

ARTICLE REVIEW: ORGANIC SOLAR CELL

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Abstract. One of the emerging technologies that has gained attention as an alternative for meeting renewable energy demands is the Organic Solar Cell (OSC). OSC is a type of photovoltaic device that utilizes organic electronic materials. The fundamental operating principle of OSC is based on the Highest Occupied Molecular Orbital (HOMO) and the Lowest Unoccupied Molecular Orbital (LUMO), with organic compounds serving as the active materials, enabling the conversion of light energy into electricity. Research on OSC has continuously evolved over the years to achieve optimal performance. The substrate/transport layer, which serves as the foundation for the organic active layer in OSC, can be categorized into several types, including ITO-based OSC, conducting polymer-based OSC, silver nanowire-based OSC, metal-based OSC, and graphene-based OSC. Organic solar cells offer several promising prospects, such as relatively low production costs, as well as flexible and transparent design features. However, OSCs also face several challenges, including relatively low efficiency and environmental stability concerns. Addressing these challenges is crucial to unlocking the full potential of OSC technology. This article first provides a general overview of OSC advancements, followed by a summary and analysis of its working principles, performance parameters, and structural components. Finally, we explore recent breakthroughs in OSC development in detail.

Keywords: Conducting Polymer-based, Graphene-based, ITO-based, Metal grid-based, Organic Solar Cell (OSC), Silver Nanowire-based

Abstrak. Salah satu teknologi baru yang menarik perhatian sebagai alternatif untuk memenuhi kebutuhan energi terbarukan adalah Sel Surya Organik (OSC). OSC merupakan salah satu jenis perangkat fotovoltaik yang memanfaatkan material elektronik organik. Prinsip dasar OSC didasarkan pada Orbital Molekul Terisi Tertinggi (HOMO) dan Orbital Molekul Terisi Terendah (LUMO), dengan senyawa organik sebagai material aktif yang memungkinkan konversi energi cahaya menjadi listrik. Penelitian tentang OSC terus berkembang selama bertahun-tahun untuk mencapai kinerja optimal. Lapisan substrat/transportasi, yang berfungsi sebagai fondasi bagi lapisan aktif organik dalam OSC, dapat dikategorikan menjadi beberapa jenis, termasuk OSC berbasis ITO, OSC berbasis polimer konduktor, OSC berbasis nanowire perak, OSC berbasis logam, dan OSC berbasis grafena. Sel surya organik menawarkan

beberapa prospek yang menjanjikan, seperti biaya produksi yang relatif rendah, serta fitur desain yang fleksibel dan transparan. Namun, OSC juga menghadapi beberapa tantangan, termasuk efisiensi yang relatif rendah dan masalah stabilitas lingkungan. Mengatasi tantangan-tantangan ini sangat penting untuk memaksimalkan potensi teknologi OSC. Artikel ini pertama-tama memberikan gambaran umum tentang kemajuan OSC, diikuti dengan ringkasan dan analisis prinsip kerja, parameter kinerja, dan komponen strukturalnya. Terakhir, kami akan membahas terobosan terbaru dalam pengembangan OSC secara mendetail.

Kata kunci: Polimer Berbasis Konduktif, Berbasis Grafena, Berbasis ITO, Berbasis Kisi Logam, Sel Surya Organik (OSC), Berbasis Kawat Nano Perak

1. Introduction

One of the renewable energy sources with significant potential to meet energy demands is solar energy. In recent years, solar energy has been utilized as a source for various technologies, including photovoltaics (PV), solar heating, artificial photosynthesis, water splitting, and solar architecture [1]. In the 21st century, as living standards and advancements in science and technology continue to rise, energy dependence and consumption have also increased. The depletion of traditional fossil fuels poses a major challenge. Additionally, the combustion of fossil fuels generates large amounts of harmful gases and environmental pollution. Given this situation, researchers have actively pursued the development of renewable energy sources, such as wind energy, hydropower, and solar energy. The major advantage of renewable energy is its sustainability, widespread availability, and relatively low cost. Among these renewable energy sources, solar energy stands out as one of the most promising alternatives [2].

