to ensure consistent film morphology, especially when scaling up the active area of the OPVs.

DOI: 10.54254/2755-2721/126/2025.20130

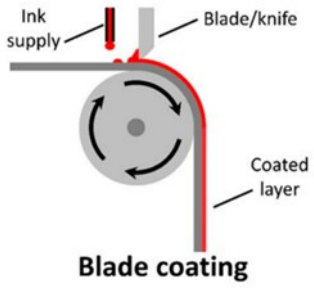


Figure 2: Basic schematic of blade coating process[1]

Gumpert et al. have developed theoretical models and computational fluid dynamics (CFD) simulations to predict wet film thickness and guide parameter optimization, reducing the need for extensive trial-and-error experiments during upscaling efforts with the following equation:

$$h(v,V) = (b + cV)v^{\frac{2}{3}} \quad (1)$$

Where h represents the wet film thickness in m, v is the coating velocity in m/s, V is the injected fluid volume in m^3, and b (in $m^{1/3}s^{-2/3}$)and c (in $m^{-8/3}s^{2/3}$) are fitting parameters with the unit of that depend on ink properties: density, viscosity, surface tension, and contact angles[2,3].

Blade coating is a versatile and efficient fabrication technique, particularly suitable for scalable production due to its compatibility with roll-to-roll (R2R) processing. While it is designed for uniform, large-area coatings rather than intricate patterns, it requires minimal ink preparation effort and generates little material waste compared to more wasteful methods such as spin coating. With a blade velocity up to 100 m/min, it supports moderate-to-fast processing, making it competitive with spray coating and screen printing, though it can be slower than high-speed slot-die coating. Blade coating accommodates a wide wet film thickness range from 0 to 100 microns, providing flexibility for various applications, but only works effectively with inks of very low viscosity (< 10 cP). This combination of scalability and material efficiency makes blade coating a strong choice for industrial applications, even though it may not achieve the pattern complexity or extremely high throughput of some alternatives[1].

3. Recent Advances in Blade Coating of OPVs

3.1. High-Efficiency Copolymer Donor

Shao et al. reported DP3 as a high-efficiency copolymer donor with its structure illustrated in Figure 3 below.

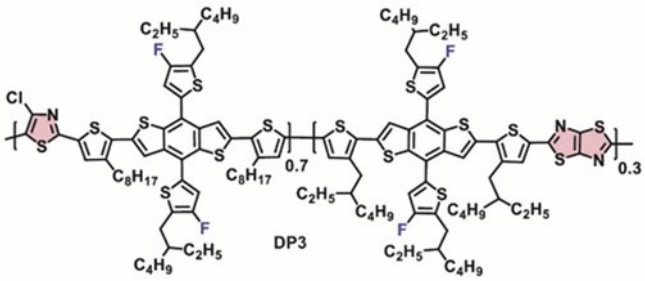


Figure 3: Structure of DP3[4]

The DP3:L8-BO system achieved a record power conversion efficiency (PCE) of 19.12% in small-area spin-coated devices(0.029 cm^2), while notably maintaining PCEs above 18% for blade-coated

DOI: 10.54254/2755-2721/126/2025.20130

devices across various number-average molecular weights of synthesized DP3 from 23.6 to 80.8 kDa, active layer thicknesses ranging from 95 to 308 nm, and blade coating velocitys spanning 3.0 to 29.1 m/min. These results showed that the DP3 does not only function well as a donor in spin-coated devices, but also is not sensitive with regards to multiple uncertainties present in supposedly blade coating manufacture process. Furthermore, DP3 exhibits significant potential on industrial scalability, delivering outstanding PCEs of 18.65% for a small-area device (0.029 cm^2) and 15.53% for a large-area module (15.40 cm^2) when processed with toluene, demonstrates the potential for achieving high efficiencies with scalable fabrication techniques[4].

