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Semitransparent Solar Cells for Agricultural Applications

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ABSTRACT

Semitransparent solar cells (ST-SCs), which combine energy generation with light transmission, hold great promise for revolutionizing agricultural practices. This review explores the integration of ST-SCs into agricultural systems. By enabling power generation without compromising crop growth, these solar cells offer a unique solution to the energy demands of modern agriculture. The advantages of ST-SCs, including improved land use efficiency, and sustainability, alongside challenges such as efficiency-tradeoffs, and integration issues. Recent advances in materials, including organic and perovskite photovoltaics, have shown significant potential for enhancing both transparency and performance. Overall, this paper highlights the transformative potential of ST-SCs in sustainable agricultural energy solutions.

1. Introduction

Agriculture stands as one of the most energy-intensive sectors globally, a demand that continues to grow in tandem with the rising need to ensure food security for an expanding population. The global food market reflects this growth, with the monetary value of food imports reaching USD 1,755 billion in 2021, as reported by the Food and Agriculture Organization (FAO) [1]. The food sector, encompassing production, processing, and distribution, accounts for approximately 30% of global energy consumption, making it one of the largest consumers of energy worldwide [2]. A substantial portion of this energy is consumed in modern agricultural practices, especially within controlled environments such as greenhouses, where significant energy is required to regulate lighting, temperature, and humidity [3]. Traditional greenhouses, in particular, rely heavily on fossil fuels or grid electricity, resulting in high operational costs and carbon emissions. The use of fossil fuels in these systems contributes to both the ongoing energy crisis and increasing greenhouse gas emissions, which pose serious risks to the environment and public health [4]. As a result, minimizing fossil fuel dependence has become a critical objective in sustainable agricultural development.

Energy management has thus become a key focus in protected cropping systems, where optimizing energy use is essential due to the high costs associated with advanced greenhouse operations. Research shows that practical strategies such as maintaining open vents while keeping

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thermal curtains closed can significantly reduce energy loads without compromising the internal climate needed for optimal plant growth. For example, daily energy consumption was observed to be lowest (70.5 kWh) under such conditions, whereas closing vents and leaving curtains open led to the highest consumption (121 kWh). Furthermore, delaying the activation of ventilation and shading systems until the plant canopy temperature reaches 25 °C can result in additional energy savings. These findings emphasize the importance of managing other environmental variables such as light intensity, humidity, and CO_2 levels for holistic energy efficiency in greenhouses [5]. Beyond greenhouse farming, open-field agriculture also presents opportunities for improved energy sustainability. Agrivoltaic systems, which involve co-locating crops and solar panels on the same land, have gained attention as a way to enhance land-use efficiency while generating renewable energy. Altogether, this escalating energy demand in agriculture combined with its environmental implications highlights the urgent need for innovative and sustainable solutions that can reduce energy consumption while preserving or even enhancing agricultural productivity.

Semitransparent solar cells (ST-SCs) have emerged as a promising technology to address these challenges by combining solar energy generation with light transmission, making them a promising solution for applications where both energy harvesting and light permeability are essential [6-13]. Unlike traditional opaque solar panels, ST-SCs are designed to convert part of the incoming sunlight into electricity while allowing the remainder especially in the photosynthetically active radiation (PAR) range to pass through. This dual functionality enables them to support both energy production and plant growth, making them ideal candidates for agricultural integration [14].

In particular, ST-SCs offer a transformative opportunity for enhancing the sustainability and efficiency of greenhouses and agrivoltaic systems. By incorporating ST-SCs into greenhouse roofs or open-field farming systems, farmers can produce renewable energy on-site while minimizing the shading impact on crops. This approach not only maximizes land use efficiency but also helps reduce dependence on fossil fuels, lower carbon emissions, and potentially decrease energy-related operating costs. Such integration supports long-term environmental and economic sustainability, aligning with global efforts to combat climate change and build resilient agricultural systems.

The objective of this review is to provide a comprehensive assessment of the current state of ST-SCs in agricultural applications, focusing on case studies and the materials currently in use. Additionally, the review will highlight the challenges that must be addressed to facilitate the widespread adoption of this technology, including issues related to efficiency, cost, and durability in agricultural environments. Finally, it will explore future directions for ST-SCs, including potential advancements in materials and technologies that could enhance their integration into agricultural systems. By synthesizing the existing literature and identifying key areas for further research, this review aims to offer a thorough understanding of the role of ST-SCs in advancing sustainable agriculture.

2. Applications of ST-SCs in Agriculture

ST-SCs are transforming agricultural practices by offering a dual advantage: generating renewable energy while allowing essential light transmission for plant growth. This innovative synergy of food production and solar energy generation on the same land is known as agrivoltaics, a concept that is gaining traction as a sustainable solution for modern agriculture. Unlike traditional solar technologies, which may obstruct sunlight and limit plant productivity, ST-SCs optimize energy harvesting while maintaining adequate light exposure, making them particularly well-suited for agricultural applications.

Figure 1 illustrates a traditional greenhouse, where plastic cladding is used for thermal insulation. In contrast, agrivoltaic greenhouse systems incorporate various photovoltaic (PV) technologies, which can be broadly categorized into non-wavelength-selective and wavelength-selective PV systems. In non-wavelength-selective systems, the use of opaque PV panels tends to inhibit crop growth due to excessive light blockage. However, semitransparent and thin-film PV technologies have been shown to enhance plant development by allowing more light penetration. Wavelength-selective PV systems, such as organic PV, take this a step further by selectively filtering and utilizing specific wavelengths of light. This targeted approach not only optimizes energy generation but can also enhance crop growth more effectively than traditional greenhouses, demonstrating the potential of agrivoltaics to improve both agricultural productivity and energy sustainability [15].

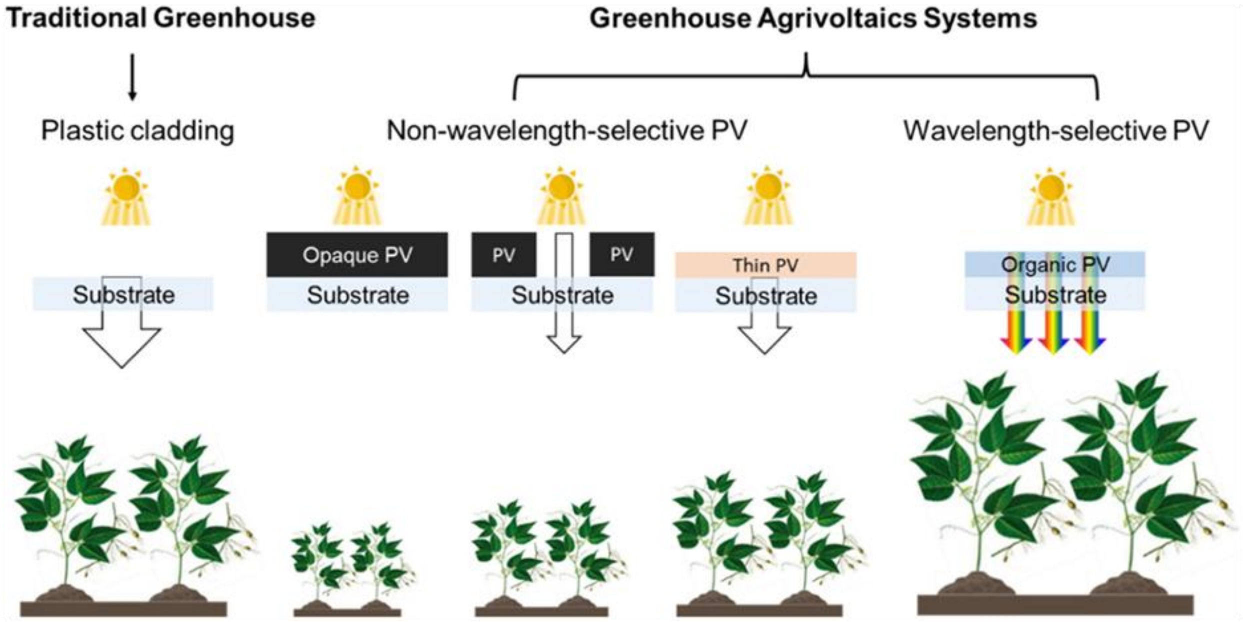


Fig. 1. Schematic of the traditional and solar-based greenhouse systems. Reproduced with permission from [15] Copyright 2023 Elsevier