Solar energy is a naturally renewable resource that is virtually inexhaustible and produces little to no waste [3]. It plays a crucial role in the renewable energy sector, prompting extensive research and investment to improve solar cell efficiency [4]. Solar cells have emerged as a key technology in the future development and utilization of energy [5]. In 1954, silicon-based solar cells were recognized as a breakthrough in future energy development, offering an effective solution to reduce fossil fuel pollution. Based on material composition, solar cells can be classified into inorganic and organic solar cells [6]. While inorganic solar cells were developed earlier, their large-scale application is hindered by high costs and complex production technologies [7]. In contrast, organic solar cells (OSCs) offer several advantages, including low-cost fabrication through solution processing and compatibility with roll-to-roll printing methods, which enable large-area production at relatively low temperatures, OSCs are also lightweight, flexible, and mechanically robust, making them suitable for integration into wearable devices and building-integrated photovoltaics [8].

As the name suggests, OSCs consist of organic materials as their primary components, mainly utilizing photosensitive organic compounds as electrical conductors to generate voltage and current through the photovoltaic effect. This enables the conversion of solar energy into electrical energy. Over time, OSC technology has continued to evolve, with significant breakthroughs paving the way for promising commercial applications.

2. Research Methods

In this study, the authors employed the literature review method. A literature review is a data and information collection method that involves gathering relevant sources such as empirical journals, review journals, and books related to the research topic. This approach was conducted by searching, reading, identifying, and compiling all discussions related to the transformation of organic solar cells, covering aspects such as fabrication processes, structural characteristics, and the advantages and disadvantages of each transformation technology.

3. Result and Discussion

3.1 Physical Quantities

Several physical quantities can influence the external quantum efficiency of Organic Solar Cells (OSCs), including:

3.1.1 Energy Gap

The energy gap, or band gap, refers to the difference between the top of the valence band (E_v) and the bottom of the conduction band (E_c). It represents the minimum energy required to excite an electron from the valence band to the conduction band. Based on electron occupancy, energy bands are classified into two types: the valence band and the conduction band. The valence band is fully occupied by electrons and serves as the region where electron transitions to the conduction band occur. In contrast, the conduction band contains a small number of electrons with sufficient energy to move within the material [9].

3.1.2 Interfacial Layer Structure

The structure of the interfacial layer significantly affects the efficiency of OSCs. The interfacial layer in organic solar cells consists of several different layers, including the donor layer, acceptor layer, and buffer layer. The influence of the interfacial layer structure on OSC efficiency can be analyzed from several aspects:

1. **Buffer Layer:** A buffer layer, such as calcium deposited between the active layer and the aluminum (Al) electrode, acts as a support layer that can enhance solar cell efficiency by 5–10%. Calcium buffer layers help reduce recombination and improve charge transfer, thereby increasing solar cell efficiency [10].
2. **Donor and Acceptor Layers:** The appropriate selection of donor and acceptor materials can improve solar cell efficiency. For example, using poly-3-hexylthiophene (P3HT) as the donor material and phenyl-C61-butyric acid methyl ester (PC61BM) as the acceptor has been shown to increase efficiency by up to 3.79%. Choosing the right donor and acceptor materials enhances the material's ability to convert light energy into electrical energy [11].
3. **Supporting Layer:** Supporting layers, such as buffer layers, help reduce recombination and enhance effective charge transfer, leading to improved solar cell efficiency. These layers also minimize resistance and optimize the material's ability to convert light energy into electricity [12].

In summary, the proper structuring of the interfacial layer can enhance OSC efficiency by reducing recombination, improving charge transfer efficiency, and minimizing resistance.

3.1.3 Electrode

The electrode plays a crucial role in OSC efficiency, as it serves as the site where electrical charges are generated and transmitted. The use of appropriate electrodes can improve solar cell efficiency by minimizing resistance and enhancing charge transfer. Research has shown that TiO₂ electrodes, used as dye-sensitized solar cells, exhibit higher efficiency compared to other electrode materials. TiO₂/graphite electrodes combined with a PCBM:P3HT mixture have demonstrated the highest efficiency when using zinc electrodes.

