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Advances in organic photovoltaic cells: a comprehensive review of materials, technologies, and performance

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This paper provides a comprehensive overview of organic photovoltaic (OPV) cells, including their materials, technologies, and performance. In this context, the historical evolution of PV cell technology is explored, and the classification of PV production technologies is presented, along with a comparative analysis of first, second, and third-generation solar cells. A classification and comparison of PV cells based on materials used is also provided. The working principles and device structures of OPV cells are examined, and a brief comparison between device structures is made, highlighting their advantages, disadvantages, and key features. The various parts of OPV cells are discussed, and their performance, efficiency, and electrical characteristics are reviewed. A detailed SWOT analysis is conducted, identifying promising strengths and opportunities, as well as challenges and threats to the technology. The paper indicates that OPV cells have the potential to revolutionize the solar energy industry due to their low production costs, and ability to produce thin, flexible solar cells. However, challenges such as lower efficiency, durability, and technological limitations still exist. Despite these challenges, the tunability and versatility of organic materials offer promise for future success. The paper concludes by suggesting that future research should focus on addressing the identified challenges and developing new materials and technologies that can further improve the performance and efficiency of OPV cells.

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1. Introduction and motivation

The importance of renewable energy sources has become increasingly apparent in recent years as concerns about climate change, energy security, and the negative impacts of non-

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renewable sources continue to grow. Renewable energy offers a more sustainable and environmentally friendly alternative to non-renewable sources such as fossil fuels, and can help to reduce our dependence on foreign oil, increase energy security, and address the climate crisis.[1,2]

One of the main reasons for the importance of renewable energy is its potential to address climate change.[3,4] Greenhouse gas emissions from the burning of fossil fuels are a major contributor to global warming and climate change, and the use of renewable energy can help to reduce these emissions. In addition to reducing emissions, renewable energy can also help to reduce air pollution, which has a number of negative health impacts. Another important reason for the need for renewable energy is energy security.[5] By relying on domestic sources of energy, individuals and society can reduce their vulnerability to disruptions in the global energy market and ensure a stable and reliable supply of energy for the future. Renewable energy sources such as solar and wind are also less prone to supply disruptions than non-renewable sources, as they do not rely on finite resources that can be disrupted by geopolitical tensions or natural disasters.[6,7]

Despite the many benefits of renewable energy, there are also challenges associated with its deployment. One of the main challenges is the upfront cost of developing and installing renewable energy technologies, which can be higher than the cost of non-renewable sources in the short term.[8] However, the long-term costs of renewable energy are often lower due to the fact that they do not require the constant purchase of fuel, and their costs are also likely to decrease as technology improves and economies of scale are achieved.[9,10]

Among renewable energy sources, solar energy is perhaps the most well-known. It is generated using photovoltaic panels, which convert sunlight into electricity. Solar energy is a clean, renewable source of energy that is widely available and can be used in a variety of applications, including electricity generation, heating, and lighting.[11] One of the main benefits of solar energy is that it is relatively easy to install and maintain, and it can be used in a variety of locations, including urban, suburban, and rural areas.[12]

Solar cells, also known as photovoltaic cells, are a type of renewable energy source that converts sunlight into electricity through a process called the photovoltaic effect.[13,14] They are made up of a semiconductor material that absorbs sunlight and releases electrons, which can be captured and used to generate electricity. There are several types of solar cells, including traditional inorganic cells made of silicon and newer organic cells made of polymers or small molecules.

Crystalline silicon cells are the most common type of solar cell and are made from a single crystal or polycrystalline silicon. They are efficient and durable, but can be expensive to produce. Organic solar cells, on the other hand, are made by depositing a thin layer of photovoltaic material onto a substrate, such as glass or polymeric material. They can also be made into a variety of shapes and sizes, making them more versatile. However, organic solar cells currently have lower efficiency rates and shorter lifetimes compared to traditional inorganic cells. Despite these limitations, research and development in the field of organic solar cells is ongoing, and there is potential for these materials to play a significant role in the future of solar energy.

As a result, there has been a growing interest in PV cell technology, which has the potential to provide clean, sustainable energy. In this context, this review paper aims to provide a comprehensive study of the evolution of PV cell technology, with a particular focus on OPV cells. The review makes several significant contributions to the existing literature on OPV cell, some of them are as follows:

- Providing a comprehensive overview of the evolution of photovoltaic cell technology and its historical context, including the classification of PV production technologies, comparison of PV cells based on the materials used, and a comparative analysis of first, second, and third-generation solar cells. This in-depth analysis provides valuable insight into the development of PV cells and the factors that have led to the emergence of OPV cells.
- Exploring the working principles and device structures of OPV cells, including a comparison of device structures. This provides a detailed analysis of the advantages and disadvantages of OPV cells, as well as their key features.
- Conducting a detailed SWOT analysis for OPV cells, revealing the strengths, weaknesses, opportunities, and threats associated with the technology. This analysis provides a comprehensive overview of the current state of the technology and the challenges and opportunities it faces.
- Analyzing the performance, efficiency, and electrical characteristics of photovoltaic cells, as well as the conversion efficiencies of OPV cells. By comparing the performance characteristics reported in recent literature on organic solar cells, the review highlights the latest trends and advancements in the field of OPV cells.
- Identifying several areas for future research and development, including improving efficiency and stability, developing new materials, and optimizing morphological characteristics for charge transport. These recommendations provide a valuable roadmap for future research and development in the field of OPV cells.

Overall, this review paper offers a detailed analysis and comprehensive perspective on the current state and future prospects of photovoltaic cell technology, with a specific focus on OPV cells. It is a valuable resource for researchers, engineers, and policymakers interested in the development of sustainable and efficient solar energy technologies.

2. PV generation technologies

Energy crises that have occurred at different times in the world have led to the search for renewable alternative energy sources and research in this direction has mainly focused on obtaining electrical energy from solar and wind energy.[15] Photovoltaics have been a subject of intense interest during this period and significant resources have been allocated to research studies.[16,17] Intensive efforts have been made to produce photovoltaic devices at lower costs and to increase their efficiency.

2.1. Historical overview of the evolution of PV cell technology

The history of PV cells can be traced back to the late 19th century, when the French physicist Alexandre-Edmond Becquerel discovered the phenomenon of the photovoltaic effect.[18,19] He observed that certain materials, when exposed to light, produced a small electrical current. This was the first step in the development of PV technology.

In the early 20th century, researchers such as Albert Einstein and Charles Fritts continued to study the photovoltaic effect and improve upon the efficiency of PV cells. Fritts, for example, created the first working PV cell by layering selenium and gold onto glass, which had an efficiency of only 1%. In the 1950s and 60s, the space race between the United States and the Soviet Union led to significant advancements in PV technology.[20,21] The US government invested heavily in the development of PV cells for use in space satellites. This led to the creation of more efficient and durable PV cells, with efficiencies reaching around 14%.[22]

In the 1970s, the oil crisis led to increased interest in renewable energy sources, including PV technology. This resulted in the development of new materials and manufacturing techniques that further improved the efficiency and cost-effectiveness of PV cells.[23] In the 1980s and 90s, silicon-based PV cells became the dominant technology and were widely used in a variety of applications. This period also saw the development of thin-film PV cells, which used less silicon and were more cost-effective to produce.

In the 21st century, PV technology has continued to evolve and improve. The efficiency of PV cells has reached over 25%, and new materials such as perovskite and quantum dots have been developed, which have the potential to further increase efficiency. The perovskite material was found to have high light absorption, high charge-carrier mobility, and a suitable band gap for solar energy conversion.[24,25] Since then, perovskite solar cells have attracted a lot of attention from the scientific community due to their high efficiency potential and low cost. The efficiency of perovskite solar cells has increased significantly over the years, with the current record efficiency at over 25%.

In parallel to the initial studies of PV cell technologies, the history of OPV cells can be traced back to the early 20th century when scientists first started to explore the potential of organic materials as a substitute for traditional inorganic materials in solar cells. The researchers in ref. 26 demonstrated that the polymer could be used as a photoconductive material, generating electrical power when exposed to light. This was a significant development in organic solar cell technology and led to the creation of new materials and device architectures. Since then, research in the field of organic solar cells has continued, resulting in the development of more efficient and stable organic solar cell technologies. However, it was only in the latter part of the 20th century that substantial progress was made in the advancement of OPV technology. In the 1970s and 80s, researchers delved into the utilization of polymers as active layers in solar cells. These early attempts yielded low efficiencies, usually below 1%. Nevertheless, they established the foundation for the creation of more sophisticated OPV cells in the following decades.