One of the most promising implementations of agrivoltaics is in greenhouse systems [16]. In conventional greenhouses, balancing light transmission with energy efficiency is a persistent challenge. By integrating ST-SCs into greenhouse roofs and walls, renewable energy can be generated without significantly compromising the light needed for plant photosynthesis. Strategically placed ST-SCs on transparent surfaces allow sunlight to be harvested for electricity while ensuring that plants receive sufficient natural light for growth. The high transparency of these solar cells reduces the greenhouse's dependence on external energy sources, creating a more energy-efficient and self-sustaining agricultural environment. This approach not only enhances sustainability but also contributes to the long-term viability of controlled-environment farming, paving the way for greener and more resilient food production systems. To assess the greenhouse's heating and cooling requirements, energy flux calculations were performed, considering interactions between the greenhouse and its surrounding environment. These fluxes were derived from ambient conditions, solar radiation levels, and the physical properties of the greenhouse. The key components analyzed include the inner soil layer, surface soil layer, vegetation layer, internal air, and roof. Figure 2 provides a detailed breakdown of the energy fluxes associated with each component in a solar cell-integrated greenhouse with shading systems in place.

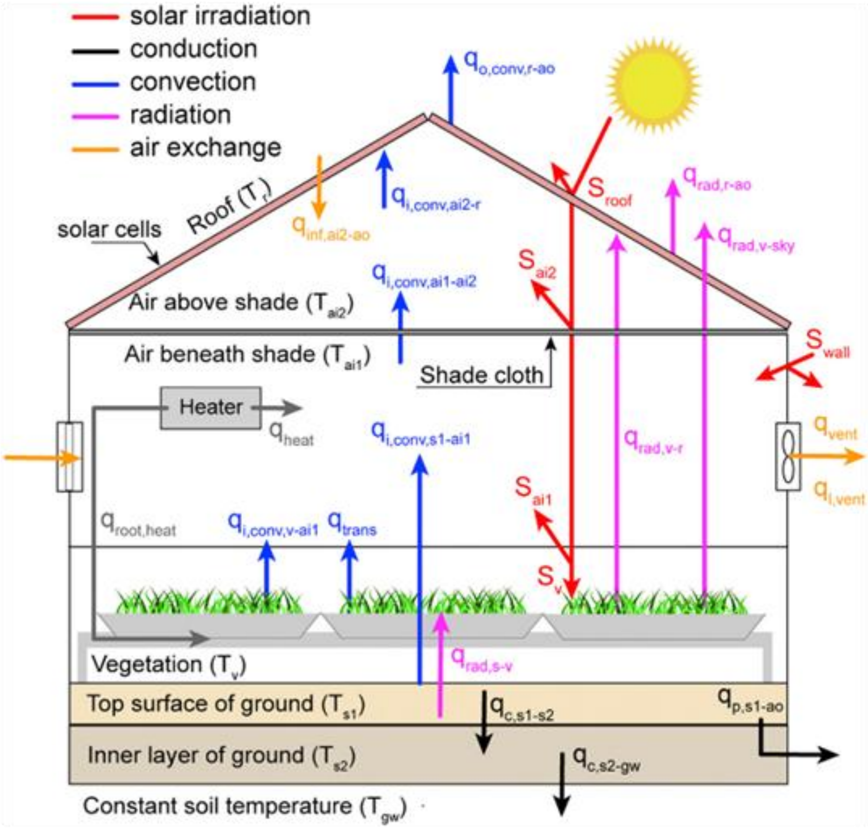


Fig. 2. Schematic of energy fluxes for ST-CSs greenhouse. Reproduced with permission from ref [17] Copyright 2020 Joule

Luo *et al.,* [18] designed and built a greenhouse featuring high-transparency PV windows integrated into the roof and walls, demonstrating its potential to enhance the sustainability of greenhouse farming at Murdoch University. As shown in Figure 3(a), the greenhouse is oriented east-west along its length to maximize solar energy capture and improve thermal efficiency, particularly during winter. The structure consists of four growth rooms: Room 1 is glazed with conventional low-iron (ultra-clear) glass, while Rooms 2, 3, and 4 use solar glass. The study also evaluated the energy potential of solar greenhouses in various geographic locations. Model simulations indicated that a fully glazed solar greenhouse could increase annual energy output by 27%, from 5,379 kWh to 6,852 kWh. Using the radiation model, a 150 m² solar greenhouse fully equipped with solar windows could generate between 6,300 and 6,800 kWh annually in cities like Cape Town, Haifa, Los Angeles, New Delhi, and Rio de Janeiro. However, in locations such as Beijing, New York, and Paris, the estimated annual output would be lower, ranging from 4,700 to 5,400 kWh (Figure 3(b)). Figure 4 illustrates the growth performance of six commercial crops—tomato, spinach mustard, snow pea, dwarf bean, bell pepper, and lettuce. Researchers measured plant height, leaf size, and leaf count, with results indicating that crops grown in the solar glass rooms appeared fresher and more vigorous compared to those in the conventional glass room. Additionally, this innovative greenhouse design significantly reduced energy consumption by 57% and water usage by 29% in research-scale greenhouse production.