3.2. Ternary Additives in Active Layer

Adding a ternary component to the active layer is a proven method for acquiring desired morphology of donor and acceptor materials. This technique encourages the facilitation of nanoscale interwoven domains that establish continuous pathways for charge movement and provide extensive interface areas for splitting excitons into separate charges. The inclusion of ternary additives fosters better molecular alignment in the active layer, which enhances charge mobility and reduces energy dissipation, ultimately improving OPV efficiency. Additionally, introducing a third element into the blend helps stabilize the charge transfer states, a key aspect for facilitating exciton splitting and efficient charge movement, minimizing charge recombination within the device. By integrating a variety of materials into the ternary blend, the absorption range is expanded, resulting in improved light capture and an increased short-circuit current density (Jsc)[5].

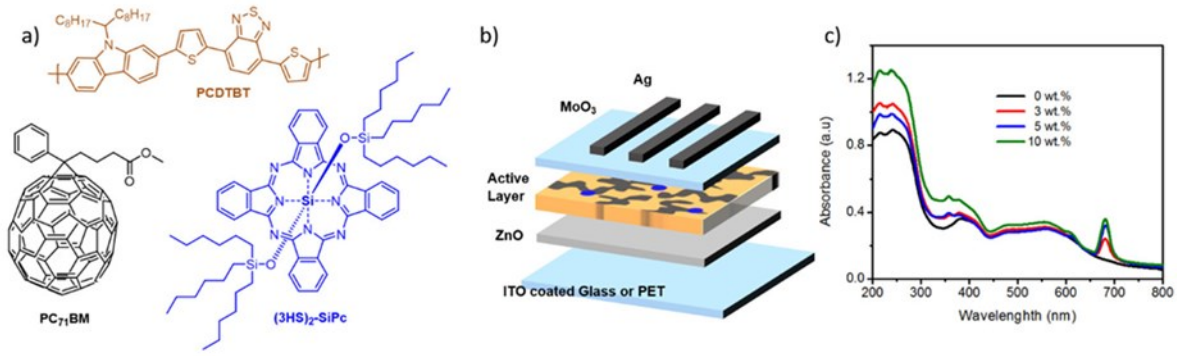


Figure 4: a) Chemical structures of PCDTBT, PC71BM, and bis(tri-n-hexylsilyl oxide) silicon phthalocyanine ($(3HS)_2$-SiPc) used in the active layer. b) Schematic of OPV (the inverted architecture). c) UV-Vis absorption spectra of PCDTBT:PC71BM binary film and ternary films with varying ($(3HS)_2$-SiPc concentrations[6]

Sundaresan et al. demonstrated an increase in the PCE of poly[[9-(1-octylnonyl)-9H-carbazole-2,7-diyl]-2,5-thiophenediyl-2,1,3-benzothiadiazole-4,7-diyl-2,5-thiophenediyl]: [6,6]-phenyl C71 butyric acid methyl ester (PCDTBT: PC71BM)-based OPVs, with its structure illustrated in Figure 4a). By incorporating in the active layer (Figure 4b)) bis(tri-hexylsiloxy) silicon phthalocyanine ((3HS)2-SiPc), a near-infrared (650-730 nm) absorbing ternary additive, the PCE increased from 4.6% to 5.4%, as shown in Figure 4c). This enhancement was achieved using a flexible ITO/PET substrate with a 1-cm^2 active area, highlighting the role of additives in optimizing film morphology and enhancing efficiency. The study also revealed that the optimal concentration of the ternary additive bis(tri-hexylsiloxy) silicon phthalocyanine ($(3HS)_2$-SiPc) depends on the processing method used for the active layer. For spin coating, a concentration of 5 wt% $(3HS)_2$-SiPc was sufficient to achieve the maximum PCE. However, for blade coating, raising the concentration to 10 wt% $(3HS)_2$-SiPc was necessary for achieving the maximum PCE. These findings underline the significant impact

DOI: 10.54254/2755-2721/126/2025.20130

of the processing technique on the additive requirements, providing valuable insights for optimizing both process conditions and device architecture to enhance performance [6].

