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Mini Review

Application of organic photovoltaic materials (OPV) as greenhouse roof structures: A review

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Abstract

Organic Photovoltaic (OPV), as a third-generation PV technology, is becoming an appropriate substance used for greenhouse roofing structures. Semi-transparent OPV has a variety of merits such as low weight, flexibility, low environment impact and short energy payback time. Besides, it can harness larger amounts of sunlight as means of a very strong light absorbent material. This study shares some of the latest research which examines the feasibility of using semi-transparent, flexible organic photovoltaic (OPV) modules as greenhouse shading material. By using such modules, it may be possible to utilize the existing greenhouse-based agricultural areas for electricity production. The concept projects OPV modules to shade greenhouses and reduces excess solar energy which may result in reducing internal surrounding heat thus helps to mitigate the control environment. This will furthermore control plant heat stress which is one of the most important factors for plant growth. Some conclusion on the quality and quantity of plants with respect to the energy consumption in the greenhouse are also discussed.

Introduction

The demand of renewable and environmental-friendly energy in the world is increasing, Photovoltaic (PV) energy is becoming the most important energy alternative among renewable energy sources such as wind, biomass and hydropower (Khatibi et al., 2019). Fig.1 shows the three generations revolution of PV technology which are crystalline silicon modules, thin film amorphous modules and organic Photovoltaic (OPV). For silicon-based PVs, there are some evident limitations. For example, the fabrication process is complicated, expensive, energy consuming and high temperature manufacturing (Khalil et al., 2016). However, as a third-generation PV technology, OPV has attracted a lot of attention due to a variety of advantages compared to other silicon-based PVs such as low environment impact, light weight and portability (HÖSEL et al., 2013, Wang and Zhan, 2016). At present, OPV is a rapidly emerging PV technology with around13.2% cell efficiency (NREL, 2020). OPV uses organic electronics for light absorption and charge transport to generate the electricity power from the sun, and electronics are used to deal with conductive small organic molecules or organic polymers (Cornaro and Di Carlo, 2016, Musselman and Poorkazem, 2019) .

Nowadays, many studies have focused on the OPV applications however there are only a few papers to study on using OPV modules as greenhouse roof shading materials. Even though silicon-based PVs are usually used for integrating on the rooftops of greenhouses due to high efficiency, they are still facing significant defects as greenhouse rooftop materials (i) high weight (ii) rigid, brittle and bulky (iii) reduced efficiency at high temperatures (iv) inhibit photosynthesis and plant growth because of opacity (Zisis et al., 2019). However, OPV has not only above-mentioned advantages, but also (i) low manufacturing cost due to roll-to-roll printing processes (ii) semi-transparent etc. Besides, over-sunlight can cause heat stress to the plants in the greenhouse (Lamnatou and Chemisana, 2013) especially in the tropical regions. OPV can also mainly absorb sunlight that is not needed for crop growth and allow the remaining sunlight to reach the plants (Magadley et al., 2020). Therefore, OPV is becoming a better candidate that applies on the greenhouse roof than silicon-based PVs. Hence, through this review, some of the latest research examines the feasibility of using OPV modules as greenhouse shading materials. OPV modules will be projected to reduce the excess solar energy and lead to the reduction of internal surrounding heat. Besides, the quality and quantity of plants in the greenhouse will be also discussed.

Working principle of OPV

The types of OPV structures normally include single layer, bilayer (double layer) and bulk heterojunction (Sen and Islam, 2018). Fig. 2 shows the basic structures for three types of OPV solar cells.

Fig. 2a is the single layer of OPV solar cell. It has only one active material. The drawback is that this type usually fails to reach acceptable efficiencies. This is because high energy for excitons is needed and the organic materials are limited. Fig. 2b is the bilayer heterojunction OPV solar cell. It is comprised of two contacted layers, which are donor and acceptor materials. They are sandwiched between two electrodes. The bilayer heterojunction structure is difficult to achieve high power conversion efficiency (PCE) due to many generated excitons cannot reach the interface. Fig. 2c is the bulk heterojunction OPV solar cell, and it consists of mixture of donor and acceptor semiconductor materials. In general, this type of structure can achieve much higher PCEs than those from bilayer heterojunction. This is because the exciton easily diffuses to a nearby interface and then dissociates into electron and hole. Besides, small molecule and polymer-based solar cells in the organic bulk heterojunction structure both attains the highest PCE. For example, the organic bulk heterojunction solar cell

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Figure 1. Revolution of PV technology (a) crystalline silicon modules (Castellano et al., 2016), (b) thin film amorphous modules (Hassanien et al., 2016) and (c) OPV (ApS, 2020)