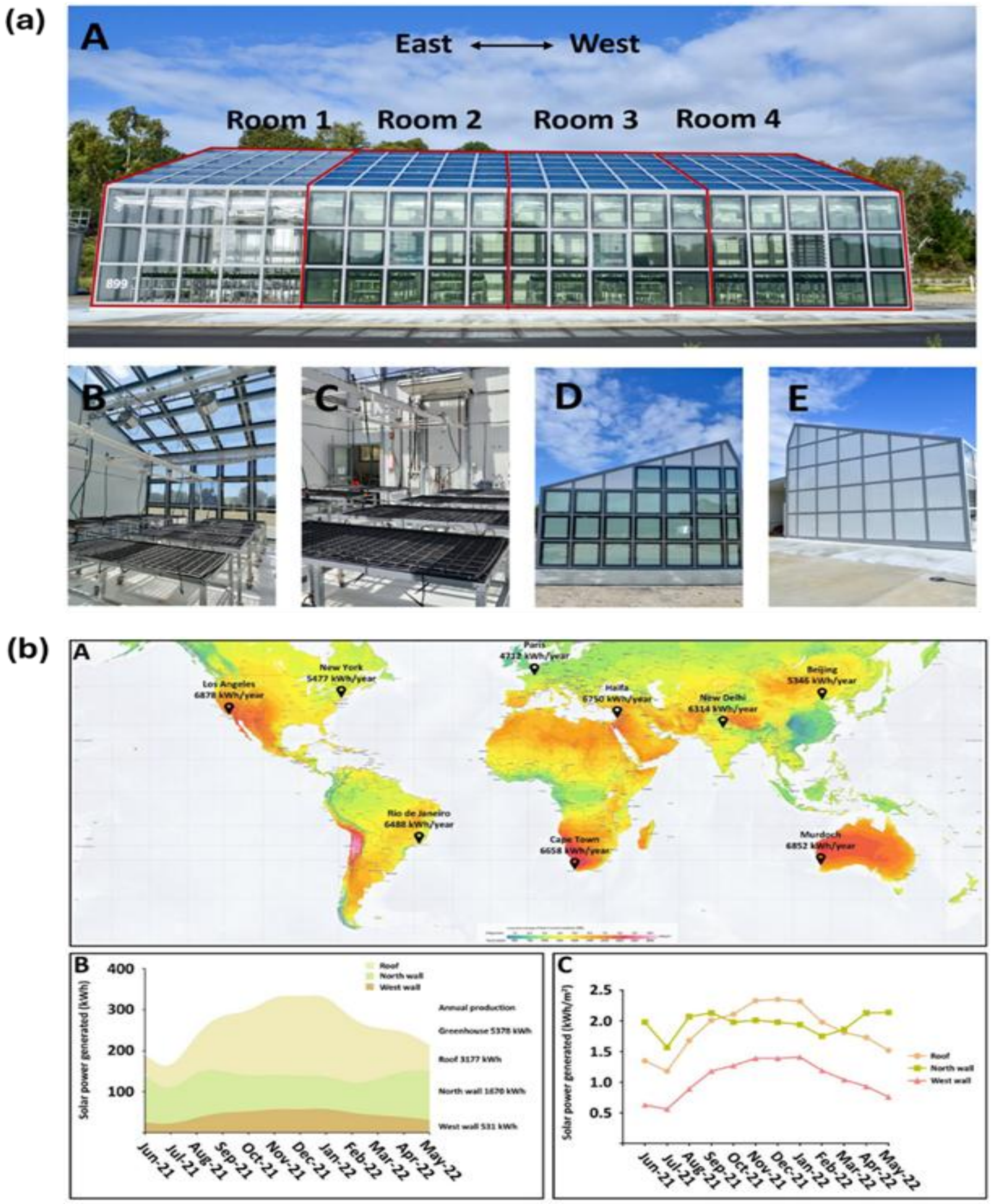


Fig. 3. (a) ClearVue solar greenhouse at Murdoch University's Grains Research Precinct. A: Four growth rooms—Room 1 (conventional glass) and Rooms 2–4 (solar glass). B: Grow benches and front windows inside a solar glass room. C: Back wall and air-conditioner inside a solar glass room. D: West end of the greenhouse with solar glass. E: East end with conventional glass (b) Solar greenhouse energy potential and electricity production. A: Global photovoltaic energy potential (per 150 m^2 land area) based on solar irradiation data. B: Monthly solar energy production from the roof and walls of the Murdoch solar greenhouse. C: Energy production per unit solar window area (kWh/m^2). Reproduced with permission from ref [18] Copyright 2025 Elsevier

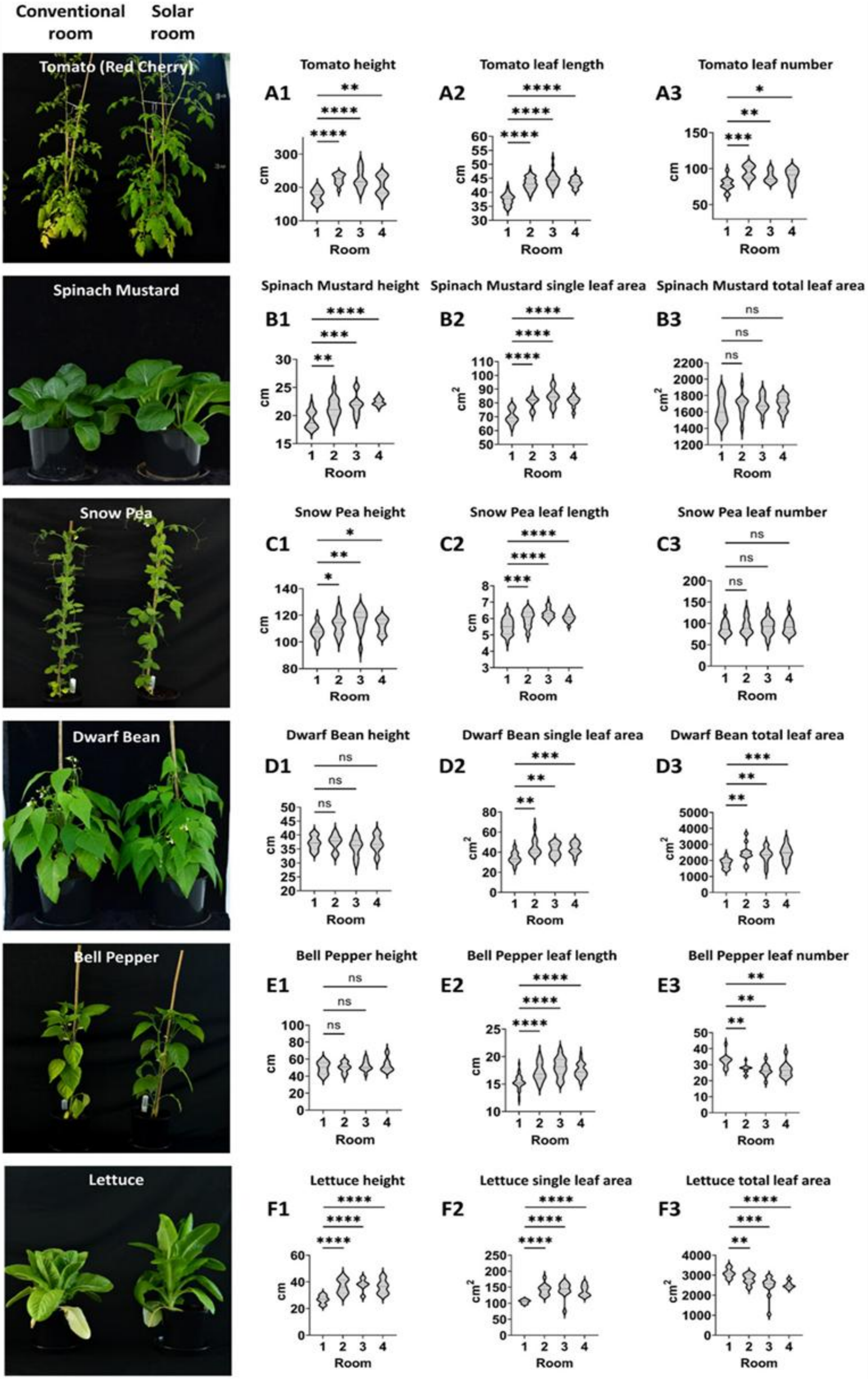


Fig. 4. Comparison of vegetative growth in six commercial crops between the conventional glass room (Room 1) and solar glass rooms (Rooms 2–4). Reproduced with permission from ref [18] Copyright 2025 Elsevier

Another study by Cossu *et al.,* [19] integrated ST-SCs into a greenhouse roof, utilizing 4,800 spherical silicon micro-cells (1.2 mm in diameter) sandwiched between glass plates and installed at a 26.5° slope (Figures 5(a) and (b)). The electrical of ST-SCs modules were measured on the Shimane University campus under partly cloudy conditions. Peak horizontal global irradiance values reached approximately 1000 Wm^{-2} in May and 800 Mw^{-2} in October. The maximum peak power (Pmax) of the ST-SCs, derived from the power-voltage (P_{PV}–V) curve, was recorded at 0.500 W at 13:00 on October 8. At this peak performance, the open-circuit voltage (V_{OC}) reached 16.03 V, the short-circuit current density (J_{SC}) was 46.13 mA, the optimal operating voltage was 12.39 V, and the optimal operating current was 40.32 mA, resulting in a fill factor (FF) of 0.68. The product of the optimal voltage and current yielded the Pmax, as shown in Figures 5(c–f).

