Transactions on Environment, Energy and Earth Sciences
ISSN: 2960-1924, eISSN: 2960-2300 | Volume 6
GEMFE 2026

# Advanced Nanomaterials in Organic Photovoltaics

Zhuoyu Huang
Department of Material Science and Engineering, Northeastern University, Shenyang, Liaoning, 110000, China
huangzhuoyu@hznu-edu.cn

**Abstract.** Organic photovoltaics (OPVs) have emerged as a sustainable alternative for electrical energy generation. The integration of nanomaterials has been instrumental in advancing the performance and functionality of OPVs, marking a significant evolution in solar energy technologies. This review aims to analyze the fundamental occupation of nanomaterials in the OPV process and give clarified categories with comprehensive function, and the potential risks in future development are pointed out as well. This review also discusses the basic OPV process, the role of nanomaterials in OPV, the specific nanomaterials of organic and inorganic with their distinguished function, the fabrication of nanomaterials in OPV, and possible difficulties in the nanomaterial's development. By comparing various types of nanomaterials, the review aims to demonstrate that all nanomaterials under consideration perform effectively in enhancing the capabilities of organic solar cells. Furthermore, it will be shown that the development of these nanomaterial composites comes with both distinct advantages and limitations. In conclusion, nanomaterials have a great capability of competing with other materials, they can better improve the power conversion efficiency in OPV, and the environmental effects are also enhanced.

**Keywords:** Organic Photovoltaics; Nanomaterials; Nanocomposites.

## 1. Introduction

As an important energy technology in both academic and industrial fields, OPV has been widely concentrated by optical developers. Having a comprehensive acknowledgment of the principle of OPV is of great benefit to make innovation in the development of novel nanomaterials for enhancing the power conversion efficiency of solar cells. The basic OPV process follows the following steps: photon absorption in the solar panels, exciton diffusion in the mixture of donor and acceptor, charge separation, and charge transportation.

Material science plays a fundamental role in the development of OPV materials. A previous study shows the changing progress of material choices [1]: silicon, organic, and perovskite solar cells, and solar cells representative of perovskite solar cells show the highest power conversion efficiency and excellent optoelectronic properties. However, a universally acknowledged truth is that opposing polymers and perovskite, it is more convenient for people to clarify, characterize, and manufacture a small molecule in the current technical situation. The apparent advantages of nanoparticle organic solar cells are demonstrated here: the initial part is the increasing surface area of the donor and acceptor for exciton diffusion. Furthermore, the mixture of nano-domains network of donor and acceptor forms a charge percolation pathway for electrons and holes moving to the anode and cathode respectively [2]. Both points provide a superior condition for the power conversion efficiency of OPV.

The review aims to discuss the progress of organic solar cells based on OPV, with a specific focus on nanomaterial-based solar cells. The review will delve into the historical research, current state of performance and application, and potential challenges in the future.

## 2. The Role of Nanomaterials in OPV

Nanomaterials are increasingly recognized for their unique and superior properties in OPV. These materials are particularly valued for their effective quantum effects, expansive surface areas, and enhanced electrical characteristics. A recent study elucidates that quantum effects enable nano-transistors to exhibit higher electrical properties and reduced energy consumption [3]. Despite the primary quantum effect, quantum interference, currently being limited to superconducting devices, it holds significant potential for breakthroughs across various unexplored nanomaterials. Additionally, the considerable surface area of nanomaterials plays a crucial role in boosting the power conversion efficiency of OPVs. The diminutive size of these particles substantially increases the surface area, offering enhanced opportunities for donor and acceptor interactions and facilitating exciton diffusion—a vital improvement for the OPV process. The roll-to-roll manufacturing process for OPVs underscores the rising demand for solar inks. Historically dominated by harmful chlorinated solvents like chloroform, chlorobenzene, and dichlorobenzene, the adoption of nanomaterials has shifted the paradigm towards water-based solar inks, now prevalent in contemporary roll-to-roll processes [2].