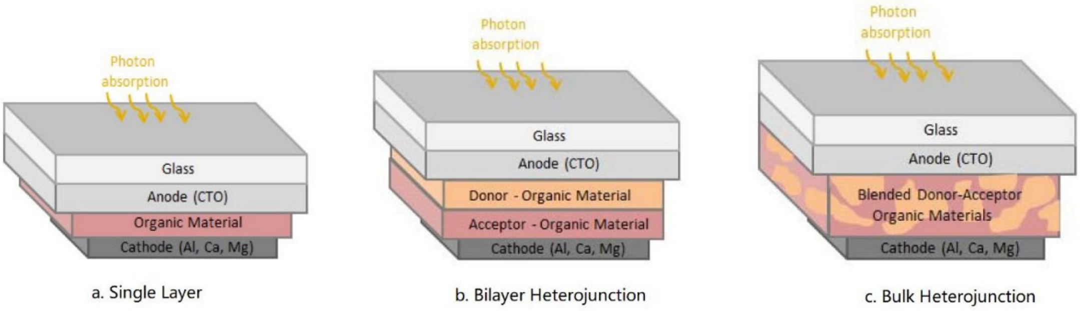

Figure 2. The basic structures of OPV solar cell for three types (Khalil et al., 2016)

based on poly (3-hexylthiophene): [6,6]-phenyl-C61-butyric acid methyl ester (P3HT:PCBM) photoactive layer is the most investigated system recently (Kalonga et al., 2013).

Fig. 3 illustrates the working process occurring in organic solar cells. It mainly includes five steps. The light absorption of photon is the first step that occurs in the donor and acceptor phase (active layer) to produce excitons. Then, exciton transport to the donor/acceptor interfaces. After this, in order to produce electrons, exciton separation at the interfaces in the lowest unoccupied molecular orbital (LUMO) of the acceptor and holes in the highest occupied molecular orbital (HOMO) of the donor. The next step is charge transportation. It means that along the acceptor network, the electrons transport to the cathode and along the donor network, the holes transport to the anode. In the end, it is the collection process of charge. This process is regularly accomplished by a transparent conductive oxide (TCO) such as Indium-doped tin oxide (ITO). In order to form photovoltage and photocurrent, the charge is collected by the anode and the cathode. The inorganic solar cells directly generates the free charge carriers, this becomes the main difference for the working principle with the organic solar cells (Jannat et al., 2013, Peretz et al., 2019, Fusella et al., 2019).

Different materials for light absorption (active layer materials)

The process of light absorption happens in the active layer of organic PV. Hence, many researchers make efforts to develop high-performance donor and acceptor materials. These materials can determine the organic semiconductors' ability of absorbing light and conducting charge (Amollo et al., 2019). In other words, the good active layer materials in OPVs could improve the device stability, increase the device efficiency and reduce the cost (Xue et al., 2018). The active layer in OPVs were composed of a single layer that only based on one component of organic material but showed very poor performances before the mid-1980s. In 1986, the first bilayer device was found by Tang. This device used copper phthalocyanine (CuPc) as donor and perylene tetracarboxylic derivative (PTCBI) as acceptor respectively, which had an efficiency of only 1% (Wang and Zhan, 2016, Muhammad et al., 2019). Recently, the active layer can be selected as small molecule-based, polymer-based or a hybrid organic-inorganic structure. Generally, materials with increased light absorption at long wavelengths are available for OPV applications (Dyer-Smith et al., 2018). The commonly used organic donors are poly(2-methoxy-5-(2-ethylhexyloxy)-1-4-phenylenevinylene) (MEH-PPV), poly(p-phenylenevinylene) (PPV), poly(p-phenylene benzobisthiazole) (PBZT), P3HT, poly[2-methoxy-5-(3′,7′-dimethyloctyloxy)]-p-1-4-phenylenevinylene (MDMO-PPV) etc. For organic acceptors, examples of the commonly used are poly(benzamidazobenzophenanthroline) (BBL), PCBM, poly(2,5,2′,5′-tetraalkoxy-7,8′-dicyanodi-p-phenylenevinylene) (CN-PPV), poly [2-alkoxy-5-alkanesulfonyl-1-4-phenylene vinylene] (SF-PPV) etc (Rwenyagila, 2017). These organic materials have attracted more considerable sight because they have the potential to provide flexible, inexpensive electronics, environmentally safe and lightweight (Jannat et al., 2013). Table 1 shows some examples of photovoltaic properties for high performance materials used in active layer of OPVs.