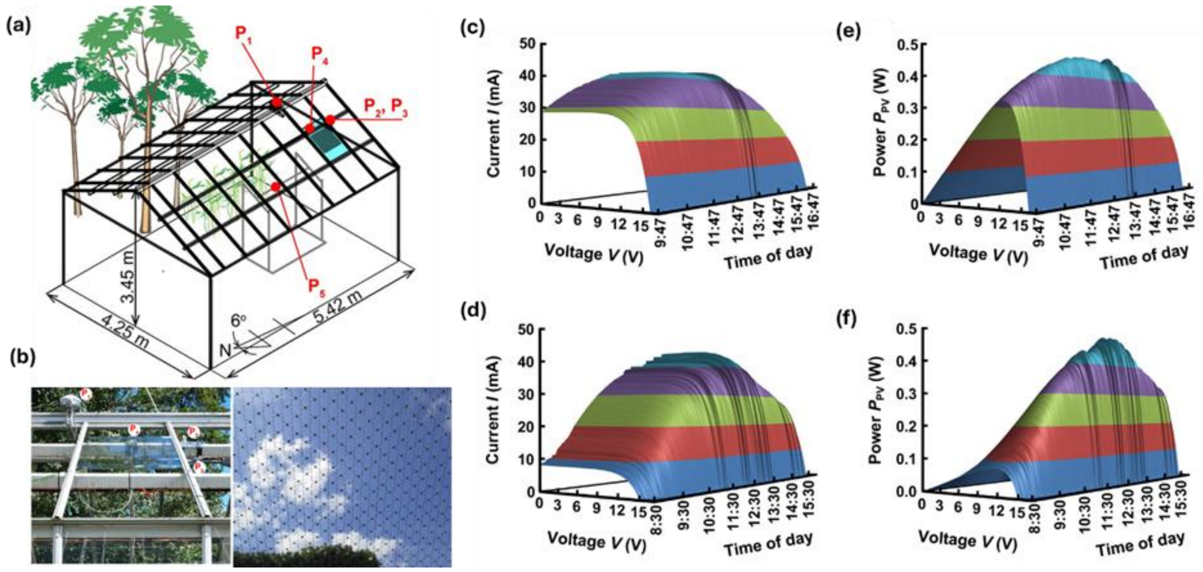


Fig. 5. (a) ST-SCs on greenhouse roof (b) The real image of ST-SCs installed on roof and image of ST-SCs panel captured from under greenhouse rooftop looking to the sky. I–V (c and d) and P_{PV}–V (e and f) characteristics of the ST-SCs module measured on May 13 (c and e) and on October 8 (d and f). Reproduced with permission from ref [19] Copyright 2016 Elsevier

Moreno *et al.,* [20] developed a holistic model using Python, Trnsys, Radiance, and TOMGRO to evaluate energy efficiency, light availability, and tomato crop performance under different organic PV coverage percentages and placements on greenhouse roofs in Almería, Spain, and Agadir, Morocco. The greenhouse structure consists of aluminum profiles that define its shape, with ethylene tetrafluoroethylene (ETFE) films enclosing both the walls and roof. In the reference case, only ETFE layers were used for coverage. The study examined organic photovoltaic (OPV) coverage percentages of 33%, 66%, and 100%, representing low, medium, and full coverage scenarios. These percentages were applied symmetrically to six-section discretized, semi-circular roof surfaces (Figure 6(a)). Simulations calculated the plant weight over a full crop cycle of 262 days (January 1 to September 19). The results indicated that incorporating OPVs as a greenhouse cover reduced the daily light integral (DLI), leading to a decrease in overall crop weight. With OPV1 technology, this reduction was more significant, corresponding to a decrease in transmitted photon flux to the crops. Similar trends were observed in both Almería and Agadir.

At 33% OPV1 coverage, crop weight declined by approximately 7%, while OPV2 coverage resulted in a smaller reduction of 5%. When coverage increased to 66%, the weight reduction reached 19% for OPV1 and 12% for OPV2. At full coverage (100%), the impact was more pronounced, with a 41% crop weight reduction for OPV1 and 23% for OPV2 (Figure 6(b)).

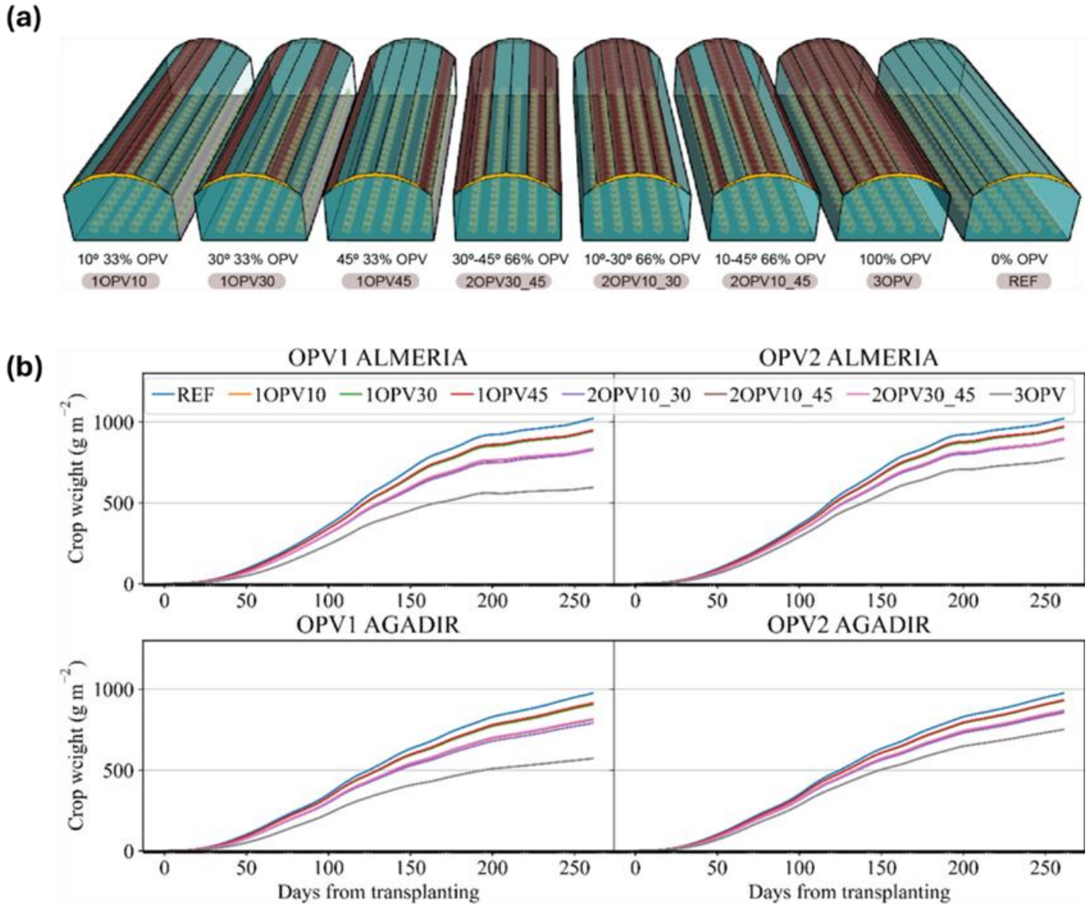
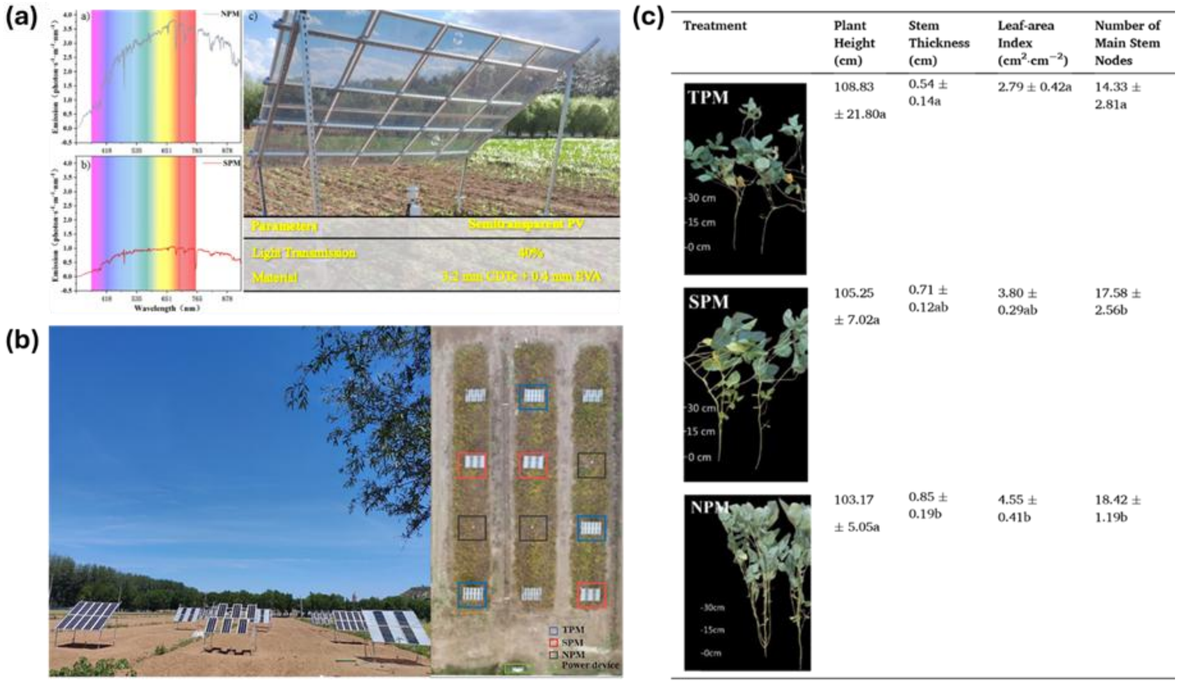