The choice of electrode material also influences OSC performance in solar window applications. When fabricating solar windows, the thickness of the working electrode layer must be carefully controlled, as it directly affects the efficiency of dye-sensitized solar cells (DSSCs). DSSCs operate as photoelectrochemical cells, where electron movement results from the combined effects of photon energy and chemical reactions [13]. Studies on the thickness variation of transparent TiO₂ working electrodes have shown a significant impact on DSSC performance in solar window applications.

In summary, the selection of suitable electrodes is essential for enhancing OSC efficiency by reducing resistance and optimizing charge transfer. Proper electrode selection ensures optimal performance in OSC applications.

3.1.4 Film Morphology Influence

The presence of cavities and rough surfaces in thin films can increase circuit resistance, potentially leading to short circuits. Figure 1 shows the SEM characterization results related to the morphology of two different materials [14].

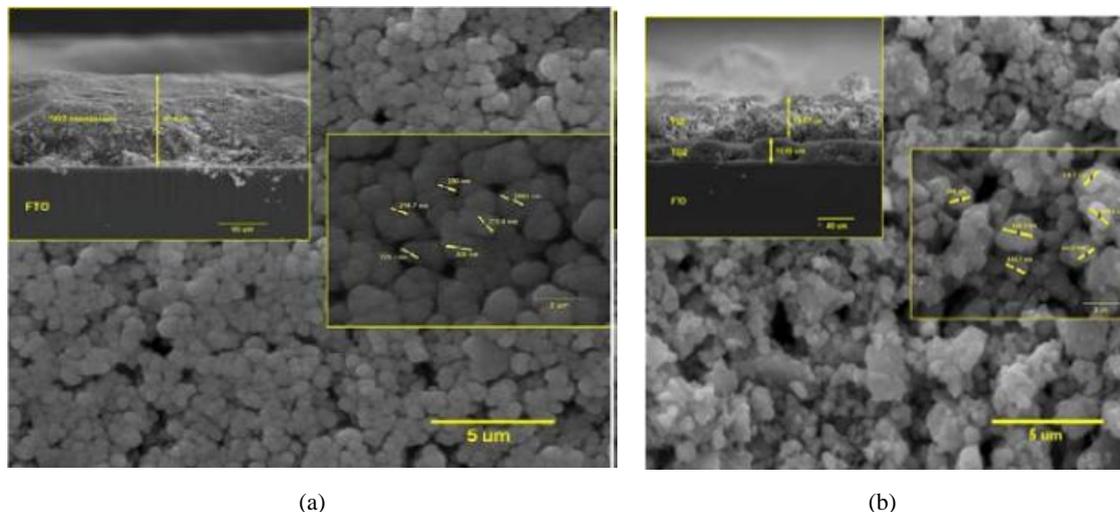


Figure 1. SEM Morphology of (a) Nanoporous TiO₂ Film and (b) Nanoporous TiO₂/YSZ Film

3.1.5 Temperature and Humidity

Temperature and humidity significantly affect the efficiency of OSCs. These environmental factors alter the characteristics of the semiconductor materials used in solar cell fabrication. Temperature can influence OSC efficiency by modifying the semiconductor's energy gap. A larger energy gap reduces efficiency, as more energy is required to activate electronic transitions. Conversely, lower temperatures can enhance OSC efficiency by reducing resistance and improving charge transfer effectiveness [15].

Given the various physical quantities discussed above and the wide range of materials that can be utilized, the efficiency of OSCs has shown continuous development over time, as presented in the Table 1 below.

Table 1. Efficiency Development of Organic Solar Cells

No.	Material p-n junction	Method	Efficiency	Ref. /year
1	NFAs	D-LBL, Injet printing	12-15%	[16] 2022
2	PTDPP	D-LBL, Iknjet Printing	10-12%	[17] 2021
3	ITO (Indium Timah Oksida)	Spin coating, doctor blade	3,53%	[18] 2012
4	Silver Nanowire	Spin coating, doctor blade	3,85%	[18] 2012
5	PEDOT:PSS	Spin coating	11,8%	[19] 2023
6	PDINOH	Spin coating	17,08%	[20] 2022
7	PBDB-TF	Spin coating	16,5%	[21] 2019
8	PCBM	Spin coating	3,61%	[22] 2014
9	PM6, L8-BO	Vacuum thermal evaporation	16,94%	[23] 2024
10	PCBM	Spin coating	1,42%	[24] 2011
11	PDBT-T1	Spin coating	7,16%	[25] 2015
12	SMD2	Roll-to-roll slot-die coating	11,3%	[26] 2019
13	PCE12	Blade coating	11%	[27] 2023
14	PTB7-Th	Spin-coating	19%	[28] 2021
15	PBDB-T dan ITIC	Blade coating	12-14%	[29] 2017