During the 1990s, the discovery of new conjugated polymers and small-molecule materials resulted in a marked improvement in the efficiency of OPV cells. Scientists were able to attain efficiencies of up to 4% using these new materials.[27,28] Additionally, the creation of new fabrication techniques, such as solution processing, made it possible to produce OPV cells at a lower cost. In the early 21st century, the efficiency of OPV cells continued to advance, reaching around 18%.[29] This was partly due to the development of new materials and device architectures, as well as advancements in fabrication techniques. Moreover, researchers started to examine the use of multiple layers in OPV cells, which led to further increases in efficiency.

In recent years, scientists have made notable progress in the development of OPV cells with improved efficiency, stability and cost-effectiveness. The efficiency of OPV cells has reached up to 20% which is relatively higher than the early stage.[30,31] The development of new materials such as perovskite, fullerene derivatives, and new device architectures such as tandem cells have contributed to this improvement. Furthermore, advancements in manufacturing techniques have made OPV cells more affordable and accessible to a wider range of consumers. Briefly, the historical development of OPV cells has been marked by consistent progress in efficiency, stability, and cost-effectiveness. While OPV cells are still less efficient than traditional inorganic solar cells, they offer several advantages such as the potential for low-cost, large-scale production, and the ability to be flexible and transparent. As research continues to enhance the performance of OPV cells, it is likely that they will become an increasingly important part of the renewable energy mix in the future.

2.2. Generations of PV production technologies

As mentioned within the previous section, PV production technologies have evolved over time, and different types of technologies are available in the market. Therefore, understanding the classification of PV production technologies is important for policymakers, investors, and consumers to make informed decisions about the implementation of solar power systems. A general classification of PV production technologies is shown in Fig. 1.[32,33]

First generation solar cells, also known as conventional or traditional solar cells, are made primarily of silicon.[34] These cells were first developed in the 1950s and have been the most widely used type of solar cell to date.[35,36] The efficiency of these cells ranges from 6–15%, but through continuous research and development, the efficiency of these cells has increased significantly over the years and now reaches levels of up to 25% as illustrated in Fig. 2.[37]

First generation solar cells have some limitations, such as a relatively low efficiency and a high cost of raw materials. Their efficiency drops significantly in high temperatures, which can cause power loss. Recent research has been focused on

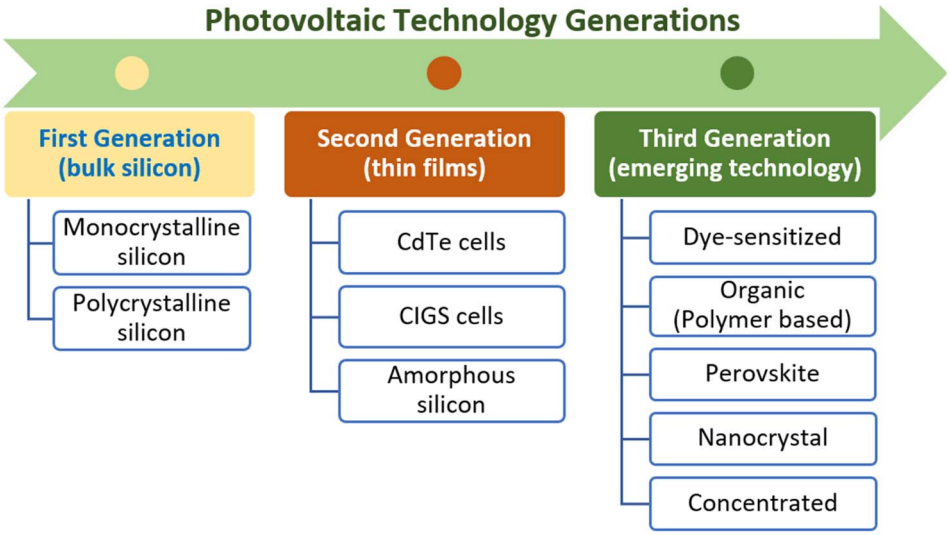

Fig. 1 Three generations of PV cells.

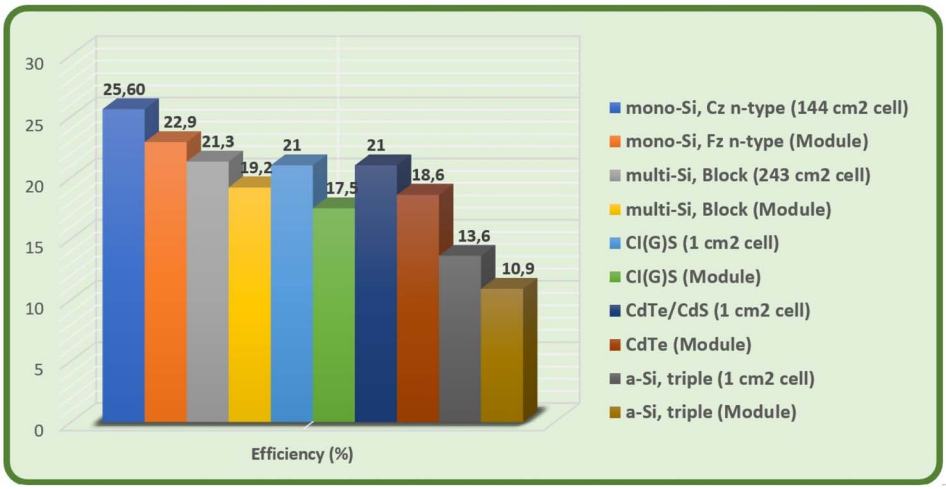

Fig. 2 Efficiency of silicon-based technology in laboratories.[37]

developing new materials and technologies to improve the efficiency and to reduce the cost of production.

Second generation solar cells, also known as thin-film solar cells, are made from materials like copper indium gallium selenide (CIGS), cadmium telluride (CdTe) and amorphous silicon (a-Si).[37,38] They are thinner than traditional solar cells and have a higher tolerance to temperature changes, with an efficiency range of 10–15%. They use less material, are more flexible, lightweight, and can be manufactured using a roll-to-roll process which makes it more cost-effective. These cells are good for building-integrated photovoltaics (BIPV) and portable and lightweight solar panels for outdoor activities.[39] They have lower efficiency and performance can degrade over time and their long-term stability and durability are not yet well understood. They are becoming more popular due to cost-effectiveness and versatility but research and development is ongoing to improve their efficiency, lifetime, and cost-effectiveness to make them more competitive with traditional solar cells.[40]

Third generation solar cells, some of which are highlighted in ref. 41–49, are important because they utilize materials that are cheaper than those used in first- and second-generation solar cells. These materials, such as perovskites, notable examples of which can be found in ref. 50–55, are abundant and can be processed using low-cost manufacturing techniques. As a result, third generation solar cells have the potential to significantly reduce the cost of solar energy,[42] making it more accessible to people around the world.[43] Additionally, third generation solar cells are capable of achieving higher efficiencies than previous generations, meaning that they can generate more electricity from the same amount of sunlight.[44,56] This makes them an attractive option for both large-scale and small-scale solar energy applications.

Table 1 Comparison between the first, the second, and the third-generation solar cells

	First generation	Second generation	Third generation
Materials	Silicon	CIGS, CdTe, a-Si	Multi-junction cells, organic materials, perovskite materials, flexible substrates
Efficiency range	6–25%	10–15%	>25%
Advantages	Proven technology, increasing efficiency	Flexible, lightweight, roll-to-roll production, cost-effective	Cheaper materials, potential to significantly reduce the cost of solar energy, higher efficiencies
Limitations	High raw material cost, performance drops in high temperatures	Lower efficiency, long-term stability and durability, not yet well understood	Still in the research and development phase
Manufacturing process	Wafer-based	Roll-to-roll	Various, depending on material and design
Applications	Residential, commercial, utility-scale projects	Building-integrated photovoltaics, portable and lightweight solar panels, small-scale projects	Large-scale projects, consumer electronics, off-grid applications
Durability	Good	Moderate	Varies, depending on material and design
Stability	Good	Moderate	Varies, depending on material and design

2.3. Comparative analysis of first, second, and third generation solar cells

While the first-generation solar cells are a proven technology, the second-generation solar cells offer more flexibility and cost-effectiveness. The third-generation solar cells are the newest and most promising technology. Table 1 presents a detailed comparison table between the first, the second, and the third-generation solar cells. As shown, first generation cells use silicon and have an efficiency range of 6–25%. They are a proven technology but have some limitations such as a high cost of raw materials and performance drop in high temperatures. Second generation cells are made from materials like CIGS, CdTe, and a-Si and have an efficiency range of 10–15%. They are flexible, lightweight, cost-effective, and have roll-to-roll manufacturing. However, their lower efficiency, long-term stability, and durability are not yet well understood. Third generation cells are a newer technology that use materials like perovskites and have an efficiency range of over 25%. They have the potential to significantly reduce the cost of solar energy and can generate more electricity from the same amount of sunlight.