This review explores several nanomaterials commonly utilized in OPVs, including nanoparticles, nanorods, and quantum dots, discussing their performance, advantages, and challenges. Nanoparticles are prominently featured in semi-transparent solar cells, integral to building-integrated photovoltaic (BIPV) systems. However, the use of semi-transparent organic solar cells generally reduces system efficiency compared to inorganic cells [4]. Innovations like employing nano silver particles as transparent electrodes have been developed to ameliorate this efficiency gap. Nanorods, serving as alternatives to conventional hole transport layers like PEDOT [5]: PSS known for their low stability, have been shown to improve stability and photoelectric conversion efficiency. Recent advancements include $MoO_x$ nanorods and zinc oxide nanorods for electron transport layers, which have demonstrated superior electrical performance and a notable increase in energy conversion efficiency to 7.86% [6]. Quantum dots, classified under advanced nanomaterials in OPVs, exhibit distinct electronic properties due to quantum confinement effects. These properties make them suitable for broadening the absorption spectrum and enhancing charge separation and transport in OPV devices. Notably, Carbon quantum dots (CDs) have been effectively utilized in various components of OPVs, replacing traditional materials like PEDOT: PSS in the hole transport layer and serving as electron acceptors in active layers [7]. CDs also improve optical absorption behaviors when used as surface modifiers of ZnO.

## 3. Advancement in OPV Materials Featuring Nanomaterials

### 3.1. Nanoparticle-enhanced Active Layers

The enhancement of photoactive layers through the incorporation of nanoparticles has been substantiated by various studies, particularly noting the impact of surface plasmonic resonance (SPR) generated by these nanoparticles. This phenomenon enhances the optical electric field within the photoactive layer, leading to increased light absorption. Specifically, nano-films made from gold or silver can amplify photoconversion at coherent wavelengths due to their SPR properties [8]. In a notable study, Ali et al. demonstrated a method to boost OPV efficiency by integrating silver nanoparticles (AgNPs) coated with PEDOT: PSS into the photoconductor transport layer [9]. This approach capitalizes on the increased electrical conductivity and light absorption afforded by the AgNPs. Conversely, another study presented a critique of the efficiency improvements attributable to silver nanoparticles, suggesting that such enhancements are not readily observable. Instead, they propose an alternative strategy that employs gold nanoparticles combined with polymers to create a reflective layer. This method leverages both the plasmonic effects of gold nanoparticles and light scattering to optimize energy conversion efficiency in OPVs. This dual approach not only harnesses the intrinsic properties of gold for plasmonic enhancement but also uses its scattering effects to further elevate the performance of organic solar cells [10].

Nanoparticles, specifically those made from semiconductors, play a pivotal role in solar cell technology by forming compact and uniform layers that facilitate efficient electron transport. A notable contribution by Stefania Zappia et al. highlights the use of semiconductor nanoparticles, constituting 5% of the electrical acceptor mixture, which uniquely requires no additional surfactants. This formulation enhances the environmental sustainability and manufacturing efficiency of solar cell devices due to their stable suspension properties [11].

Further advancing the field, another study demonstrates the innovative use of p-SnS/n-ZnS heterojunction nanowires within the active layer of solar cells. This approach is complemented by the incorporation of novel silver nanoparticles serving as electrodes, showcasing exemplary photovoltaic performance [12]. This configuration not only enhances the electrical properties but also leverages the unique optical characteristics of silver nanoparticles, contributing significantly to the overall efficiency and functionality of the solar cells [12].

### 3.2. Nanocomposites as electron or hole transport layers

A huge number of conductive nanomaterials are used on electron or hole transport layers, which are based on the photon absorption caused by surface plasmonic resonance in the active layers of organic solar cells. A recent study shows that the Au-$WO_3$ can be used as hole transport layers gets a superior current density in HTL, and finally acquires high power conversion efficiency [13]. The nanocomposites used on electron or hole transport layers can effectively enhance charge mobility and device efficiency, and it always happens with the mixture of inorganic composites and fullerene as the fabrication of nanocomposites on perovskite-based solar cells. hybrid organic-inorganic layers offer a versatile and effective approach to improving interface quality and overall device stability in various electronic and optoelectronic devices. Their unique combination of organic and inorganic properties can lead to enhanced performance, durability, and reliability, making them a promising solution for next-generation technologies. An investigation reveals that one type of fullerene capped P3HT Dyad, which is the nanocomposites in OPV, has the great ability to prompt the production of photovoltaic charge and subsequent migration to electrodes [14]. Hybrid organic-inorganic layers play a crucial role in improving interface quality and overall device stability in various applications.

### 3.3. Quantum Dots in OPV

Quantum dots offer tunable absorption spectra through their unique size-dependent electronic structure. The absorption spectra of quantum dots can be tuned by controlling their size, shape, and composition. This tunability arises from the quantum confinement effect, where the energy levels of electrons and holes are quantized due to the confinement of charge carriers within the nanoscale dimensions of the quantum dot. Quantum dot-sensitized solar cells have gained attention for their potential to enhance the performance of OPV devices using quantum dot-sensitized layers. These layers can improve light absorption, charge separation, and overall efficiency of the solar cells. This study investigated the incorporation of quantum dot-sensitized layers in organic photovoltaic devices to enhance their efficiency. In an essay, graphene QDs can be used in the hole transport layers and perform uniform sizes and excellent capability of stability, which leads to a more reproducible nanomaterial and better substitution for traditional materials [15].