3.3. Electrodes and Interlayers

All-printed OPVs, including the top electrode, are highly advantageous for enabling cost-efficient, high-throughput, and large-scale photovoltaic production by eliminating steps in energy-intensive physical vapor deposition. Liu et al. demonstrated the use of Field's metal (FM), a low-melting-point alloy (32.5% Bi, 51% In, 16.5% Sn), as a top electrode through blade coating with PCEs up to 17.28% [7]. Field's Metal (FM) offers multiple advantages as a low-melting-point alloy for optoelectronic applications: (1) Its low melting point of 62°C enables processing at moderate temperatures, avoiding damage to sensitive layers like the active material in devices; (2) FM can be applied using a cost-effective, scalable blade-coating process that requires significantly simpler and less expensive equipment compared to physical vapor deposition under vacuum; (3) FM electrodes exhibit strong adhesion to substrates, with detachment points for spin-coated electron transport layers (ETLs) measured at 295 kPa for PDINO and 306 kPa for PNDIT-F3N, significantly enhancing device durability and electrical performance; (4) With a work function of 3.78 eV, lower than silver's 4.26 eV, FM facilitates efficient charge extraction, and with its superior thermal and environmental stability, FM-coated devices showed 60% greater stability over time compared to silver-based devices, retaining over 60% of the initial PCE after 500 hours of thermal stress at 55°C; (5) Furthermore, FM is composed of non-toxic elements, making it a sustainable choice[7]. While there are discrepancies in the total light absorptions between Ag and FM devices, the differences are minimal, with absorption variations within 4% across UV, visible, and IR regions, ensuring FM remains highly efficient in its applications[7].

Employment of novel hole transport materials, such as phosphomolybdic acid (PMA) has further improved device efficiency and stability. When processed using blade coating, PMA-based devices achieved 17.79% PCE[7]. In particular, PMA-based devices demonstrated higher hole mobility of 2.79×10^{-4} cm²/Vs compared to 1.60×10^{-4} cm²/Vs for traditional PEDOT:PSS-based devices, which was crucial for enhancing the overall charge transport and minimizing recombination losses [8]. Transient photovoltage (TPV) measurements showed that PMA-based devices had a charge carrier lifetime of 2.734 μs, compared to 2.194 μs for traditional PEDOT:PSS-based devices, highlighting the importance of material choice in improving performance[8]. Additionally, an increase in JSC and FF was observed when MoO_x was replaced with PMA in inverted devices(11.78 mA/cm^2 vs 12.85 mA/cm^2, 5.67% vs 6.05%) even when fabricated using the blade coating process[8].

3.4. Nanoparticle Additives for Enhanced Morphology Control

Achieving optimal film morphology is one of the major challenges in blade coating OPVs. Phase separation, crystallinity, and molecular packing must be carefully controlled to ensure efficient charge transport and minimal recombination. Wang et al. have shown that manipulating the surface energy of the substrate by incorporating NiO nanoparticles into the commercial PEDOT:PSS hole transport layer, can help control the morphology of the active layer and improve device performance[9]. By adding NiO, the surface energy of PEDOT increased from 53.35 mN/m to 70.30 mN/m, leading to a significant improvement in PCE, with the blade-coated OPV cell (1.03 cm²) reaching a 18.70% (18.51% certified) PCE and the module(23.60 cm²) reaching 16.5% PCE[9]. However, achieving consistent morphology across large areas remains a significant hurdle, with variability often resulting in performance losses.

DOI: 10.54254/2755-2721/126/2025.20130

3.5. Accelerated Blade Coating for Film Uniformity

Scaling up OPVs from small-area laboratory devices to large-area modules presents challenges in maintaining uniformity and minimizing defects. Non-uniform film thickness, thickness gradients, and defects such as pinholes can significantly reduce device performance. Strategies such as accelerated blade coating have been developed by Basu et al. to maintain consistent thickness across large areas by gradually increasing the blade velocity to compensate for fluid loss during coating[3]. As seen in Figure 5, the wet film thickness decreases as the blade moves at a constant velocity towards the x-positive direction. Through modelling and simulation, an appropriate velocity scheme with the blade moving faster and faster towards the x-positive direction was developed and a more uniform film thickness profile was acquired as seen in Figure 6. The approach maintained film thickness deviations of less than 5% over an area of 204 cm² as seen in Figure 5, with a PCE of 14.5% [3]. This method also improves efficiency by minimizing the need for costly experimental iterations, as validated by simulations and theoretical predictions.