3. Advances in material preparation for PV cells

PV cells are made from various materials and technologies, which result in different types of photovoltaic cells. A general classification of them can be made as in the following section.

3.1. Classification and comparison of PV cells based on materials used

While other types or variations exist, photovoltaic cells can generally be classified into groups based on material composition, fabrication technology, and application, as shown in Fig. 3. The figure also provides a timeline of when the technology was introduced.

Silicon-based cells are the most common type of photovoltaic cells, comprising over 90% of the global PV market. They were first invented by Bell Labs in 1954 and are used in residential and commercial solar power systems.[57,58] Crystalline silicon cells are made from silicon wafers, while amorphous silicon cells are made from a thin film of silicon deposited on a substrate. While crystalline silicon cells have high efficiency, durability, and reliability, amorphous silicon cells are less efficient but cheaper to produce and can be used in flexible and lightweight applications.

Thin-film cells are another type of photovoltaic cells made from materials like CdTe, CIGS, and amorphous silicon. The first thin-film solar cell, made from CdTe, was developed by the U.S. government's National Renewable Energy Laboratory in 1981.[59] Thin-film cells are cheaper to produce and have a lower environmental impact than silicon-based cells. CdTe cells are widely used in utility-scale solar projects, while CIGS cells are used in residential and commercial applications due to their higher efficiency.[60,61] Amorphous silicon cells are suitable for small-scale applications like pocket calculators and electronic watches.

Dye-sensitized cells (DSSC) are another type of photovoltaic cells that use a photosensitive dye to absorb light and generate electricity.[62] Brian O'Regan and Michael Grätzel co-invented the contemporary edition of a DSSC in 1988, which they continued to refine until the release of the initial high-performance DSSC in 1991. These cells are less efficient than silicon-based cells but are cheaper to produce and can be made into flexible and transparent materials. DSSCs are used in portable devices, building-integrated photovoltaics, and other low-power applications.

Organic cells use organic materials such as polymers[63–65] to generate electricity. The first organic solar cell was reported by researchers at the University of California, Santa Barbara in 1986. These cells are lightweight, flexible, and have a low environmental impact.[66–68] However, their efficiency is lower than

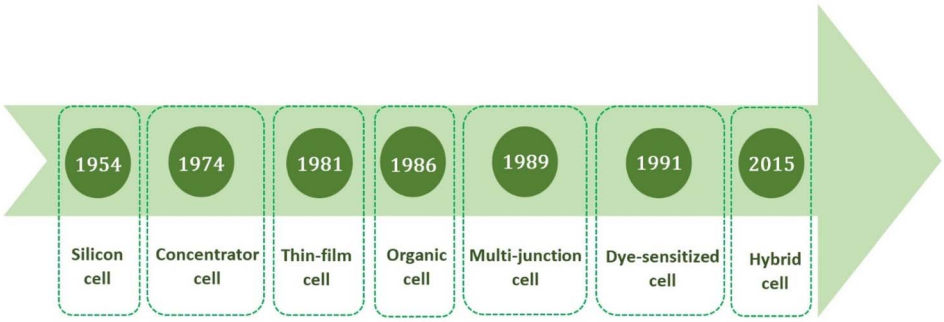

Fig. 3 Types of PV cells on a timeline.

that of silicon-based cells, and they have a shorter lifespan.[69] Organic cells are used in small-scale applications such as portable devices and flexible electronics.[70,71]

Multi-junction cells are photovoltaic cells made from layers of different materials that can absorb different wavelengths of light. The first multi-junction solar cell was made by the U.S. Air Force Research Laboratory in 1989.[72,73] These cells are used in high-concentration photovoltaic systems and space applications. Multi-junction cells have the highest efficiency among all photovoltaic cells, with a record efficiency of 47.1% in the laboratory.

Concentrator cells use lenses or mirrors to focus sunlight onto a small area of a solar cell. This can significantly increase the efficiency by reducing the amount of material needed to generate electricity.[74,75] The first concentrator solar cell was made by Boeing in 1974. Concentrator cells are used in utility-scale solar projects and high-concentration PV systems.[76–78]

Hybrid cells, some of which are highlighted in ref. 78–84, use a combination of different types of materials to achieve higher efficiencies. In 2015, the first-ever of perovskite/silicon tandem solar cell with two terminals was introduced.[85] Perovskite cells have high efficiency but are not durable, while silicon solar cells have lower efficiency but are durable. By combining these two types, a hybrid cell can achieve both high efficiency and durability.[86,87]

It is important to note that the development of these photovoltaic cell technologies is ongoing, and new advancements and breakthroughs are constantly being made. However, relying on the above summarized descriptions, a general comparison for different types of PV cells can be made as in Table 2 that demonstrates that OPV cells have attracted

Table 2 A general comparison for different types of PV cells

Technology	Advantages	Disadvantages
Silicon-based	Most efficient technology with the longest track record High efficiency with a proven track record Wide availability of raw materials	Expensive to produce and manufacture Limited flexibility Energy-intensive to produce Susceptible to shading, soiling, and temperature variations
Thin-film	Cheaper to produce than silicon-based cells Flexible, lightweight, and adaptable to various surfaces Wide range of materials available for thin-film production	Lower efficiency compared to silicon-based cells Shorter lifespan than silicon-based cells Can be less stable under prolonged exposure to sunlight May contain toxic materials
Concentrator	Higher efficiency compared to other PV technologies Uses less photovoltaic material, reducing cost	Requires direct sunlight, making it less adaptable Requires sophisticated tracking systems Requires specialized design, making it less accessible
Multi-junction	High efficiency for concentrated sunlight applications Ideal for space applications Wide range of materials available for multi-junction cells	Expensive and complex to manufacture Less suitable for terrestrial applications Not yet cost-competitive for large-scale production
Organic	Cheaper and easier to produce than silicon-based cells Can be manufactured using low-cost printing methods Flexible and lightweight, allowing for greater versatility	Lower efficiency compared to other PV technologies Limited lifespan due to degradation of organic materials Susceptible to temperature and moisture variations Less stable under prolonged exposure to sunlight
Dye-sensitized	Cheap to produce and can be manufactured using printing Flexible and lightweight, allowing for greater versatility Can be manufactured in different colors and transparency	Low efficiency compared to other PV technologies Susceptible to temperature and moisture variations Shorter lifespan than other PV technologies Relatively new technology, still being developed
Hybrid	Potentially high efficiency, combining multiple technologies Cheaper and easier to produce than some other technologies Can be manufactured using low-cost printing methods More stable than some organic and dye-sensitized cells	Limited lifespan due to degradation of organic materials Still in development, not yet widely available Requires specialized design, making it less accessible Requires further research and development

significant attention among PV technologies due to their several benefits. Firstly, they offer the potential for low-cost, sustainable production due to their use of organic materials and low-energy manufacturing processes. Secondly, their flexibility and lightweight design make them ideal for use in a variety of applications, including indoor and portable settings where direct sunlight may not be available. Thirdly, their performance in low-light conditions is better than that of traditional silicon-based PV cells. Finally, because OPV technology is still in its early stages of development, there is considerable scope for innovation and discovery in the field, providing opportunities for cutting-edge research and new applications.