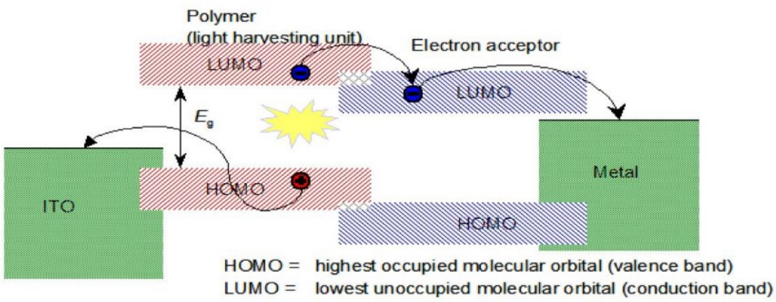

Figure 3. The working process in organic solar cell (Bagher, 2014a)

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Table 1. Some examples of high-performance materials used in active layer of OPV

Donor material	Acceptor material	Voc (volts)	Jsc (mA/cm^2)	FF (%)	PCE (%)	Ref.
P3HT	$PC_{61}BM$	0.75	14.8	72.0	8.0	(Cheng and Zhan, 2015)
PTB7	$PC_{71}BM$	0.76	16.3	70.0	8.7	(Cheng and Zhan, 2015)
PDTP-DFBT	$PC_{71}BM$	0.7	18.0	63.4	8.0	(Chang et al., 2018)
PDPP4T-2F	$PC_{71}BM$	0.79	15.9	65.8	8.2	(Zheng et al., 2016)
PTB7-Th	$PC_{71}BM$	0.8	15.73	74.3	9.35	(Liao et al., 2013)
PTB7-Th	ITIC	0.81	14.21	59.1	6.8	(Lin et al., 2015)
PTB7-Th	IHIC	0.754	19.01	68.1	9.77	(Wang et al., 2017)
PTB7-Th	IEICO-4F	0.74	22.8	59.4	10.0	(Yao et al., 2017)
PBDTTT-E-T	IEICO	0.82	17.7	58.0	8.4	(Yao et al., 2016)
PDBT-T1	ITIC-Th	0.88	16.24	67.1	9.6	(Lin et al., 2016)
PBDB-T	PBI-Por	0.78	14.5	66	7.4	(Zhang et al., 2017)
PBDB-T	ITIC	0.899	16.81	74.2	11.2	(Zhao et al., 2016)
PBDB-T	SFBRCN	0.93	17.86	73.9	12.27	(Xu et al., 2017)
PBDB-TF	IDTN	0.946	16.58	78	12.2	(Li et al., 2017)
PBDB-T-SF	IT-4F	0.88	20.88	71.3	13.1	(Zhao et al., 2017b)
PBDB-T-2CI	IT-4F	0.86	21.8	77	14.4	(Zhang et al., 2018)
J71	ITIC	0.94	17.32	69.77	11.41	(Bin et al., 2016)
FTAZ	ITIC-Th1	0.849	19.33	73.73	12.1	(Zhao et al., 2017a)
PFBDB-T	C8-ITIC	0.94	19.6	72	13.2	(Xue et al., 2018)

Note: Jsc is short-circuit photocurrent, Voc is open-circuit photovoltage, FF is fill factor, PCE is power conversion efficiency. The magnitude of Jsc, Voc and FF depends on PV properties such as light intensity, temperature, composition of the components and thickness of the active layer (Bagher, 2014b).

For OPVs, the donor and acceptor materials in blend active layer have played a decisive role on achieving high PCE. Hence, the four intrinsic properties should be possessed for donor and acceptor materials. The first is that matched absorption spectrum with solar spectrum, which accompany with high extinction coefficient, should be possessed. Then, materials should have suitable molecular energy levels alignment. Besides, high crystallinity and nanoscale phase separation are required for materials. The last is that materials also should have high-charge carrier mobility. Before 2015, the dominant organic acceptor materials in high-efficiency OPVs are the soluble C_{60} derivative 6,6-phenyl-C61-butyric acid methyl ester ($PC_{61}BM$) and its corresponding C_{70} derivative 6,6-phenyl-C71-butyric acid methyl ester ($PC_{71}BM$). In table 1, P3HT: $PC_{61}BM$ donor-acceptor active layer has achieved the 8% PCE of OPV. And the PCE of $PC_{71}BM$-based device has reached above 8%. In 2015, a new acceptor material ITIC was reported by Lin and co-workers, and PTB7-Th worked as donor material, the PCE of OPV achieved at 6.8%. Compared with conventional fullerene acceptor materials, this new acceptor material ITIC exhibits higher electron mobility, better absorption in visible region and improves miscibility with donor materials. With the donor material PFBDB-T, the non-fullerene acceptor material C8-ITIC exhibited higher absorptivity and lower bandgap. The PCE has reached 13.2% with increased crystallinity (Xue et al., 2018).

Recent studies related to OPV application as greenhouse shading material

Like some other PV materials e.g. silicon-based PV, Dye-sensitized solar cell (DSSC) have been used for greenhouse roof in many studies. Recently, several studies that used OPV as greenhouse roof shading material have been performed.