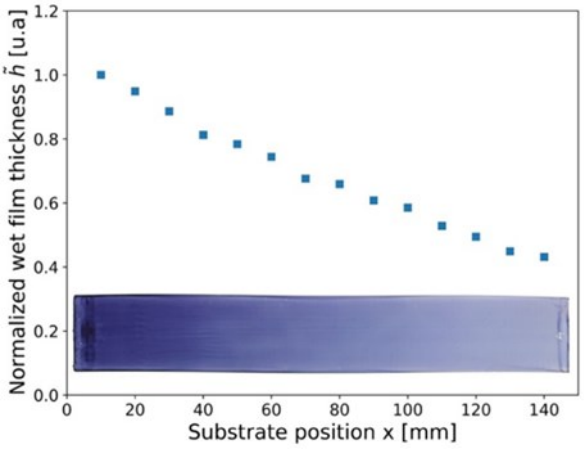


Figure 5: The normalized thickness profile of a P3HT:O-IDTBR film, fabricated via blade coating at a constant velocity of 80 mm/s over a coating distance of 15 cm with an initial volume of 60 µl, reveals a steady decrease in film thickness from left to right [3]

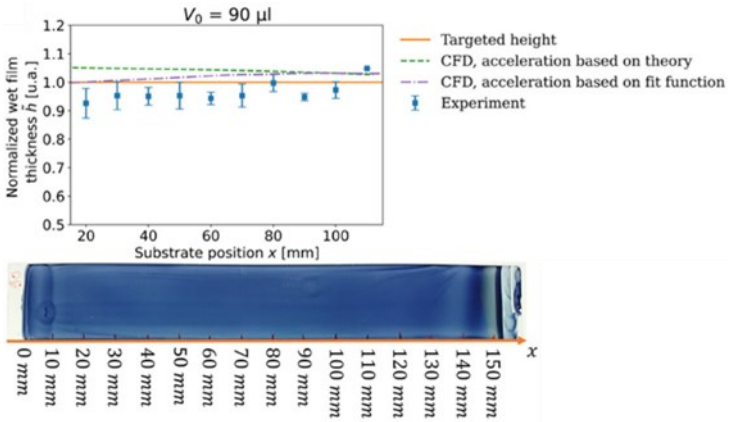


Figure 6: The normalized thickness profile of a P3HT:O-IDTBR film, fabricated via blade coating at an increasing velocity over a coating distance of 15 cm with an initial volume of 90µl, together with two CFD simulation results, reveals more uniformity in film thickness throughout the coated area[3]

DOI: 10.54254/2755-2721/126/2025.20130

3.6. Solvent and Solvent Additives

Devices fabricated with blade coating often face challenges related to trap-assisted recombination and reduced charge transport efficiency, particularly when processed under ambient conditions. The morphology of the film can be affected by solution characteristics, including suitable surface energy, viscosity, and boiling point. Hong et al. demonstrated that among isopropyl alcohol (IPA), methanol, and 1-butanol, as solvents for Bathocuproine (BCP) cathode interlayer, IPA resulted in the best performance, achieving a PCE of 14.0% for 1-cm^2 devices and 10.8% for 10-cm^2 modules, attributed to uniform morphology and reduced recombination[10]. Importantly, achieving 14% efficiency in 1-cm^2 OPVs, especially at a high-throughput blade velocity of 50 mm/s, showcased a viable alternative to spin coating.