4. Organic PV cells

Organic photovoltaic (OPV) cells, also known as organic solar cells, are a type of solar cell that converts sunlight into electricity using organic materials such as polymers and small molecules.[83,84] These materials are carbon-based and can be synthesized in a laboratory, unlike inorganic materials like silicon that require extensive mining and processing.[84,85] OPV cells work by absorbing photons of light and generating an electrical current through the flow of electrons in the organic material.[86,87] The cells are typically made up of multiple layers, including a layer of organic material sandwiched between two electrodes.[88] When light is absorbed, it creates a flow of electrons from one electrode to the other, producing a current.[89–91]

OPVs currently have lower efficiency levels, typically around 5–10%, compared to 15–20% for silicon-based cells.[92–95] Despite this, research in the field is ongoing and scientists are working to improve the efficiency of polymer-based solar cells through various methods such as incorporating new materials and optimizing the cell structure.[96,97] In recent years, the rapid increase in the power conversion efficiency of OPVs has led to increased scientific and economic interest.[98–101]

4.1. Working principles of OPV cells

4.1.1 Absorption of light. When light is incident on the active layer of the OPV cell, the organic materials absorb photons and generate electron–hole pairs. The process of light absorption in an OPV cell involves the interaction of photons with the organic semiconducting materials in the active layer of the cell. When a photon with energy equal to or greater than the bandgap energy of the material is absorbed, it generates electrical current. Therefore, the materials are designed to have strong absorption in this spectral range to maximize the conversion of sunlight into electrical power. The absorption of light in organic materials is influenced by various factors such as the chemical structure, molecular weight, and orientation of the materials.[102] For example, the use of conjugated polymers, such as polythiophenes and polyfluorenes, has been shown to increase the absorption coefficient and extend the absorption range into the near-infrared region. Additionally, the morphology of the active layer plays a crucial role in light absorption. The active layer of an OPV cell is typically a blend of an electron-donor material and an electron-acceptor material, which form a heterojunction that facilitates efficient charge separation.[103,104] The morphology of this blend is crucial to ensuring that the donor and acceptor materials are in intimate contact and that the excitons generated by light absorption are efficiently separated and transported to the respective electrodes. To increase the absorption of light in OPV cells, researchers have developed various strategies, including the use of light-trapping structures and the incorporation of plasmonic nanoparticles into the active layer. Light-trapping structures, such as textured substrates or photonic crystals, increase the path length of light in the active layer and enhance light absorption. Plasmonic nanoparticles, such as gold or silver, can be used to enhance the absorption of light through the excitation of surface plasmon resonance, which can confine and concentrate electromagnetic fields in the active layer.[104,105] In conclusion, the absorption of light is a fundamental process in OPV cells, which is strongly influenced by the properties of the organic semiconducting materials and the morphology of the active layer. Researchers are continuing to develop new materials and strategies to improve light absorption and increase the efficiency of OPV cells.[106,107]

4.1.2 Charge separation. The electron–hole pairs are separated by a built-in electric field that exists within the active layer. This electric field is created by a difference in the energy levels of the donor and acceptor materials that make up the active layer. The process of charge separation involves the separation of the electron–hole pair generated by the absorption of light in the organic semiconducting material in the active layer of the cell.[108] Efficient charge separation is essential to ensure that the generated charges can be collected at the respective electrodes to generate a current. The active layer of an OPV cell typically consists of a blend of an electron-donor material and an electron-acceptor material, which form a heterojunction that facilitates charge separation. The donor material, such as a conjugated polymer, is designed to have a high ionization potential, meaning that it has a strong tendency to donate an electron. The acceptor material, such as a fullerene or non-fullerene acceptor, is designed to have a low electron affinity, meaning that it has a strong tendency to accept an electron.[109,110] When a photon is absorbed in the active layer, an exciton is generated, which is a bound state of an electron and a hole. The exciton is then dissociated into free charge carriers at the donor–acceptor interface, and the electron and hole are separated and transported to the respective electrodes. The morphology of the active layer plays a crucial role in charge separation. The donor and acceptor materials must be in intimate contact to ensure that the exciton can efficiently dissociate into free charge carriers. The morphology is typically optimized through the use of solvent processing or annealing to ensure that the donor and acceptor materials form a well-ordered and continuous heterojunction. The electronic properties of the donor and acceptor materials also play a significant role in charge separation. The energy levels of the donor and acceptor materials must be appropriately aligned to facilitate efficient charge separation.[109,111] The energy offset between the donor and acceptor materials determines the driving force for charge separation, and an appropriate offset is required to ensure that

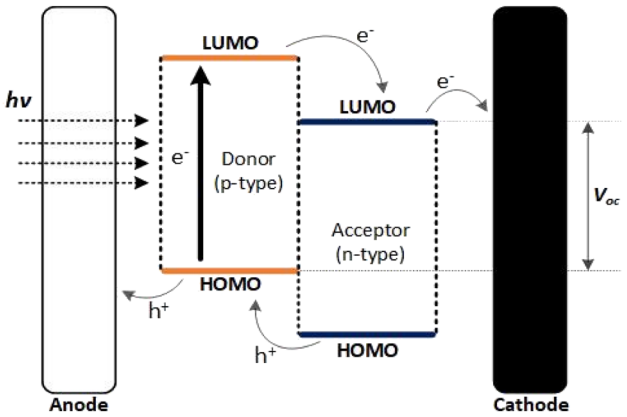

Fig. 4 Working principles of the OPV.[114]

the generated charges can be efficiently collected at the respective electrodes.[112,113] The working principle of OPV is demonstrated in Fig. 4.[114] To improve charge separation in OPV cells, researchers have developed various strategies, including the use of alternative acceptor materials, such as non-fullerene acceptors, and the development of tandem structures, which allow for multiple exciton dissociation and can enhance the overall efficiency of the device.

4.1.3 Charge collection. The separated electrons and holes are collected by electrodes, which are typically made of transparent conductive materials that are coated onto the surface of the active layer. The process of charge collection in OPV cells involves the movement of separated charges to their respective electrodes to generate a current. Charge collection is a critical process and its efficiency directly affects the overall performance of the device.[115] In OPV cells, the separated charges, which are generated by the process of charge separation, are transported to their respective electrodes through the organic semiconducting material in the active layer. The electrodes, typically made of conductive materials such as indium tin oxide (ITO), aluminum, or silver, are in contact with the active layer and collect the generated charges.[116,117] The efficiency of charge collection is influenced by several factors, including the morphology of the active layer, the mobility of the charge carriers, and the alignment of the energy levels of the donor and acceptor materials.

4.1.4 Electrical output. The electrical output of an OPV cell is the result of the charge separation and collection processes. The efficiency of the electrical output is a key factor in determining the overall performance of the device. The electrical output of an OPV cell is characterized by its short-circuit current density (J_{sc}), open-circuit voltage (V_{oc}), fill factor (FF), and power conversion efficiency (PCE).[118,119] For a comprehensive understanding of these terms and their consequential effects on cell efficiency, Section 4.4 offers a detailed information.

4.2. Device structure of OPV cells

As shown in Fig. 5, recent research on OPV cells has revealed that various structures have been developed over time, each with its own unique advantages and disadvantages.[117,120–122] These structures are composed of the materials described in the following sections.

4.2.1 Single-layered OPV cells. These are the simplest type of OPV cells, consisting of only one layer of organic material that is designed to efficiently harvest light and generate electrical power. Single-layered OPV cells typically have lower efficiency compared to other types of OPV cells. In single-layer OPV cells, the donor and acceptor materials are mixed together in the same layer, which allows for a simpler device architecture and potentially lower production costs.[116] When light is incident on the donor–acceptor layer, it generates electron–hole pairs that are separated by the built-in electric field. The separated electrons and holes are then collected by the electrodes to create a flow of electrical current, which can be used to power external devices or stored in a battery.

The single-layer OPV cell typically includes the following layers.

Transparent electrode. This layer is typically made of a transparent conductive oxide material such as indium tin oxide (ITO) or zinc oxide (ZnO), and is used as the anode.

Donor–acceptor blend. This layer is a single layer that combines both the donor and acceptor materials. The donor material is typically a polymer or small molecule that absorbs light and generates electrons, while the acceptor material is typically a fullerene derivative that accepts electrons.

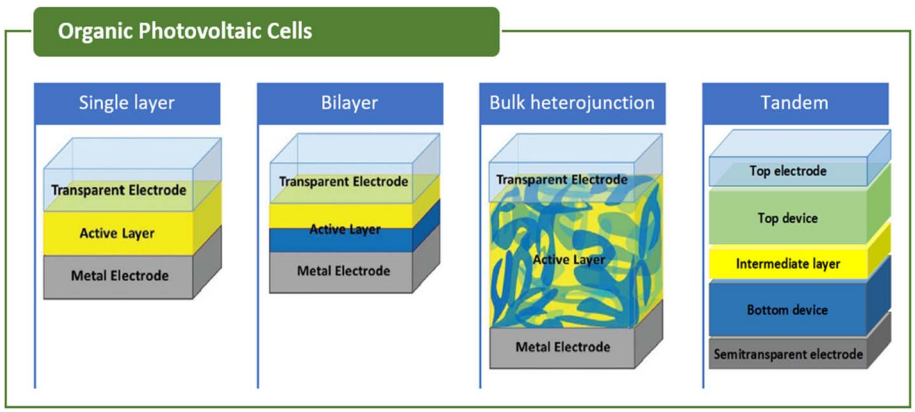

Fig. 5 Device structure of OPV cells.

Metal electrode. This layer is typically made of a metal such as aluminum or silver, and is used as the cathode.