3.2 OSC Working Principle

OSC is composed of materials in which carbon atoms participate in their chemical structure. Unlike conventional solar cells that use a p-n junction, where free charge carriers are generated immediately after photon absorption, OSC operates differently. In OSCs, electron-hole pairs are inherently generated in the form of excitons (loosely bound electron-hole pairs) before they dissociate into free charge carriers, electrons and holes. The separation of excitons into free electrons and holes occurs only at the donor-acceptor interface due to the internal electric field difference within the photovoltaic active layer.

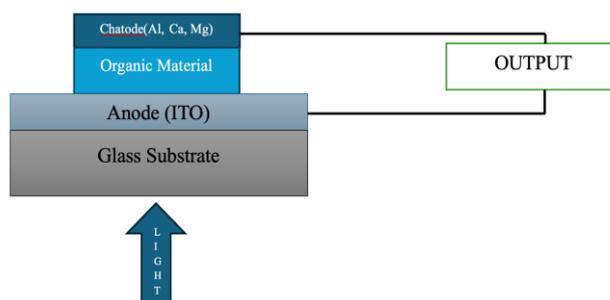


Figure 2. OSC Structure

As shown in Figure 2 regarding of OSC structure, the first electrode must be semi-transparent, typically with a transmittance of more than 90%, to allow light to be absorbed by the active layer. Indium tin oxide (ITO) is commonly used as the first electrode; however, other ultra-thin metal layers can also be utilized. The second electrode most commonly used is one of the following metals: aluminum, calcium, magnesium, or gold [30].

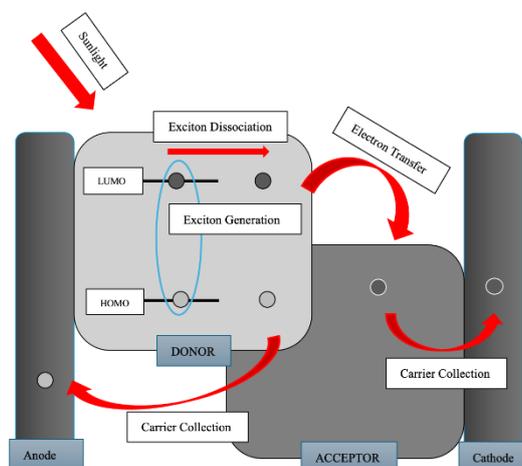


Figure 2. Working Principle of OSC

Figure 3 illustrates how organic solar cell works. When the active layer absorbs photons, electrons are excited from the Highest Occupied Molecular Orbital (HOMO) to the Lowest Unoccupied Molecular Orbital (LUMO), forming excitons. In OSCs, this process must be followed by exciton dissociation, where the electron-hole pair must be separated so that electrons reach the cathode while holes migrate to the anode [31].

Once excitons are generated through photon absorption, they can diffuse approximately 5–15 nm toward the donor-acceptor (DA) interface, where dissociation occurs [32]. Electrons can jump from the donor's LUMO to the acceptor's LUMO if the potential difference between the donor's ionization potential and the acceptor's electron affinity is greater than the exciton binding energy.

Free charge carriers may undergo recombination, either geminate recombination or transport via diffusion and drift forces, where they recombine with oppositely charged carriers. Alternatively, they can be transported to the corresponding electrodes and extracted into an external circuit, leading to the formation of an electric current [33].