The use of o-methylanisole (o-MA), a certified food additive, as a green solvent in combination with blade coating has demonstrated significant potential for sustainable organic photovoltaic (OPV) production. In a study conducted by Ye et al., o-MA was used as the processing solvent for PBDT-TSR-based OPVs, achieving a PCE of approximately 8.4% for devices fabricated in ambient air conditions—one of the highest PCEs reported for OPVs using a single green solvent. Calorimetric and morphological (hard/soft X-ray scattering) analyses revealed that o-MA produces domain spacing/purity and crystalline properties comparable to those acquired with traditional binary halogenated solvents, such as 1,8-diiodooctane and chlorobenzene. This similarity in morphology was further demonstrated in spin-coated films, yielding comparable photovoltaic performance to that of halogenated solvents. Additionally, o-MA's effectiveness extends to blade-coated OPVs processed in air, including all-polymeric devices such as PBDT-TS1:PPDIODT, which achieved a PCE of approximately 5.2%. These results highlight the capability of o-MA as a non-toxic, single-component solvent to produce OPVs with high PCE. The use of o-MA as the solvent, compatible with scalable roll-to-roll manufacturing, offers a commercially viable, environmentally friendly, and low-cost approach to OPV production. By replacing toxic halogenated solvents with o-MA, this technology not only mitigates health and environmental risks but also advances the development of greener, more sustainable solar cell technologies, underscoring the potential of non-hazardous solvents in industrial OPV manufacturing[11].

In addition, Schneider et al. demonstrated a solvent additive approach for polymer crystallinity control in blade-coated all-polymer OPVs, which provides critical insights into enhancing the scalability of OPV production. They showed that the addition of phthalates as trace-amount solvent additives helped regulate polymer crystallization and reduce undesirable phase separation in PTB7-Th/P(NDI2OD-2T) all-polymer systems. This approach improved device performance significantly, with PCE increasing from 2.09% to 4.50%, effectively mitigating performance losses associated with transitioning from spin-coating to blade-coating. Real-time X-ray diffraction data indicated that the phthalate additives act as compatibilizers, suppressing the separation of donor and acceptor polymers during film formation, resulting in more favorable morphology and improved performance. This method holds promise for implementing other all-polymer systems to scalable, high-efficiency, printed OPVs[12].

3.7. Process and Molecular Engineering

Innovative process modifications and molecular engineering have proven effective in overcoming the challenges associated with blade-coating organic photovoltaic devices. For example, Won et al. has shown that blade coating at only 40°C can improve film morphology, reduce root-mean-square roughness values to 0.690–0.899 nm and achieve PCEs of 16.43% for small-area devices and 14.95% for large-area devices using BTP-eC9-γ in nonhalogenated toluene solvent[13]. This contrasts with the 80°C required for BTP-eC9 to achieve similar efficiencies(16.14%), underscoring the benefits of

DOI: 10.54254/2755-2721/126/2025.20130

reducing thermal energy consumption[13]. The γ-position branched inner side chains of BTP-eC9-γ enhance solubility and reduce aggregation during film formation, improving reproducibility and supporting efficient charge transport networks[13]. These advancements highlight the synergy between process optimization and material engineering, addressing scalability and stability challenges in industrial applications.

4. Conclusion

Blade coating has emerged as a transformative technique for the scalable production of organic photovoltaics (OPVs), offering a pathway to address many of the challenges that have hindered their industrial viability. Recent advancements in materials and processing methods have demonstrated the immense potential of OPVs as a sustainable energy solution. For instance, the development of high-efficiency copolymer donors like DP3 showcases how innovative material design can enhance performance while maintaining scalability. Similarly, the incorporation of ternary additives as a component of the active layer has improved film morphology and charge transport, creating more efficient pathways for energy conversion and boosting device performance. Equally transformative are advances in electrode and interlayer materials, such as Field's Metal (FM) and phosphomolybdic acid (PMA), which have significantly enhanced both device stability and operational efficiency. These materials offer robust solutions for long-term performance, addressing a critical need in the commercialization of OPVs. To complement these innovations, nanoparticle-modified interlayers have enabled precise control over film morphology, ensuring uniformity across large-area modules—an essential factor for industrial scalability. Further improvements in processing techniques, such as accelerated blade coating, have tackled challenges related to film consistency, reducing variability and ensuring high-quality coatings over large areas. Sustainability has also taken center stage, with the introduction of green solvents like o-methyl anisole providing an eco-friendly alternative that maintains efficiency while addressing environmental concerns. Process and molecular engineering innovations, including optimized thermal and solvent systems, have enhanced reproducibility and scalability, bringing OPVs closer to widespread commercial adoption.