4.2.2 Bilayer OPV cells. Bilayer OPVs are a type of thin-film solar cell that consist of two organic semiconductor layers sandwiched between two electrodes, where the two layers are typically an electron-donating (or p-type) layer and an electron-accepting (or n-type) layer. In bilayer OPVs, the electron-donating layer is typically a conjugated polymer or a small molecule with a low ionization potential, while the electron-accepting layer is usually a fullerene derivative or a non-fullerene acceptor with a high electron affinity.[119,120] The two layers are usually deposited using solution-based methods such as spin-coating. When light strikes the bilayer OPV, it creates an exciton in the electron-donating layer. The exciton is then separated into an electron and a hole, which are transported to the electron-accepting layer and the anode, respectively. The electron and hole then flow through their respective layers and the external circuit, creating a photocurrent that can be used to generate electricity.

4.2.3 Bulk heterojunction OPV cells. Bulk heterojunction OPV cells are a type of thin-film solar cell that consist of an interpenetrating network of electron-donating and electron-accepting materials.[121] In a bulk heterojunction OPV cell, the electron-donating and electron-accepting materials are typically conjugated polymers or small molecules that are blended together in a solution and deposited onto a substrate using spin-coating or other solution-based methods. The blend forms an interpenetrating network of donor and acceptor materials, which allows for efficient charge separation and transport. The anode and cathode are the two electrodes that sandwich the blend of electron-donating and electron-accepting materials.[122,123]

The anode is typically made of a transparent conductive oxide such as indium tin oxide or fluorine-doped tin oxide, while the cathode is typically made of a metal such as aluminum, silver, or gold. When sunlight strikes the bulk heterojunction OPV cell, it creates an exciton in the electron-donating material. The exciton is then separated into an electron and a hole, which are transported to the electron-accepting material and the anode, respectively. The electrons and holes then flow through their respective materials and the external circuit, creating a photocurrent that can be used to generate electricity.[124]

4.2.4 Tandem OPV cells. A tandem PV cell typically consists of two or more sub-cells that are connected in series to improve the efficiency of the device. The sub-cells can be made of different materials and have different band gaps to allow them to absorb different parts of the solar spectrum. In the tandem PV cell, each sub-cell is comprised of an absorber material and an electron transport material.[122,125] The absorber material is responsible for absorbing the incoming photons and generating electron–hole pairs (excitons), while the electron transport material facilitates the separation and transport of the generated charge carriers.

The junction between the two sub-cells allows for the efficient transfer of charge carriers between the two sub-cells. In a tandem PV cell, the bandgap of the first sub-cell is typically higher than the bandgap of the second sub-cell, which allows the first sub-cell to absorb the high-energy photons while the second sub-cell absorbs the low-energy photons.[126,127] Overall, the use of tandem PV cells can improve the efficiency of a solar cell by allowing for a wider range of the solar spectrum to be absorbed and converted into electricity.

4.2.5 A brief comparison for device structures. As given within the previous sections, different types of OPV structures have been developed, each with unique advantages and disadvantages. Table 3 makes a brief comparison focusing on some key features. This comparison will provide insights into the performance and potential of these structures, and help identify the most promising candidates for future research and development.

4.3. Parts of the OPV cells

The basic structure of an OPV cell involves the use of several materials, including organic semiconducting materials for the

Table 3 A brief comparison between device structures of OPV cells

Structure	Advantages	Disadvantages	Key features
Single-layered	Simple device architecture and potentially lower production cost	Lower efficiency compared to other OPV cells	Single layer of organic material that combines both the donor and acceptor materials, three layers in total
Bilayer	Higher efficiency compared to single-layered OPV cells	More complex device architecture than single-layered OPV cells	Two layers of organic semiconductor sandwiched between two electrodes, solution-based methods such as spin-coating
Bulk heterojunction	High efficiency and excellent flexibility	Complexity in blending donor and acceptor materials	Interpenetrating network of electron-donating and electron-accepting materials, typically deposited by spin-coating
Tandem	Higher efficiency due to wider range of solar spectrum	More complex device architecture than single-layered OPV cells	Two or more sub-cells connected in series, with different band gaps to absorb different parts of the solar spectrum

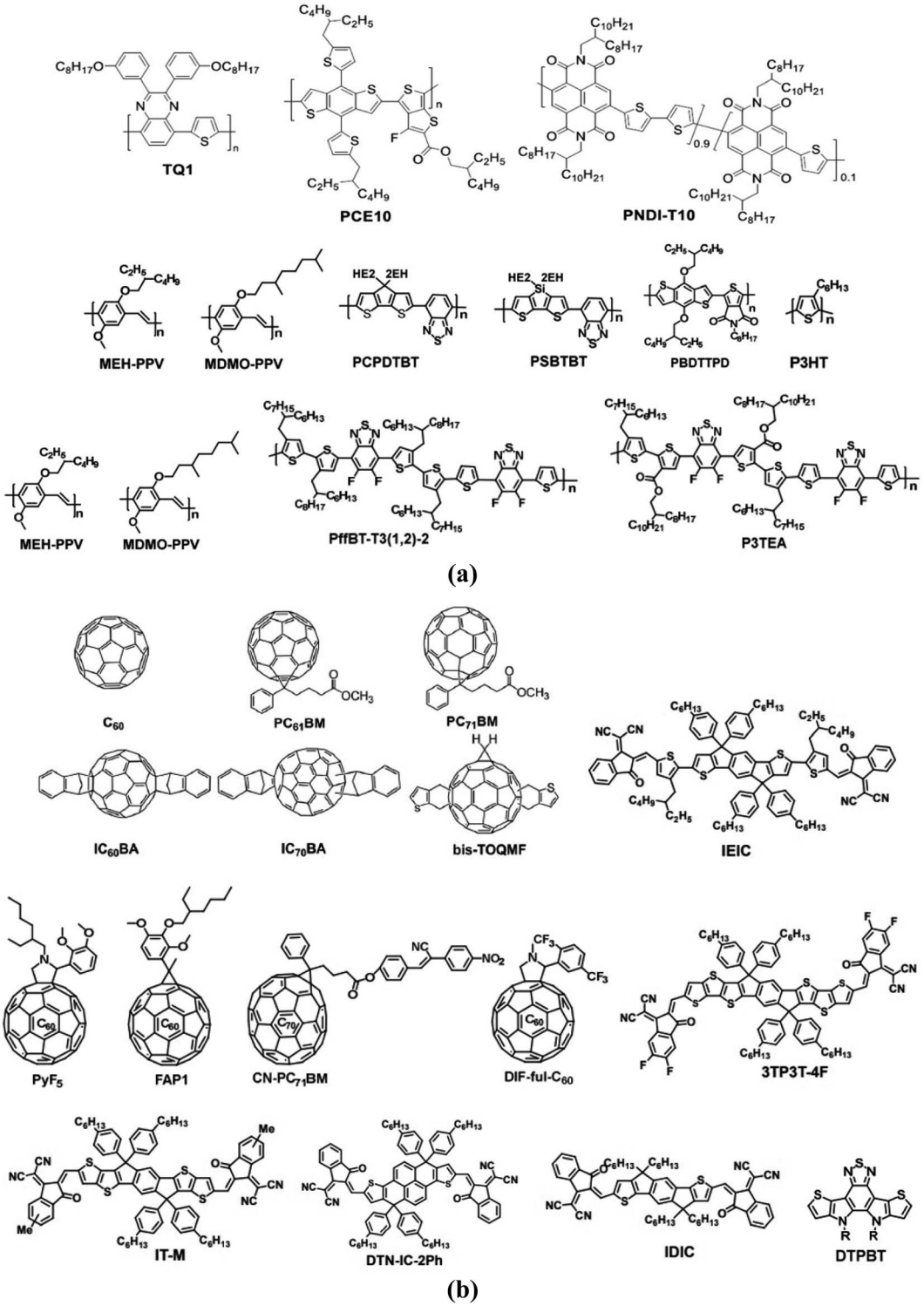

Fig. 6 Recent advances on the chemical structures of (a) donor molecules (b) acceptor molecules.[130–134]

active layer, conductive materials for the electrodes, and encapsulation materials for protection.[128,129] The performance of these materials is critical to the efficiency and durability of the OPV cell, and ongoing research is focused on improving their properties and developing new materials to enhance the performance and reduce the cost of OPV cells.