3.3 Developments of Organic Solar Cell

So far, OSCs have been developed due to their flexibility, with power conversion efficiency (PCE) surpassing 19% in recent years [34]. OSC devices have been fabricated on rigid

substrates to enhance efficiency through active layer material design, device optimization, and mechanical investigations. Meanwhile, flexible transparent electrodes (FTEs) have been modified to produce flexible solar cells. The advancements in OSC technology include the following:

- a. Flexible OSCs can be used in portable devices with self-powering functionality.
- b. Semi-Transparent OSCs have significant potential for applications in building-integrated photovoltaic (BIPV) systems, energy-efficient windows, and modern greenhouses. Three key approaches can be employed to simultaneously achieve high transmittance and PCE in semi-transparent OSCs:
 - Solvent engineering to create a patterned perovskite layer,
 - Self-assembled perovskite on photoanodes, and
 - Ultra-thin perovskite films.
- c. OSCs in Space
With the development of the Internet of Things (IoT), space-based solar cells exhibit low sensitivity to series resistance, active layer thickness, and light operating conditions [35].

3.4 Types of OSC

3.4.1 ITO-Based OSC

Indium Tin Oxide (ITO) is the most commonly used material in OSCs due to its high transmittance, low resistance, and smooth surface. However, ITO has some disadvantages, such as high density, high cost, and limited availability of indium.

The performance of ITO-based OSCs tends to degrade over time due to cracks forming in the ITO layer, which increases its resistance. ITO electrodes deposited on flexible substrates such as polyethylene terephthalate (PET) and polyethylene naphthalate (PEN) are commercially available and are highly suitable for OSC fabrication [36]. For instance, the use of ZnO as an Electron Transport Layer (ETL) has proven to be highly effective for electron transport.

3.4.2 Conducting Polymer-Based OSC

This type of OSC utilizes conducting polymers that are optically transparent, highly flexible, easy to process in solution, and commercially available. PEDOT:PSS is the most widely studied conductive polymer due to its optical transparency, good conductivity, suitable work function, high flexibility, easy processing, and commercial availability. Currently, PEDOT:PSS-based materials, such as Clevios (Heraeus) and Orgacon (Agfa), are widely used in organic electronics [37]. Clevios P VP A14083 is specifically employed as a Hole Transport Layer (HTL) to modify the work function and enhance charge extraction efficiency in OSCs.

3.4.3 Silver Nanowire-Based OSC

Silver Nanowires (AgNWs) exhibit high transmittance, low sheet resistance, and excellent flexibility, making them a promising alternative to ITO for organic electronic devices. Due to their high optical transmittance, low resistance, and excellent flexibility, AgNW-based electrodes have been considered a primary candidate to replace ITO in organic electronic devices [38]. In recent years, comprehensive studies have been conducted on AgNW-based flexible electrodes for flexible electronic devices such as OSCs. Despite their numerous advantages, AgNW-based OSCs still face two major challenges: surface roughness and the trade-off between conductivity and transmittance. Surface roughness can impair interface quality, lead to shunt pathways, elevate leakage currents, and decrease device efficiency [39]. At the same time, achieving high conductivity requires denser AgNW networks, which unavoidably reduce optical transmittance, limiting the amount of light entering the active layer and constraining overall photovoltaic performance [40].

3.4.4 Metal Grid-Based and Ultrathin Metal-Based OSC

Metal grids serve as an alternative to transparent electrodes, where the metal provides conductive pathways, and the grid openings allow light transmission. In recent years, metal grids, especially Ag grid-based flexible transparent electrodes (FTEs), have been extensively studied for applications in organic electronic devices. The metal grid structure enables efficient electrical conductivity while maintaining high optical transmittance [41].

3.4.5 Graphene-Based OSC

Triple-layer graphene electrodes have demonstrated the best balance between sheet resistance, optical transmittance, and surface roughness. By using a common transfer process and improving adhesion between electrode layers, these electrodes can achieve a highly clean graphene surface without polymer residue. Due to its high transparency, excellent conductivity, and low contact resistance with organic materials, graphene has emerged as a promising material for flexible transparent electrodes (FTEs) and has been extensively studied for flexible organic electronic devices [42].