Fig. 6. (a) Nomenclature of the multi-tunnel studied configurations based on the percentage of coverage and the position of organic PV (b) Simulated tomato crop weight vs days after transplanting. Reproduced with permission from ref [20] Copyright 2025 Elsevier

In addition to greenhouse systems, agrivoltaics can also be implemented by installing solar panels above crops or on structures such as shade structures, barns, or canopies. In this setup, the solar panels are elevated or strategically positioned to optimize light distribution to the plants below.

Hu *et al.,* [21] investigated the feasibility of using ST-SC panels with 40% solar transmittance to enhance soybean yield and quality in a field environment. Their study provided a comprehensive evaluation of three different treatments in soybean cultivation: traditional photovoltaic (PV) panels (monocrystalline silicon), 40% ST-SC panels (3.2 mm CdTe + 0.4 mm EVA), and a control group without PV panels. The assessment covered various factors, including environmental conditions, photosynthesis rate, plant phenotype, dry matter accumulation, grain yield, and quality (Figures 7(a) and (b)). Results showed that ST-SC panels-maintained soybean yield without significant reduction while preserving key quality metrics. Compared to the control (no PV panels), crude fat content remained at 97.20%, soluble sugar content at 94.93%, and starch content at 98.73%. Additionally, plant height and stem thickness in soybean crops grown under ST-SC panels showed no significant differences from those grown without PV panels, ensuring compatibility with mechanical harvesting in agrivoltaic systems (Figure 6(c)).



Treatment	Plant Height (cm)	Stem Thickness (cm)	Leaf-area Index ($cm^2 \cdot cm^{-2}$)	Number of Main Stem Nodes
TPM	108.83 ± 21.80a	0.54 ± 0.14a	2.79 ± 0.42a	14.33 ± 2.81a
SPM	105.25 ± 7.02a	0.71 ± 0.12ab	3.80 ± 0.29ab	17.58 ± 2.56b
NPM	103.17 ± 5.05a	0.85 ± 0.19b	4.55 ± 0.41b	18.42 ± 1.19b

Fig. 7. (a) Light intensity at each wavelength under natural light (top) and light intensity at each wavelength under a ST-SCs (bottom) and setup of appearance and parameters of the ST-SCs (b) Subdivision plot map of the traditional panel materials (TPM) and semitransparent panel materials (SPM), and no photovoltaic module (NPM) treatments. The boxes of blue, red, grey, and green represent the TPM, SPM, NPM, and power-consuming devices, respectively (c) Phenotypic parameter of the three treatments. Reproduced with permission from ref [21] Copyright 2024 Elsevier

Willockx *et al.,* [22] implemented ST-CSs in pear orchard farming in Bierbeek, Belgium, replacing traditional hail netting with this system. The theoretical framework used to design the optimal agrivoltaic layout considered factors such as the levelized cost of electricity, electricity generation, and incident irradiance. This irradiance was modeled using a 3D light simulation tool, which accounts for light distribution within the canopy. Considering practical constraints, such as orchard orientation, planting distance, maximum wind load, and the need for protection, a double-inclined PV structure with 40% module transparency was chosen (Figure 8(a)). A schematic of the selected pear orchard is shown in Figures 8(b) and (c). The results from the first year of operation are presented, and the models are validated. The study concludes that this agrivoltaic application shows promise, with positive effects on local climatological conditions, robust energy generation, and a minimal 16% reduction in pear yield.

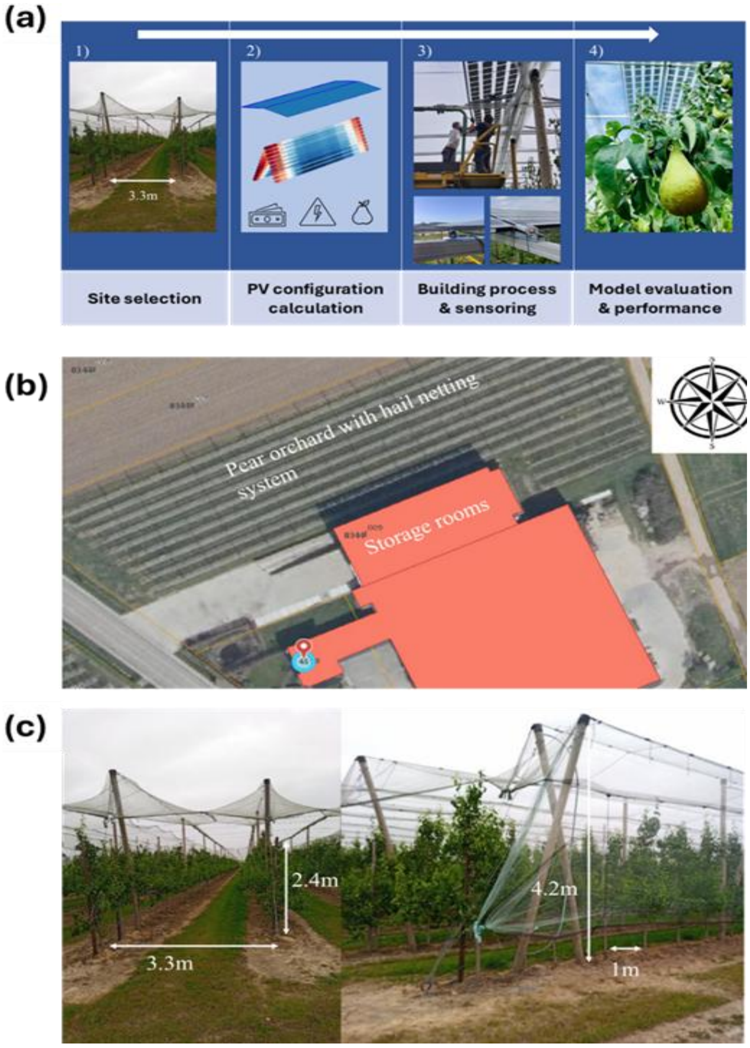


Fig. 8. (a) Study Methodology: The first step identifies the practical constraints of the existing orchard. The second step involves estimating the optimal photovoltaic (PV) layout using a 3D light model. In step 3, the proposed setup is constructed, and sensors are installed. Finally, the models are evaluated, and their performance is analyzed (b) Aerial view of the selected pear orchard (c) Dimensions of the selected pear orchard, including the hail netting system. Reproduced with permission from ref [22] Copyright 2024 Elsevier