4.3.1 Organic semiconducting materials. The active layer of an OPV cell typically consists of a blend of electron-donor and electron-acceptor materials, which together form an organic semiconductor.[130] These two materials function together to create a charge-separated state upon exposure to light, leading to the production of electrical energy. Without either of these

components, the OPV would be unable to operate effectively. Therefore, the proper selection and pairing of these materials are critical to achieving high efficiency and stability in OPVs. Donor–acceptor molecules typically have a conjugated backbone consisting of alternating electron-rich (donor) and electron-deficient (acceptor) moieties. This allows for efficient charge transfer and separation when the material is exposed to sunlight.[131] Some of the most frequently used donor–acceptor compounds in OPV cells are conjugated polymers and small molecules as electron donors illustrated in Fig. 6(a) and fullerene and non-fullerene derivatives as electron acceptors illustrated in Fig. 6(b).[130–134]

The conjugated polymer can be designed with a low ionization energy, allowing it to donate electrons when excited by light. In contrast, the fullerene derivative has a high electron affinity, enabling it to accept electrons from the excited polymer. The resulting exciton dissociation leads to the generation of free electrons and holes, which can then be collected at the electrodes to produce an electric current. The selection of donor–acceptor compounds depends on factors such as their absorption spectra, energy levels, and solubility, as well as the desired efficiency and stability of the OPV cell.

In recent years, there has been a significant amount of research focused on the development of organic semiconductors for use in OPV cells.[135,136] The performance of these devices is highly dependent on the electronic properties and structure–function relationships of the materials used.[137,138] As a result, a deep understanding of these properties and relationships is essential for designing and developing high-performance organic semiconductors for use in OPV cells.[139]

4.3.2 Electrodes. OPV cells typically have two types of electrodes: the transparent conductive electrode (TCE) and the metallic electrode.[140] The TCE is typically made of materials such as indium tin oxide (ITO) or fluorine doped tin oxide (FTO) and is placed on the side of the cell facing the incident light.[141,142] This electrode is transparent so that the light can pass through it and reach the active layer, and it is electrically conductive so that it can collect the electrons produced by the active layer. The metallic electrode, on the other hand, is typically made of materials such as aluminum or silver and is placed on the opposite side of the cell, away from the incident light.[143] This electrode is not transparent, but highly reflective in that it can reflect back from the cell any light that is not absorbed by the active layer to increase the chance of absorption. There are also different types of OPV cells that can use different materials and configurations for the electrodes, depending on the particular design and application.[144,145]

4.3.3 Encapsulation materials. Encapsulation is an important step in the manufacturing process of OPV cells as it protects the device from moisture, oxygen, and other environmental factors that can degrade the performance and lifetime of the device. The encapsulation materials used in OPV cells are typically selected based on their ability to provide a barrier against moisture and oxygen while still allowing light to pass through.[146,147] Glass is a common encapsulation material for OPV cells, but it can be brittle and crack under stress. Polymer films, such as PET and PEN, are flexible and lightweight, making them a good choice for encapsulating OPV cells. Metal foils, such as aluminum and copper, provide a high barrier to moisture and oxygen but are less suitable for encapsulating flexible OPV cells.[148,149] Thin film coatings like SiO_2 and TiO_2 are also used as encapsulation materials for OPV cells, but their application requires specialized equipment and processes. The choice of encapsulation material for OPV cells depends on the specific requirements of the device, such as flexibility, transparency, and barrier properties.[150,151]

4.4. Performance and efficiency of OPV cells

The performance and electrical characteristics of photovoltaic cells play a crucial role in determining the efficiency and effectiveness of photovoltaic systems. Performance of photovoltaic cells is measured by various parameters such as power output, efficiency, and fill factor.[152,153] The power output of a photovoltaic cell is defined as the maximum power that it can generate under standard test conditions.[154] The efficiency of a photovoltaic cell is expressed as:

$$\eta = \frac{P_{\text{out}}}{P_{\text{in}}}$$

where η is the efficiency, P_{out} is the output power and P_{in} is the incoming solar power. The fill factor (FF) of a photovoltaic cell is defined as the ratio of the maximum power to the product of the open-circuit voltage (V_{OC}) and the short-circuit current (I_{SC}). It is given by:

$$\text{FF} = \frac{P_{\max}}{(V_{\text{OC}} \times I_{\text{SC}})}$$

where $P_{\max}$ is the maximum power output of the cell. The electrical characteristics of photovoltaic cells include the open-circuit voltage (V_{OC}), short-circuit current (I_{SC}), and maximum power point voltage (V_{mp}). The open-circuit voltage is the voltage across the cell when no current is flowing through it, and it is given by:

$$V_{\text{OC}} = \frac{nkT}{q}\ln\left(\frac{I_{\text{L}}}{I_0} + 1\right)$$

where n is ideality factor, k is Boltzmann's constant, T is the temperature in Kelvin, q is the charge of an electron, I_{L} is the light-generated current and I_0 is the reverse saturation current. The short-circuit current is the current that flows through the cell when the voltage across it is zero and it is given by:

$$I_{\text{SC}} = I_{\text{L}} - I_0\left(e^{\frac{qV}{nkT}} - 1\right)$$

where e is the base of the natural logarithm. It should be noted that the short circuit current (I_{SC}) represents the maximum current at zero voltage. Ideally, if $V = 0$, $I_{\text{SC}} = I_{\text{L}}$.

The maximum power point voltage (V_{mp}) is the voltage at which the photovoltaic cell generates the maximum power and it is given by:

$$V_{\text{mp}} = V_{\text{OC}} - \frac{kT}{q}\ln\left(1 + \frac{qV_t}{kT}\right)$$

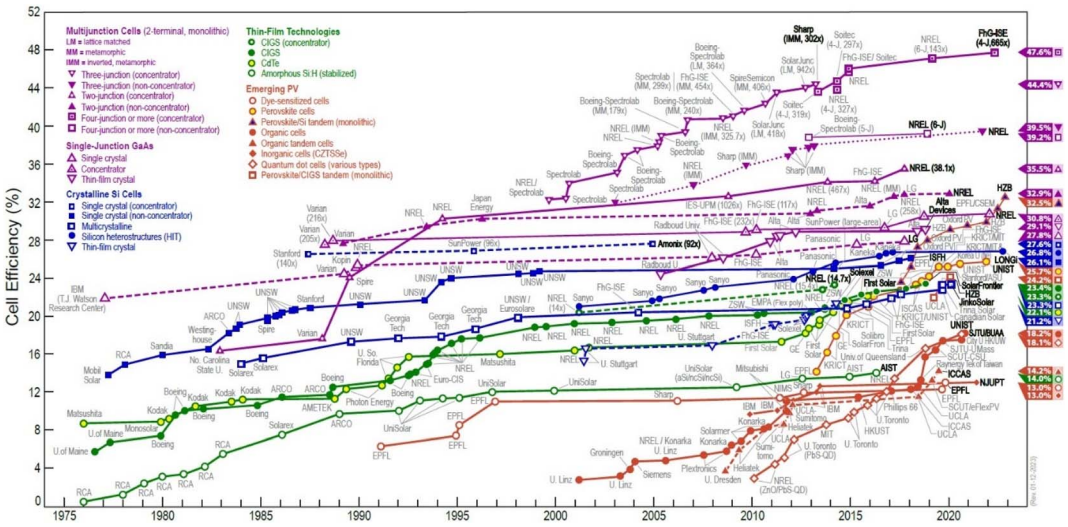

Fig. 7 A chart of the highest confirmed conversion efficiencies for PV cells.[157]

Power conversion efficiency (PCE) is one of the most important parameters of photovoltaic cells. PCE is a term used to express how effective the device is at converting solar energy into electrical energy.

$$\mathrm{PCE} = \frac{V_{\mathrm{OC}} \times J_{\mathrm{SC}} \times \mathrm{FF}}{P_{\mathrm{in}}}$$

In addition to the above-mentioned characteristics, the temperature coefficient of photovoltaic cells is also an important parameter that needs to be considered. This coefficient refers to the change in the performance of the cell with respect to temperature changes. Photovoltaic cells generally have a negative temperature coefficient, meaning that their performance decreases with an increase in temperature.[155,156]

The National Renewable Energy Laboratory (NREL) is a reputable research center that specializes in renewable energy and energy efficiency.[157] They publish detailed reports on these topics and maintain a chart that tracks the highest confirmed conversion efficiencies for research cells across various photovoltaic technologies. This chart spans from 1976 to the present day and serves as a valuable tool for tracking the historical development of PV cell technology. NREL's data is particularly noteworthy, as it provides a comprehensive view of the progression of PV cell technology across different structures. Fig. 7 in their report illustrates this development over time.