3.5 Prospects of OSC

Organic Solar Cells (OSCs) are a highly promising renewable energy technology as they can reduce dependence on fossil fuels. Furthermore, in the future, these solar cells have the potential to replace silicon-based solar cells because OSCs are made from polymers. This difference in base materials makes OSCs more cost-effective in terms of production. Additionally, the fabrication process of OSCs is environmentally friendly since it requires less energy during manufacturing [43].

The application of OSCs is quite versatile due to their lightweight and flexible nature. These characteristics make OSCs suitable for various applications, unlike rigid silicon-based solar cells.

3.6 Challenges of OSC

Despite the potential and promising future of OSCs, several challenges need to be addressed. One of the main challenges is that the efficiency of this technology is still relatively low compared to conventional silicon-based solar cells. Therefore, further research is needed to improve efficiency, including optimizing materials and expanding key parameters such as layer thickness and bandgap tuning.

Another significant challenge is the stability of OSCs, which tends to be lower than that of conventional solar cells. Environmental factors such as humidity, degradation due to ultraviolet radiation, and oxygen exposure can significantly affect the durability of OSCs. Additionally, the operational lifetime of OSCs is relatively short, with commercial products currently having a lifespan of approximately five years [44].

It is expected that continuous research and development efforts will be made to address these challenges, enabling OSCs to be improved and developed as a viable solution for future energy demands.

4. Conclusion

Organic Solar Cells (OSCs) are a solar energy technology classified based on their material composition. OSCs contain carbon atoms that actively participate in their chemical structure. They are categorized into several types, including ITO-Based OSCs, Conducting Polymer-Based OSCs, Silver Nanowire-Based OSCs, Metal Grid-Based and Ultrathin Metal-Based OSCs, and Graphene-Based OSCs. Each type of OSC has its own advantages and limitations, and the best choice depends on the specific application, such as required flexibility, production costs, and desired energy efficiency. OSCs hold

great promise as they can reduce dependence on fossil fuels, aligning with the primary goal of renewable energy sources.

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References

1. S. A. Putri, A. D. Farhani, A. S. Anjani, A. D. Saragih, P. N. N. Sari, and N. S. Gultom, "Transformasi teknologi dalam sel surya film tipis generasi kedua," *Journal of Applied Mechanical Engineering and Renewable Energy*, vol. 5, no. 1, pp. 34–42, 2025.
2. H. Purnomo, "Laporan Dewan Energi Nasional (DEN)," Jakarta, 2004, pp. 1-59.
3. A. A. N. Sugandi, A. P. Dew, K. Qulsum, M. Elisabet, B. S. Aprillia, S. Hidayat, P. N. N. Sari, M. Simanjuntak, and N. S. Gultom, "First Generation Solar Cell: History and Development of Silicon-Based Photovoltaics," *Jurnal Ilmu dan Inovasi Fisika*, vol. 9, no. 1, pp. 9–23, 2025. DOI: https://doi.org/10.24198/jiif.v9i1
4. S. Zhang, X. Yang, Y. Numata, and L. Han, "Highly efficient dye-sensitized solar cells: progress and future challenges," *Energy & Environmental Science*, vol. 6, pp. 1443–1464, 2013.
5. M. Gratzel, "Nature," vol. 414, pp. 328-344, 2001.
6. D. M. Chapin, C. S. Fuller, and G. L. Pearson, "A New Silicon p-n Junction Photocell for Converting Solar Radiation into Electrical Power," *J. Appl. Phys.*, vol. 25, pp. 676–677, May 1954.
7. S. Li, K. Zhang, and J. Hou, "Recent progress in organic solar cells: from materials to devices," *J. Energy Chemistry*, vol. 27, no. 4, pp. 1057–1068, 2018.
8. Z. Zhou *et al.*, "Perspective on Flexible Organic Solar Cells for Self-Powered Wearables," *ACS Appl. Mater. Interfaces*, 2025.
9. D. Triwardiati and I. R. Ernawati, "Analisis Bandgap Karbon Nanodots (C-Dots) Kulit Bawang Merah Menggunakan Teknik Microwave," *Jurnal Seminar Nasional Teknoka*, vol. 3, pp. 25-30, 2018.
10. L. Barkat, N. Stephant, Z. El Jouad, and J. C. Bernède, "Ca/Alq₃ hybrid cathode buffer layer for the optimization of organic solar cells based on a planar heterojunction," *J. Phys. Chem. Solids*, vol. 98, pp. 128–135, 2016.
11. M. T. Dang, L. Hirsch, and G. Wantz, "P3HT:PCBM, best seller in polymer photovoltaic research," *Adv. Mater.*, vol. 23, no. 31, pp. 3597–3602, 2011.
12. S. Li and K. Bachagha, "Application of buffer layer to improve the efficiency of organic solar cells," *Energy Technology*, vol. 12, no. 2, 2024, Art. no. 2300822.
13. K. Kalyanasundaram, *Dye-Sensitized Solar Cells*, Lausanne, Switzerland: EPFL Press, 2010.
14. A. H. Ahliha, F. Nurosyid, A. Supriyanto, and T. Kusumaningsih, "Optical properties of anthocyanin dyes on TiO₂ as photosensitizers for application of dye-sensitized solar cell (DSSC)," in *IOP Conference Series: Materials Science and Engineering*, vol. 333, no. 1, p. 012018, IOP Publishing, 2018.
15. Y. Qin et al., "The performance-stability conundrum of BTP-based organic solar cells," *Joule*, vol. 5, no. 8, pp. 2129-2147, 2021.