3. Fundamentals of ST-SCs Based on Organic and Perovskite Photoactive Layers

ST-SCs operate based on the same fundamental principle as conventional solar cells which converting sunlight into electricity through the photovoltaic effect. However, unlike traditional opaque solar cells, ST-SCs are engineered to transmit a portion of incoming light, making them partially transparent. This transparency is essential for applications such as greenhouse agriculture, where crops beneath the panels still require sunlight to grow. Achieving this dual functionality which are light transmission and efficient energy conversion presents a significant design challenge. As more light is allowed to pass through the device, less is available for power generation, which often results in reduced efficiency. Balancing these two competing objectives requires careful tuning of both materials and device architecture. Several strategies have been developed to fabricate ST-SCs that maintain acceptable transparency without severely compromising performance. These include reducing the thickness of opaque metal electrodes, integrating wavelength-selective photoactive materials that primarily absorb non-visible light (such as near-infrared or ultraviolet), and incorporating optical elements like color filters to achieve specific aesthetic or functional effects [23,24]. Through such innovations, ST-SCs can be tailored for specific applications while optimizing both light transmission and energy output.

Among the various materials explored for ST-SCs, organic and perovskite materials have gained significant attention due to their tunable optical properties, ease of fabrication, and potential for high transparency. Organic ST-SCs use organic materials such as polymers or small molecules that are lightweight, easy to fabricate, low-cost, and have ability for tunable absorption [25-34]. In Figure 9(a), the photosynthetically active pigments chlorophyll a and b in plants are well known for their absorption bands in the blue and red wavelength regions. Thus, Chatterjee *et al.,* [35] proposed a green-light wavelength-selective organic solar cell designed to optimize solar energy harvesting while maintaining an environment conducive to crop growth (Figure 9(b)). This solar cell utilizes poly(3-hexylthiophene) (P3HT) as the donor material and fluorinated naphtho[1,2-c:5,6-c']bis[1,2,5]thiadiazole (FNTz-FA) as a nonfullerene acceptor (NFA). The device structure was fabricated with layers of glass/Indium Tin Oxide (ITO)/aluminum-doped Zinc Oxide (ZnO) nanoparticles (AZO):polyetheleneimine (PEI)/P3HT:FNTz-FA/PEDOT:PSS/ Gold (Au), as illustrated in Figure 9(c). The resulting power conversion efficiency (PCE) reached 3.02% in run 1 and 2.17% in run 2 for a cell-sized device (Figure 9(d)). Meanwhile, a large-area module device demonstrated a PCE of 1.32%, with a short-circuit current density (J_{SC}) of 45.5 mA, an open-circuit voltage (V_{OC}) of 4.50 V, and a fill factor (FF) of 0.41 (Figure 9(e)).

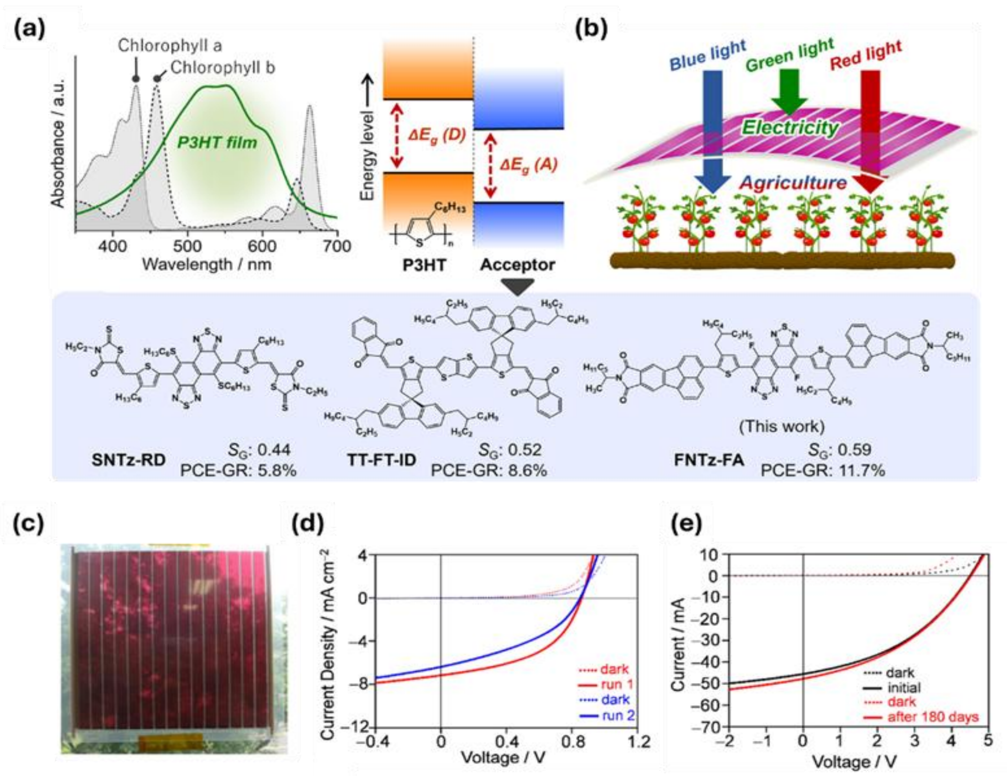


Fig. 9. (a) Absorption spectra of chlorophylls a, chlorophyll b, and P3HT with energy level of P3HT and NFA (b) Schematic image of agriculture absorbs blue and red light and Organic solar cell absorp green light (c) Photos of the 400 cm^2-scale P3HT:FNTz-FA-based modules. J-V curves of (d) cell-sized and (e) module-size P3HT:FNTz-FA devices. Reproduced with permission from [35] Copyright 2024 Elsevier

In another study, Ravishankar *et al.,* [17] investigated an inverted solar cell structure composed of a 100 nm thick ITO layer, followed by a 35 nm ZnO layer, and two variations of bulk heterojunction (BHJ) active layers. The BHJ thicknesses were optimized based on previously reported values for maximizing opaque solar cell performance, with 105 nm for FTAZ:IT-M and 126 nm for PTB7-TH:IEICO-4F. This was followed by a 5 nm layer of molybdenum oxide (MoO_3) and a final 100 nm ITO layer. The entire solar cell structure was encapsulated between two 2 mm thick glass layers, one of which also functioned as the greenhouse surface. The use of glass provided robust encapsulation, offering extremely low permeability to oxygen and water, thereby extending the device's operational lifetime for greenhouse applications, as illustrated in Figures 10(a) and (b). PTB7-TH:IEICO-4F was chosen for its absorption characteristics, which are primarily concentrated in the near-infrared (NIR) region, minimizing transmittance loss within the photosynthetically active radiation (PAR) spectrum. Meanwhile, FTAZ:IT-M demonstrated comparable efficiency but exhibited greater absorption across the PAR range. Under standard AM 1.5G conditions, the modeled efficiency for reference opaque devices with a silver reflective back electrode was approximately 11% and 12%, whereas the ST-SCs achieved PCEs of around 9.5% and 10%, respectively (Figure 10(c)). The resulting transmittance of these solar cells is presented in Figure 10(d), revealing a wavelength-averaged transmittance over the PAR spectrum of 32% for FTAZ:IT-M and 45% for PTB7-TH:IEICO-4F.