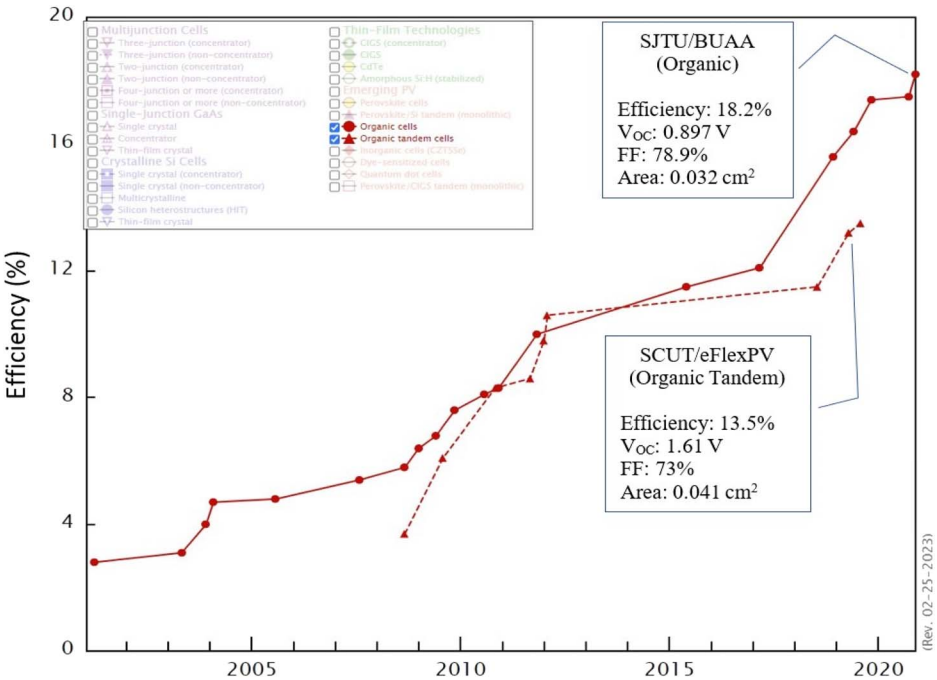

Fig. 8 Conversion efficiencies for OPV cells from 2001 to 2021.[157]

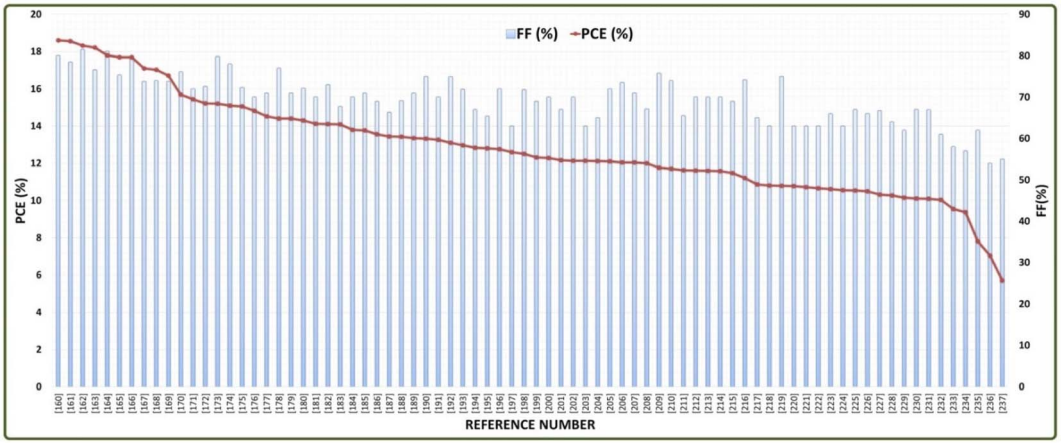

Fig. 9 Performance of organic solar cells reported in recent literature.[160–237]

Additionally, the report includes a more detailed graph, shown in Fig. 8, which specifically focuses on OPVs.

Fig. 7 and 8 demonstrate that current PV cell technologies are capable of achieving efficiencies greater than 40%. However, this level of efficiency is currently limited to multi-junction and concentrated cells, which are efficient but not yet widely used due to their high cost and limited economic feasibility. A similar scenario is also observed in cells based on inorganic materials. In the case of organic cell technology, current efficiencies can reach up to 18%. While this is not as high as multi-junction or concentrated cells, it is noteworthy given the lower cost and greater feasibility of organic cells. Continued research and development in all areas of PV cell technology will be necessary to further improve efficiency, reduce costs, and increase economic viability.

Recent literature on the OPV cell technology corroborates the efficiency rates reported by NREL. For example, recent review studies conducted by Li Y. *et al.*[158] and H. Gao *et al.*[159] reported that the latest developments in OPV cells have achieved a PCE% of up to 18.6% and an FF% of approximately 80%. These findings are consistent with the data presented in NREL's report. Fig. 9, which depicts reported PCE and FF rates of OPV cells in above references, provides advances achieved in recent studies. As seen, the FF% values range from 54% to 81.5%, while the PCE% values range from 5.72% to 18.6%. The highest FF% and PCE% values reported are 81.5% and 18.6%, respectively, while the lowest values reported are 54% and 5.72%, respectively.

Fill factor is an important parameter that measures how effectively a solar cell can convert incident light into electrical power. A higher FF% value indicates that the device can collect a larger fraction of the generated current, which results in higher output power. In Fig. 9, the average FF% value is 70.2%, which indicates that most of the devices have good fill factors.

Similarly, power conversion efficiency (PCE) is the most commonly used parameter to compare the performance of different solar cell technologies. It measures the percentage of incident solar energy that can be converted into electrical power. The highest PCE% value reported in Fig. 9 is 18.6%, which is close to the current record for OPV cells. However, the average PCE% value is only 13.7%, indicating that there is still significant room for improvement.

Fig. 9 also verifies that there exists a positive relationship between fill factor and power conversion efficiency in photovoltaic cells. Specifically, a higher fill factor typically results in a higher power conversion efficiency. This can be attributed to the fact that a higher fill factor indicates that a larger portion of the incident light is being converted into useable electrical power, which in turn leads to an increase in overall efficiency. However, there is typically a trade-off between fill factor and power conversion efficiency. This is because improving one parameter often comes at the expense of the other. For example, increasing the fill factor can be achieved by reducing the resistance of the solar cell, but this can also lead to an increase in the recombination rate of charge carriers, which can reduce the overall efficiency of the cell. Similarly, increasing the power conversion efficiency can be achieved by improving the collection of charge carriers, but this can also lead to an increase in the dark current, which can reduce the fill factor. Therefore, the optimal balance between fill factor and power conversion efficiency depends on the specific design and operating conditions of the solar cell, and requires careful optimization.

5. Evaluation and assessment

OPV cells have the potential to offer a sustainable and eco-friendly alternative to traditional solar cells, with low production costs and design flexibility. However, they also face challenges in terms of efficiency, durability, and competition from established renewable energy technologies. Table 4 presents a detailed SWOT analysis for OPV cells, highlighting the key strengths, weaknesses, opportunities, and threats facing this technology. The strengths of OPV cells, such as their low production costs and design flexibility, make them an attractive option for a range of applications, including consumer-facing products and emerging industries. The opportunities presented by growing demand for renewable energy sources, favorable government policies and incentives, and increasing consumer awareness of sustainability and environmental

Table 4 SWOT analysis for OPV cells

Strengths
Flexible and lightweight: OPV cells are thin and flexible, which makes them suitable for a range of applications including wearable technology, building-integrated photovoltaics, and solar-powered fabrics. They are also less susceptible to damage from wind and impact compared to rigid solar panels
Low-cost production through printing techniques: OPV cells can be produced using roll-to-roll printing or other low-cost printing techniques, which reduces manufacturing costs and enables scalability. The use of printing techniques also allows for customization and the creation of unique shapes and designs
Eco-friendly and easy to dispose of: OPV cells are made from non-toxic materials, such as carbon-based polymers, and are free of rare and expensive materials like silicon and metals. This makes them environmentally friendly and easy to dispose of at the end of their lifespan. OPV cells can also be recycled into new cells or other products
Modular and scalable: OPV cells can be produced in different shapes and sizes, and can be interconnected to form modules or arrays. This allows for scalability and the customization of solar panels to fit specific applications and installation sites
Low-light performance: OPV cells have a higher efficiency under low-light conditions compared to traditional silicon-based solar cells. This makes them suitable for use in regions with less sunlight, or for indoor applications such as powering smart buildings and IoT devices
Weaknesses
Limited efficiency compared to traditional silicon-based solar cells: OPV cells have a lower conversion efficiency compared to traditional silicon-based solar cells. They typically have an efficiency of 10–20%, while silicon-based solar cells are higher than this rate. This limits the power output of OPV cells, which may not be sufficient for certain applications
Durability and stability issues: OPV cells are less durable and stable compared to traditional solar cells, and their performance may degrade over time due to exposure to UV light, moisture, and other environmental factors. The encapsulation and protection of OPV cells is a key challenge that needs to be addressed to improve their durability
Low production volume compared to traditional solar cells: OPV cells are produced in much smaller quantities compared to traditional silicon-based solar cells, which makes them less commercially viable at large-scale production. This also limits the availability of OPV cells and may increase their cost
Sensitivity to temperature: OPV cells have a lower operating temperature range compared to silicon-based solar cells. They may degrade or malfunction in high temperatures, reducing their efficiency and lifespan
Limited lifespan: OPV cells have a shorter lifespan compared to traditional silicon-based solar cells, typically around 10–15 years. This may make them less suitable for certain applications that require long-term reliability and durability
Opportunities
Development of new materials: advances in the development of new materials for OPV cells may lead to improved performance and stability
Growing demand for renewable energy sources: the increasing focus on reducing carbon emissions and transitioning to renewable energy sources creates a significant opportunity for OPV cells, as they offer a sustainable and eco-friendly alternative to traditional solar cells
Favorable government policies and incentives: governments offer subsidies, tax incentives, and other financial incentives for the adoption of renewable energy technologies. These policies create a favorable environment for the development and deployment of OPV cells