16. D. Zhou, J. Wang, Z. Xu, H. Xu et al., "Recent Advances of Nonfullerene Acceptors in Organic Solar Cells," *Nano Energy*, vol. 103, Art. no. 107802, Sep. 2022. doi: 10.1016/j.nanoen.2022.107802.
17. J. Tang, J. Ji, R. Chen, Y. Yan, Y. Zhao, and Z. Liang, "Achieving Efficient p-Type Organic Thermoelectrics by Modulation of Acceptor Unit in Photovoltaic π -Conjugated Copolymers," *Advanced Science (Weinh.)*, vol. 9, no. 4, Art. no. 2103646, Dec. 2021. doi: 10.1002/advs.202103646.
18. J. Ajuria et al., "Insights on the working principles of flexible and efficient ITO-free organic solar cells based on solution processed Ag nanowire electrodes," *Solar Energy Materials and Solar Cells*, vol. 102, pp. 148-152, 2012.
19. B. Liu et al., "Efficient and stable organic solar cells enabled by multicomponent photoactive layer based on one-pot polymerization," *Nature Communications*, vol. 14, no. 1, Art. no. 967, Feb. 2023, doi: 10.1038/s41467-023-36413-3.
20. M. Zi et al., "Organic solar cells with efficiency of 17.6% and fill factor of 78.3% based on perylene-diimide derivative as cathode interface layer," *Chemical Engineering Journal*, vol. 443, p. 136455, 2022.
21. Y. Cui et al., "Over 16% efficiency organic photovoltaic cells enabled by a chlorinated acceptor with increased open-circuit voltages," *Nature Communications*, vol. 10, no. 1, p. 2515, 2019.
22. Y. Chen et al., "Benzo [1,2-b:4,5-b'] dithiophene and benzotriazole based small molecule for solution-processed organic solar cells," *Organic Electronics*, vol. 15, no. 2, pp. 405-413, 2014.
23. F. Bernal - Texca and J. Martorell, "Four - Terminal Tandem Based on a PM6: L8 - BO Transparent Solar Cell and a 7 nm Ag Layer Intermediate Electrode," *Solar RRL*, vol. 2300728, 2024.
24. H. Choi et al., "Synthesis of annulated thiophene perylene bisimide analogues: their applications to bulk heterojunction organic solar cells," *Chemical Communications*, vol. 47, no. 19, pp. 5509-5511, 2011.
25. C. B. Nielsen et al., "Non-fullerene electron acceptors for use in organic solar cells," *Accounts of Chemical Research*, vol. 48, no. 11, pp. 2803-2812, 2015.
26. Y. W. Han et al., "Evaporation - free nonfullerene flexible organic solar cell modules manufactured by an all - solution process," *Advanced Energy Materials*, vol. 9, no. 42, p. 1902065, 2019.
27. M. C. Scharber, D. Mühlbacher, M. Koppe, P. Denk, C. Waldauf, A. J. Heeger, and C. J. Brabec, "Design rules for donors in bulk-heterojunction solar cells—Towards 10 % energy-conversion efficiency," *Advanced Materials*, vol. 18, no. 6, pp. 789–794, Mar. 2006, doi: 10.1002/adma.200501717.
28. J. Yuan et al., "Single-junction organic solar cell with over 15% efficiency using fused-ring acceptor with electron-deficient core," *Joule*, vol. 3, no. 4, pp. 1140-1151, 2019.
29. J. Liu et al., "High-Efficiency Polymer Solar Cells with Thick Active Layers Fabricated by Doctor Blading," *ACS Applied Materials & Interfaces*, vol. 9, no. 37, pp. 31206-31213, 2017.
30. H. Spanggaard and F. C. Krebs, "A brief history of the development of organic and polymeric photovoltaics," *Solar Energy Materials and Solar Cells*, vol. 83, pp. 125-146, 2004.
31. T. Kietzke, "Recent Advances in Organic Solar Cells," *Advances in OptoElectronics*, p. 15, 2007.