However, despite these advancements, critical challenges remain. Achieving precise morphology control, ensuring scalability, and improving device stability are essential to fully unlock the potential of blade-coated OPVs for industrial-scale production. Addressing these challenges will require a concerted effort in research and development. The focus should be on designing novel materials with high solubility, low aggregation, and controlled crystallinity, tailored specifically for the blade coating process. Simultaneously, optimizing key coating parameters, such as surface temperature, blade velocity, and solvent composition, as well as incorporating advanced techniques like in-situ annealing and solvent blending, will be crucial for enhancing PCE and overall device performance. With continued innovation and collaboration, blade coating stands poised to play an essential role in the future of OPVs, transforming them into a cost-effective, high-performance, and environmentally sustainable energy technology.

References

[1] *Kirk B P, Bjuggren J M, Andersson G G, Dastoor P and Andersson M R 2024 Printing and Coating Techniques for Scalable Organic Photovoltaic Fabrication Materials 17 2511*

[2] *Gumpert F, Janßen A, Brabec C J, Egelhaaf H-J, Lohbreier J and Distler A 2023 Predicting layer thicknesses by numerical simulation for meniscus-guided coating of organic photovoltaics Eng. Appl. Comput. Fluid Mech. 17 2242455*

[3] *Gumpert F, Janßen A, Basu R, Brabec C J, Egelhaaf H-J, Lohbreier J and Distler A 2024 On the theoretical framework for meniscus-guided manufacturing of large-area OPV modules Prog. Org. Coat. 192 108505*

[4] *Shao Y, Gao Y, Sun R, Yang X, Zhang M, Liu S and Min J 2024 A High-Performance Organic Photovoltaic System with Versatile Solution Processability Adv. Mater. 36 2406329*

DOI: 10.54254/2755-2721/126/2025.20130

[5] Wang M 2024 Significant improvement of organic solar cells with ternary additives Front. Phys. 12 1503644
[6] Sundaresan C Silicon Phthalocyanines in Large Area, Flexible Organic Photovoltaics processed by Blade Coating
[7] Liu L, Yu B, Kang L, Deng W and Zhao X 2023 Blade Coating of Alloy as Top Electrodes for Efficient All-Printed Organic Photovoltaics Adv. Funct. Mater. 33 2214781
[8] Li Z, Huang H, Zeng X, Deng B, Li C, Gao C, Zhang G, Li S and Xie C 2024 A universal hole transport layer for efficient organic solar cells processed by blade coating Org. Electron. 133 107104
[9] Wang J, Wang Y, Du M, Yu Y, Wang C, Wang W, Guo Q, Cui Y, Zhang S and Hou J 2024 Interlayer surface energy control for high-efficiency printed organic photovoltaic cells Energy Environ. Sci. 17 8368–78
[10] Hong S, Park B, Balamurugan C, Lee J and Kwon S 2023 Impact of solvents on doctor blade coatings and bathocuproine cathode interlayer for large-area organic solar cell modules Heliyon 9 e18209
[11] Ye L, Xiong Y, Yao H, Gadisa A, Zhang H, Li S, Ghasemi M, Balar N, Hunt A, O'Connor B T, Hou J and Ade H 2016 High Performance Organic Solar Cells Processed by Blade Coating in Air from a Benign Food Additive Solution Chem. Mater. 28 7451–8
[12] Schneider S A, Gu K L, Yan H, Abdelsamie M, Bao Z and Toney M F 2021 Controlling Polymer Morphology in Blade-Coated All-Polymer Solar Cells Chem. Mater. 33 5951–61
[13] Won D, Kang S, Park J, Park J, Kim W, Mai T L H, Lee S and Yang C 2024 Low-Temperature Processed Efficient and Reproducible Blade-Coating Organic Photovoltaic Devices with γ -Position Branched Inner Side Chains-Containing Nonfullerene Acceptor Small Sci. 4 2400034