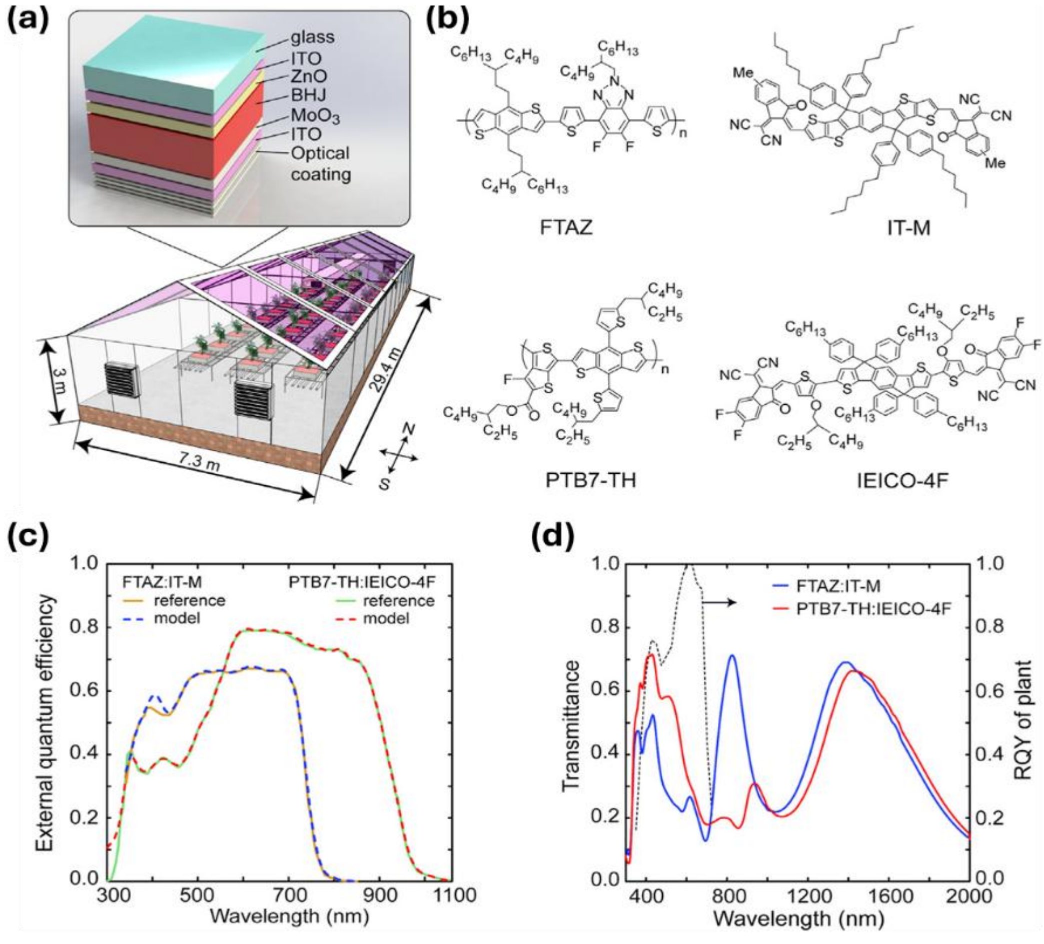


Fig. 10. (a) Absorption spectra of chlorophylls a, chlorophyll b, and P3HT with energy level of P3HT and NFA (b) Schematic image of agriculture absorbs blue and red light and Organic solar cell absorp green light (c) Photos of the 400 cm^2-scale P3HT:FNTz-FA-based modules. J-V curves of (d) cell-sized and (e) module-size P3HT:FNTz-FA devices. Reproduced with permission from ref [17] Copyright 2020 Joule

Another study by Wang *et al.,* [36] explored organic materials ST-OSCs using a quaternary blend system. This system comprised a polymer donor (PM6), two non-fullerene acceptors (A-2ThCl and A-4Cl), and a fullerene acceptor ($PC_{71}BM$), as illustrated in Figure 11(a). The absorption properties of the newly developed ST-OSCs are shown in Figure 11(b). The polymer donor PM6 exhibited strong absorption primarily in the 580–620 nm range, while the two NIR acceptors, A-2ThCl and A-4Cl, displayed strong absorption between 780–850 nm. In contrast, $PC_{71}BM$ had a relatively weak absorption coefficient in the 300–500 nm range. The quadruple-blend BHJ films demonstrated high transmittance in the 400–500 nm and 650–750 nm regions, aligning well with the absorption spectra of plant pigments. Due to these favorable optical properties, this material system was selected for greenhouse applications, as depicted in Figures 11(c) and 11(d). The PCEs were 17.71% for opaque devices. Meanwhile, the ST-OSC variant achieved a PCE of 13.02%, with plant growth factor of 26.3% demonstrating its potential for sustainable energy integration in greenhouse environments.

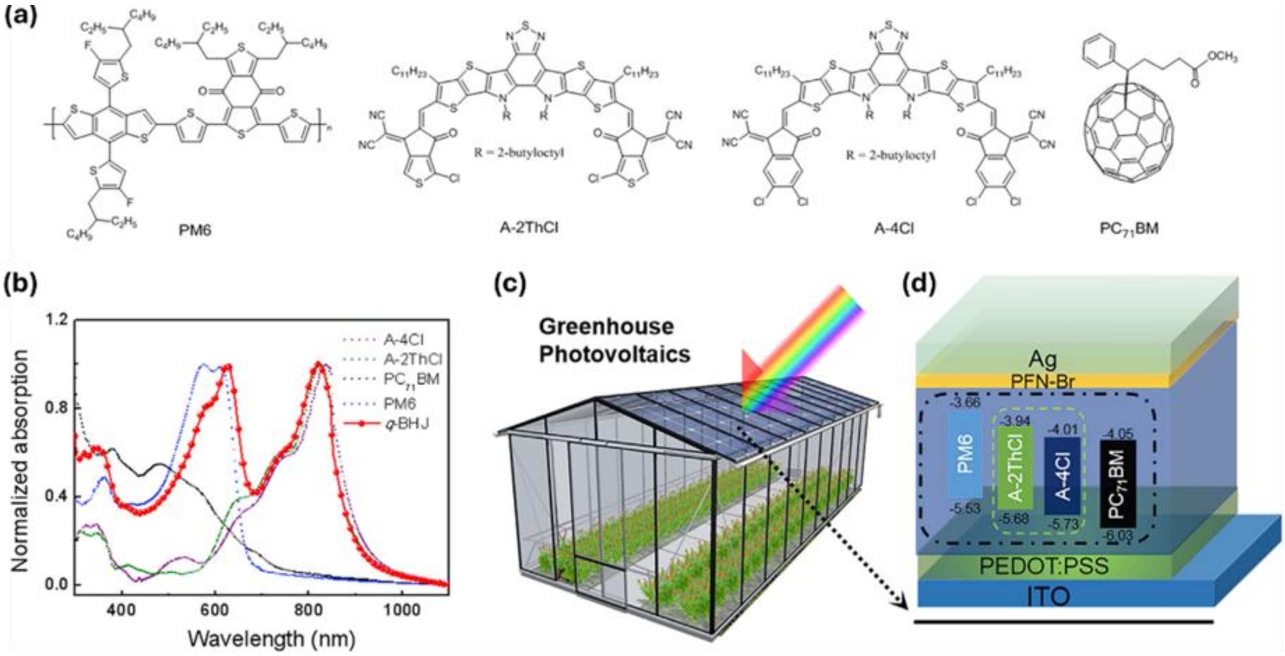


Fig. 11. (a) Chemical structures of polymer donor (PM6), two NFA acceptors (A-2ThCl and A-4Cl), and fullerene acceptor ($PC_{71}BM$) (b) Normalized film absorption of PM6:A-2ThCl:A-4Cl:$PC_{71}BM$ (1:0.36:0.84:0.2, by wt %) (c) Illustration of ST-OSCs for greenhouses (d) Device structure and energy diagrams. Reproduced with permission from ref [36] Copyright 2021 Joule