32. G. Dennler and N. S. Sariciftci, "Flexible Conjugated Polymer-Based Plastic Solar Cells: From Basics to Applications," *Proceedings of the IEEE*, vol. 93, no. 8, pp. 1429-1439, 2005.
33. S. E. Shaheen, C. J. Brabec, and N. S. Sariciftci, "2.5% efficient organic plastic solar cells," *Applied Physics Letters*, vol. 78, no. 6, pp. 841-843, 2001.
34. L. Zhu et al., "Single-junction organic solar cells with over 19 % efficiency enabled by a refined double-fibril network morphology," *Nature Materials*, vol. 21, pp. 656–663, 2022.
35. J. Wu, M. Gao, Y. Chai, P. Liu, B. Zhang, J. Liu, and L. Ye, "Towards a bright future: the versatile applications of organic solar cells," *Materials Reports: Energy*, vol. 1, no. 4, Art. no. 100062, Nov. 2021. doi: 10.1016/j.matre.2021.100062.
36. S. Savagatrup et al., "Mechanical degradation and stability of organic solar cells: molecular and microstructural determinants," *Energy & Environmental Science*, vol. 8, no. 1, pp. 55-80, 2015.
37. X. Fan et al., "PEDOT: PSS for flexible and stretchable electronics: modifications, strategies, and applications," *Advanced Science*, vol. 6, no. 19, p. 1900813, 2019.
38. M. R. Azani, A. Hassanpour, and T. Torres, "Benefits, problems, and solutions of silver nanowire transparent conductive electrodes in indium tin oxide (ITO) - free flexible solar cells," *Advanced Energy Materials*, vol. 10, no. 48, p. 2002536, 2020.
39. J. Wu, J. Wang, and Z. Zhou, "Fabrication and applications of flexible transparent electrodes based on silver nanowires," in *Nanowires - Recent Advances*, IntechOpen, 2018. doi: 10.5772/intechopen.76825.
40. J. Lee, M. Ahn, and S. Hong, "Recent advances in silver nanowire-based transparent conductive films: From synthesis to applications," *Coatings*, vol. 15, no. 7, p. 858, 2025. doi: 10.3390/coatings15070858.
41. P. Bellchambers et al., "High performance transparent silver grid electrodes for organic photovoltaics fabricated by selective metal condensation," *Adv. Mater.*, vol. 35, no. 21, Art. no. 2300166, 2023. doi: 10.1002/adma.202300166.
42. Y. Li, M. Sha, and S. Huang, "A review on transparent electrodes for flexible organic solar cells," *Coatings*, vol. 14, no. 8, Art. no. 1031, 2024. doi: 10.3390/coatings14081031.
43. A. M. Bagher, "Introduction to organic solar cells," *Sustainable Energy*, vol. 2, no. 3, pp. 85-90, 2014.
44. A. Jannat, M. F. Rahman, and M. S. H. Khan, "A review study of organic photovoltaic cell," *International Journal of Scientific & Engineering Research*, vol. 4, no. 1, pp. 1-6, 2013.