## 4. Nanostructuring techniques for OPV Fabrication

The top-down and bottom-up are two methods that are used in the fabrication of nanomaterials in the OPV process. Specifically, the former means the reduction of the material size to make the structure achieve a level of nano, while the latter is to form a relatively larger molecule structure that originates from a small atom or molecule [16]. In terms of the top-down approach, although this method is relatively convenient for researchers to apply, the dilemma of obtaining a proper shape and size has become the controversial issue of such a method; however, the bottom-up approach can make completely personal nanomaterials through the combination of small atoms or molecules [17]. These two methods have advantages separately. By controlling the morphology and structure of nanomaterials, the light absorption capability of the photovoltaic device led by the top-down approach can be adjusted to enhance the photoelectric conversion efficiency; as the bottom-up approach, it can synthesize and assemble nanomaterials, and the structure and interface properties of the device can be controlled to improve the stability and reliability of the photovoltaic device. By optimizing the band structure and charging transport properties of nanomaterials, both methods can enhance the photoelectric conversion efficiency of the photovoltaic device.

Self-assembly and templating are two powerful strategies used in the field of OPV to create well-ordered nanostructures, which are crucial for achieving high efficiency in converting sunlight into electricity. Self-assembly is a process where molecules spontaneously organize themselves into well-defined structures without external intervention. In the context of OPV, self-assembly can be used to create ordered arrangements of donor and acceptor molecules, which are essential for efficient charge separation and transport. By carefully designing the molecular structures and interactions, researchers can promote self-assembly to form well-defined nanostructures such as bulk heterojunctions, where the donor and acceptor materials are intimately mixed at the nanoscale. This controlled organization enhances the efficiency of charge generation and collection in OPV. Templating involves using a pre-existing template or scaffold to guide the organization of materials into a desired structure. In OPV, templating can be achieved by using various techniques such as nanoimprinting, soft lithography, or self-assembly. By choosing an appropriate template with the desired morphology, researchers can control the arrangement of donor and acceptor materials at the nanoscale, leading to improved device performance. Templating can also help in achieving uniformity and reproducibility in the fabrication of OPV by providing a well-defined starting point for the nanostructure formation.

Both self-assembly and templating offer unique advantages in creating well-ordered nanostructures within OPV. Self-assembly is a bottom-up approach that relies on the inherent properties of the molecules to organize themselves, offering simplicity and cost-effectiveness in fabrication. On the other hand, templating provides a top-down approach that allows for precise control over the nanostructure morphology, enabling the design of complex and tailored structures for enhanced device performance.

## 5. Challenges and Future Perspectives

Although the nanomaterial technology brings enormous convenience and superior performance in OPV devices, researchers still meet severe difficulties and inevitable challenges in the synthesis and integration process of nanomaterials in OPV, which is because of the complicated nature of both the nanomaterials and device structure.

Nanomaterials often have different chemical and physical properties compared to traditional organic semiconductors used in OPVs. Ensuring compatibility between the nanomaterials and other components of the device, such as electrodes and interfacial layers, is crucial for achieving efficient charge transport and collection; Nanomaterials can be susceptible to degradation under the harsh operating conditions of OPV devices, such as exposure to light, heat, and moisture. Ensuring the stability of nanomaterials over the lifetime of the device is essential for long-term performance and reliability. Some nanomaterials may need an overall high expense to proceed with the synthesis process, which could raise the whole cost of OPV devices to an expensive level. Under the circumstances that the performance of devices has been assured in a perfect criterion, Finding cost-effective synthesis methods and integration strategies for nanomaterials without compromising device performance is a key challenge in the field.

## 6. Conclusion

Nanomaterials have played a transformative role in OPV, such as quantum dots, nanowires, and nanoparticles, and have been utilized in OPV to improve light absorption, charge separation, and charge transport. By engineering the size, shape, and composition of these nanomaterials, researchers have been able to tailor their optical and electronic properties to optimize energy conversion efficiency in OPV. For example, incorporating nanostructured materials in the active layer of OPV can increase the surface area available for light absorption, leading to improved power conversion efficiency. One of the major challenges in OPV technology has been the stability of the devices over time, particularly when exposed to environmental factors such as moisture, oxygen, and light. Nanomaterials have been employed to enhance the stability of OPV by providing protective barriers, improving interfacial adhesion, and reducing degradation processes. For instance, encapsulating OPV with nanomaterial-based coatings can shield the active layers from harmful environmental conditions, thereby extending the device's lifetime. The advancements in efficiency and stability brought about by nanomaterials have propelled OPV technology toward commercial viability. However, the potential for nanomaterials to continue driving innovation in OPV development remains significant.