Okada *et al*. demonstrated a simulation model integrating electricity generation by OPV panels on the greenhouse roof. The greenhouse used in this model is a single span Quonset greenhouse, which is located at the University of Arizona Controlled Environment Agriculture Center (UA-CEAC) in Tucson, Arizona. Under various OPV coverage ratios on the greenhouse roof, the plant produce yield and energy production could be evaluated. In this simulation model, 3 cases were tested based on the daily light integral (DLIs). Case 1 was 25% OPV coverage for the cultivation period and 100% OPV coverage with no cultivation during the summer period; Case 2 was 25% OPV coverage for the cultivation period and 49% OPV coverage with cultivation during the summer period; Case 3 was 25% OPV coverage for the cultivation period and 100% coverage with cultivation during the summer period. The fresh shoot weights at each of ten crop cycles for Case 2 were 138.4, 249.9, 209.4, 229.7, 368.6, 257.0, 239.5, 158.7, 165.0 and 135.1g.head^{-1}. However, results for Case 1 were 138.4, 249.9, 209.4, 229.7, 123.9, 167.2 and 120.8g.head^{-1}. The results for Case 3 were 138.4, 249.9, 209.4, 229.7, 119.7, 99.1, 96.3, 156.4, 165.0 and 135.1g.head^{-1}. Moreover, the yearly electric energy generated per unit for Case 3 and 100% OPV coverage during the whole year were 8.9kWh $\cdot m^{-2} year^{-1}$ and 17.4kWh $\cdot m^{-2} year^{-1}$ respectively. However, 49% OPV coverage for Case3 generated 11.64kWh $\cdot m^{-2} year^{-1}$. Compared with the value of annual measured energy consumption from this greenhouse (11.7kWh $\cdot m^{-2} year^{-1}$), 11.64kWh $\cdot m^{-2} year^{-1}$ under 49% OPV coverage could be satisfied. Taken together, therefore, It was estimated that 49% coverage ratio of OPV was the best for the model to generate the sufficient electricity to meet the energy demand of the off-grid greenhouse system and meanwhile greenhouse was also able to produce acceptable crop fresh shoot weights. Hence, based on the different cases' results, this study also told that in semi-arid or arid regions, OPV-integrated greenhouse might be a good alternative for agrivoltaics application for crop production (Okada et al., 2018).

The semi-transparent OPV modules based on P3HT:PCBM photoactive layer was installed on the roof of the 24m^2 experimental Mediterranean greenhouse with 22% coverage. It was observed that the production of pepper plants was significantly developed under the shade of OPVs, and the height of "OPV-shaded" pepper plants was 21.8% larger than the unshaded pepper plants at the end of the growing period. Besides, the study also revealed that without the demand for additional shading systems, the integration of OPVs on the roof of Mediterranean greenhouses will provide the optimum temperature and light conditions for plants growth (Zisis et al., 2019).

Peretz *et al.* investigated that in the wavelength range 390-1100nm, the transmittances of two types of OPV modules were equivalent to 27.1% (72.9% shading) and 20.9% (79.1% shading) respectively, hence it means that partial coverage of a greenhouse by OPV modules can reduce the transmittance of excess solar energy and then reduce the heat stress on the crops instead of using the shading screens (Peretz et al., 2019).

Magadley *et al.* described that OPV panels were installed on the greenhouse tunnel roof, the outdoor behavior of OPV panels e.g. electrical behavior was measured, and it was found that OPV on the rooftop led to higher outputs, fill factors and efficiencies. Moreover, when the panels on the sides of East and West for roof, the midday peaks would be reduced and therefore a more balanced power supply would be provided throughout the whole day (Magadley et al., 2020).

The idea of Achieving Net Zero Energy greenhouses by deploying organic solar cells as shading material was proposed. Based on the results, it revealed that the system can have an annual surplus of energy during the warm and moderate climates. Besides, OSCs were suggested as an excellent candidate for implementing in the greenhouses and thus offer a significant chance to improve the environmentally-sustainable agriculture (Ravishankar et al., 2020).

Conclusion

This paper reviews some latest researches on the semi-transparent OPV modules that used as greenhouse roof shading material. Based on these studies, OPVs have the potential to be an excellent candidate to significantly develop the quality and quantity of plants in the greenhouse. At the same time, it also can be helpful to improve the internal surrounding heat and increase the electricity production. According to some examples of high-performance materials used in active layer of OPVs, although PCE of organic PV is still low when compare with silicon-based PVs, it will be enhanced while the materials of active layer (donor-acceptor materials) could become better. It is meaningful to apply OPV as greenhouse roof shading material to continue the further study.

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Author contributions

The authors have declared no conflict of interests.

Conflict of interests

Li Lu carried out the literature review and performed the main writing part. Mohammad Effendy Ya'acob supported the study by providing the concept and the structure of the manuscript and supervised the study as well as giving advice on the manuscript revision.

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