Table 4 (*Contd.*)

Opportunities
Growing consumer awareness and demand for sustainable and environmentally friendly products: consumers are becoming more aware of the environmental impact of their choices and are seeking out more sustainable and eco-friendly products. This trend creates an opportunity for OPV cells to gain market share and be adopted in a range of consumer-facing applications
Emerging markets and industries for OPV cells: OPV cells offer a range of new opportunities in industries such as agriculture, transportation, and architecture. In agriculture, they can be used to power irrigation systems and crop monitoring systems, while in transportation, they can be used to power electric vehicles, boats, and drones. In architecture, they can be integrated into building facades, windows, and roofs to provide solar power and reduce energy consumption
Collaboration and investment from major companies: many companies are investing in the development and production of OPV cells, which provides an opportunity for collaboration and knowledge sharing to further improve the technology and increase its adoption. This may make them less suitable for certain applications that require long-term reliability and durability
Threats
Competition from traditional solar cells and other renewable energy technologies: traditional silicon-based solar cells and other renewable energy technologies, such as wind and hydropower, are well-established and offer higher efficiency and reliability compared to OPV cells. This creates a threat to the adoption and commercial viability of OPV cells
Technological limitations and research challenges: OPV cells face a range of technological limitations and research challenges, such as improving their efficiency, durability, and stability. Addressing these challenges requires significant investment and research, which may slow down the adoption and commercialization of OPV cells
Regulatory and policy risks: the regulatory environment for renewable energy technologies is subject to change and may create uncertainty and risk for the adoption of OPV cells. Changes in government policies and regulations could limit the development of the OPV cell industry
Supply chain risks: OPV cells' complex supply chain involves material production, manufacturing, and distribution. Any disruption, such as material or component shortages, could affect their availability and cost
Economic risks: the commercial success of OPV cells depends on production costs, market demand, and competition. Any changes to these economic factors can threaten the industry's adoption and commercialization

impact are all factors that could drive the growth and adoption of OPV cells in the future. However, the weaknesses and threats facing OPV cells cannot be ignored. The lower efficiency and durability of OPV cells compared to traditional solar cells present a challenge for their commercial viability, and competition from established renewable energy technologies may limit their market share. Additionally, the technological limitations and research challenges faced by OPV cells require significant investment and research, which may slow down their adoption and commercialization. Finally, the regulatory environment for renewable energy technologies is subject to change and may create uncertainty and risk for the adoption of OPV cells.

As clearly seen in Table 4, organic PV cells have a natural advantage over other types of PV cells due to their transparent characteristics, which make them ideal for integration with building-integrated photovoltaics, such as windows. However, a critical challenge for efficient organic PV cells is the trade-off between average visible light transmittance (AVT) and power conversion efficiency (PCE). The recent development of materials that yield simultaneously high levels of efficiency and transparency brings the opportunity to enter important niche markets. Researchers have successfully designed and constructed a superior transparent rear electrode for efficient transparent organic photovoltaics *via* integrating an aperiodic band-pass filter (ABPF). The integrated rear electrode exhibits an AVT of up to 78.69%, a color-rendering index (CRI) of 97.54, and a total reflection in the near-infrared region (700–900 nm). As a result, ABPF-integrated transparent organic photovoltaics demonstrate a record-breaking light utilization efficiency (LUE) of 5.35%, accompanied with an AVT of 46.79% and CRI of 85.39. Reinforcing research efforts on topics such as improvement in device lifetime, color portfolio, and module design and efficiency will help in making a significant effect on changing the status of organic photovoltaics from a novel technology to a mature industry.[238–240]

Similar to their transparent characteristics, one of the key features of OPV cells is their tunability, which refers to their ability to be easily modified to meet specific application requirements. Organic materials used in PV cells can be easily synthesized and modified, allowing for a high degree of control over the cell's optical and electrical properties. This means that the cells can be designed to absorb specific wavelengths of light, making them suitable for a range of applications, from powering small electronic devices to generating electricity on a larger scale. Another important feature of OPV cells is their versatility. Unlike traditional silicon-based solar cells, OPV cells can be manufactured using low-cost, flexible substrates, such as plastic or metal foils. This flexibility allows for the cells to be integrated into a variety of surfaces, including curved or irregular shapes, making them ideal for use in portable and wearable electronics, as well as building-integrated photovoltaic systems. Additionally, OPV cells have the potential to be produced in large quantities using roll-to-roll printing techniques, which could significantly reduce production costs and increase their accessibility to a wider range of applications.

On the other hand, to overcome the challenges emphasized in Table 4, it will be important for the OPV cell industry to focus on research and development to improve the efficiency, durability, and stability of the technology.[241–246] Addressing these technological limitations will help to increase the commercial viability of OPV cells and enable them to compete with traditional solar cells and other renewable energy technologies. Additionally, collaboration with governments, policymakers, and stakeholders can help to create a more favorable regulatory environment for OPV cells and facilitate their adoption.

In conclusion, while OPV cells face significant challenges, their potential for sustainable and eco-friendly energy production is promising. The OPV cell industry should work towards addressing the weaknesses and threats identified in the SWOT analysis, while continuing to build on their strengths and opportunities, to enable the widespread adoption of this technology in the future.

6. Conclusion

This state-of-the-art review provides a comprehensive overview of the evolution of photovoltaic (PV) cell technology. It includes the classification of PV production technologies and a comparative analysis of first, second, and third-generation solar cells. The working principles and device structures of OPV cells are also explored and compared focusing on their advantages, disadvantages, and key features. Furthermore, the paper discusses the various parts of OPV cells and analyzes the performance, efficiency, and electrical characteristics of photovoltaic cells. The conversion efficiencies for OPV cells are presented, and a detailed SWOT analysis is conducted for OPV cells.

The SWOT analysis reveals a promising future for the technology, but also highlights several challenges and areas for improvement. Despite the strengths of OPV cells, the technology still faces weaknesses such as limited efficiency, durability and stability issues, sensitivity to temperature, and limited lifespan. However, there are opportunities to improve the technology, including the development of new materials, growing demand for renewable energy sources, favorable government policies and incentives, growing consumer awareness and demand for sustainable and environmentally friendly products, emerging markets and industries, and collaboration and investment from major companies. The review also identifies potential threats to the adoption and commercial viability of OPV cells, including competition from traditional solar cells and other renewable energy technologies, technological limitations and research challenges, regulatory and policy risks, supply chain risks, and economic risks.

The review indicates that OPV cells have the potential to revolutionize the solar energy industry due to their compatibility with printing technologies and the ability to produce thin, flexible solar cells. However, challenges such as preventing recombination, improving absorption in the visible to near-infrared part of the solar spectrum, and optimizing morphological characteristics for charge transport still exist. Despite these challenges, researchers are making steady progress, and the tunability and versatility of organic materials offer promise for future success. The potential applications for thin, flexible OPV cells are exciting, including powering remote or underdeveloped areas and charging internal devices.

Overall, this review highlights the significant advancements and challenges in the development of OPV cells. It is hoped that this paper will serve as a valuable resource for researchers, policymakers, and stakeholders interested in the development of sustainable and efficient solar energy technologies. Future research should focus on addressing the challenges identified in this paper and developing new materials and technologies that can further improve the performance and efficiency of OPV cells.

Conflicts of interest

There are no conflicts to declare.

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