In conclusion, nanomaterials have been instrumental in advancing the efficiency and stability of OPV, and their continued integration and innovation hold great promise for the future development of this technology. By leveraging the unique properties of nanomaterials, researchers can further enhance the performance, durability, and versatility of OPV, paving the way for the widespread adoption of this renewable energy technology.

## References


[1] Machín A, Márquez F. Advancements in Photovoltaic Cell Materials: Silicon, Organic, and Perovskite Solar Cells. Materials, 2024, 17 (5): 1165.

[2] Holmes N P, Marks M, Kumar P, et al. Nano-pathways: Bridging the divide between water-processable nanoparticulate and bulk heterojunction organic photovoltaics. Nano Energy, 2016, 19: 495-510.

[3] Chen Z, Grace I M, Woltering S L, et al. Quantum interference enhances the performance of single-molecule transistors. Nature Nanotechnology, 2024: 1-7.

[4] Ong G L, Ong T S, Yap S L, et al. A brief review of nanoparticles doped PEDOT: PSS nanocomposite for OLED and OPV. Nanotechnology Reviews, 2022, 11 (1): 1870-1889.

[5] Ahn J H, Ahn J S, Jang M J, et al. Enhanced organic photovoltaic cells with MoOx nanorods as a hole transfer layer. Molecular Crystals and Liquid Crystals, 2017, 654 (1): 17-21.

[6] Kim J, Nasir S N F M, Teridi M A M, et al. Zinc oxide nanorod doped graphene for high efficiency organic photovoltaic devices. RSC advances, 2016, 6 (90): 87319-87324.

[7] Vercelli B. The role of carbon quantum dots in organic photovoltaics: a short overview. Coatings, 2021, 11 (2): 232.

[8] Ali A M, Said D A, Khayyat M, et al. Improving the efficiency of the organic solar cell (CuPc/C60) via PEDOT: PSS as a photoconductor layer doped by silver nanoparticles. Results in Physics, 2020, 16: 102819.

[9] Morfa A J, Rowlen K L, Reilly T H, et al. Plasmon-enhanced solar energy conversion in organic bulk heterojunction photovoltaics. Applied Physics Letters, 2008, 92 (1).

[10] Lim S J, Kim D U, Song J H, et al. Enhanced performance of semi-transparent OPV with nanoparticle reflectors. Organic Electronics, 2018, 59: 314-318.

[11] Zappia S, Scavia G, Ferretti A M, et al. Water-Processable Amphiphilic Low Band Gap Block Copolymer: Fullerene Blend Nanoparticles as Alternative Sustainable Approach for Organic Solar Cells. Advanced Sustainable Systems, 2018, 2 (3): 1700155.

[12] Wang G, Meng X. A high-performance broadband photodetector with p-SnS/n-ZnS heterojunction nanowires as active layer and novel nanoparticle-anchored silver nanowires as efficient plasmonic electrodes. Journal of Materials Science: Materials in Electronics, 2022, 33 (8): 5380-5395.

[13] Lee Y H, Kim D H, Kim T W. Enhanced power conversion efficiency of organic photovoltaic devices due to the surface plasmonic resonance effect generated utilizing Au-WO3 nanocomposites. Organic Electronics, 2017, 45: 256-262.

[14] Kamkar D A, Wang M, Wudl F, et al. Single nanowire OPV properties of a fullerene capped P3HT dyad investigated using conductive and photoconductive AFM. ACS nano, 2012, 6 (2): 1149-1157.

[15] Li M, Ni W, Kan B, et al. Graphene quantum dots as the hole transport layer material for high-performance organic solar cells. Physical Chemistry Chemical Physics, 2013, 15 (43): 18973-18978.

[16] Christian P, Von der Kammer F, Baalousha M, et al. Nanoparticles: structure, properties, preparation and behaviour in environmental media. Ecotoxicology, 2008, 17: 326-343.

[17] Abid N, Khan A M, Shujait S, et al. Synthesis of nanomaterials using various top-down and bottom-up approaches, influencing factors, advantages, and disadvantages: A review. Advances in Colloid and Interface Science, 2022, 300: 102597.