Perovskite materials, which utilize a specific type of crystalline structure, are known for their higher efficiency than organic materials and ease of fabrication, making them an attractive option for agricultural applications [37-42]. A study by Subhani *et al.,* [43] explored the use of the perovskite material $CH_3NH_3PbBr_3$ for integrating into greenhouse roofs (Figure 12(a)). To achieve semitransparency, they employed gold (Au) as a transparent electrode, with thicknesses of 20 nm and 60 nm. The transmittance properties of the resulting ST-SCs are illustrated in Figure 12(b). Due to the intrinsic absorption characteristics of $CH_3NH_3PbBr_3$, the device remains opaque in the 300–530 nm wavelength range. Beyond this point, transmittance begins to increase, with ST-SCs incorporating a 60 nm Au layer achieving a transmittance of approximately 10%. Reducing the Au thickness to 20 nm significantly improves transmittance, reaching 40% at 560 nm. Notably, devices without an Au layer exhibit exceptionally high transmittance of up to 80% in the 550–1000 nm region, as visually confirmed by the photograph in Figure 12(c). The representative J–V curves of these devices are displayed in Figure 12(d). The average PCEs achieved were 7.51% for ST-SCs with a 20 nm Au layer and 7.75% for those with a 60 nm Au layer, demonstrating the potential of this design for greenhouse applications.

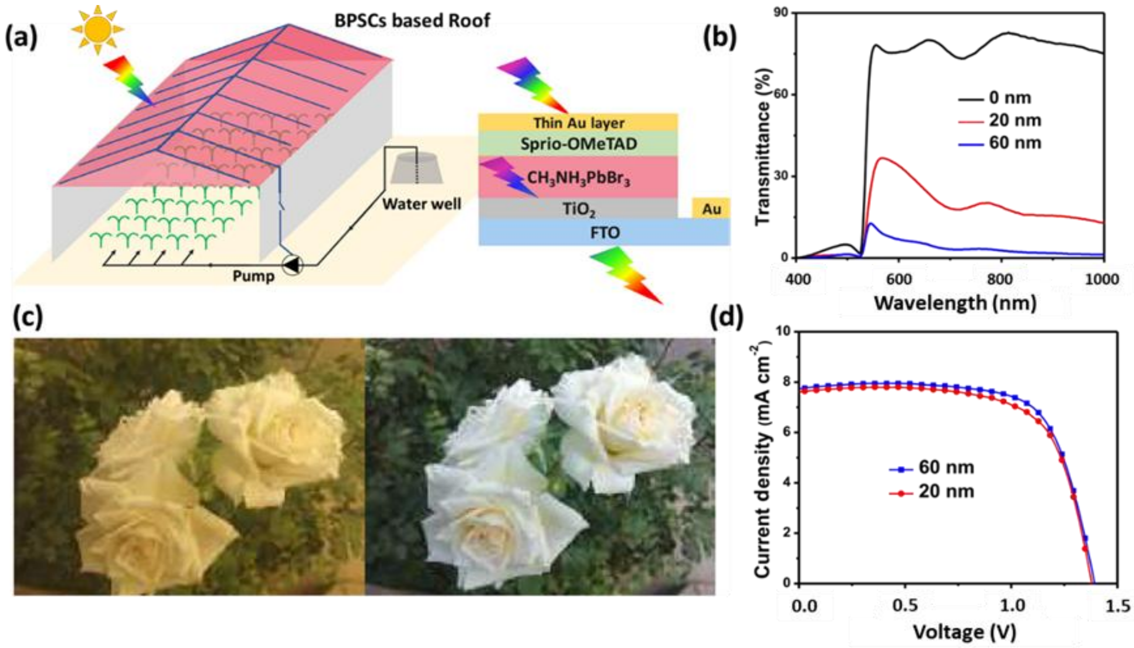


Fig. 12. (a) Schematic diagram of ST-SCs based roofs for greenhouse (b) the transmittance of ST-SCs with Au layers of various thicknesses (c) the photograph taken through the ST-SCs without the Au electrode (left) and the normal photograph for comparison (right) (d) J–V curves of ST-SCs with Au layers of various thicknesses. Reproduced with permission from ref [43] Copyright 2019 Elsevier

4. Challenges and Barriers

While ST-SCs offer significant potential for improving sustainability in agriculture, there are several challenges and barriers to their widespread adoption in agricultural settings.

One major challenge is the trade-off between efficiency and transparency. ST-SCs are designed to allow light to pass through for plant growth, but this reduces their electrical efficiency. The more transparent the solar cell, the less solar energy it captures, resulting in lower energy generation. Achieving a balance between sufficient light for crops and effective energy generation remains a difficult challenge.

Another significant barrier is the high production costs associated with ST-SCs. The higher upfront cost can be a deterrent for farmers, especially in regions where agricultural budgets are tight. These higher costs may make ST-SCs less competitive compared to traditional methods of energy generation, such as fossil fuels which are typically more affordable.

Installation and integration into existing agricultural infrastructure is also a complex issue. Retrofitting greenhouses, barns, or other agricultural structures to accommodate ST-SCs requires careful planning and additional costs. The integration process may involve modifying existing designs, and the structural integrity of the buildings must be considered to ensure they can support the added weight and electrical systems.

The durability and maintenance of ST-SCs in outdoor agricultural environments also present challenges. Agricultural settings are often harsh, with exposure to elements such as high winds, rain, dust, and temperature fluctuations. These conditions can affect the longevity of the solar cells, leading to reduced performance or damage over time.

Importantly, there are ethical and environmental concerns that must be considered, particularly regarding material sustainability and toxicity. Many high-performance perovskite ST-SCs rely on lead-based compounds, which pose significant toxicity risks if not properly contained or recycled. Improper disposal or damage to ST-SCs could lead to environmental contamination, raising ethical questions about their deployment in open agricultural settings. To address this, researchers are actively exploring lead-free alternatives, such as tin-based perovskites, which offer a more sustainable path forward. While these materials currently exhibit lower efficiencies and stability, ongoing research is making progress in narrowing the performance gap.

Lastly, material recycling and end-of-life management remain challenges. The long-term environmental impact of degraded or discarded solar modules, especially those incorporating heavy metals or complex organic layers, needs to be considered in lifecycle assessments and future policy development.

5. Future Prospects and Research Directions

The future prospects of ST-SCs in agriculture are promising, with several key areas of research and technological advancements that could drive their widespread adoption and improve their overall effectiveness. One important area for future development is technological innovations. Researchers are focused on enhancing the efficiency, cost-effectiveness, and transparency of ST-SCs. By improving the PCE of these cells without compromising their ability to allow light through for crop growth, future advancements could make them even more effective in agricultural environments. Innovations in materials, such as perovskite solar cells [44] or transparent conductive coatings, are showing potential for boosting efficiency while maintaining high transparency. These developments could reduce production costs, making ST-SCs more accessible to farmers and enabling their integration into a broader range of agricultural systems.

Scaling up production is another critical aspect of the future of ST-SCs. As demand for renewable energy solutions in agriculture grows, the need for large-scale production becomes essential. Advances in manufacturing techniques and economies of scale could drive down costs and make ST-SCs more competitive with conventional solar technologies. Additionally, developing standardized methods for mass production could make integration into agricultural infrastructure more streamlined. If production scales up successfully, ST-SCs could become a mainstream solution for farmers seeking to improve energy efficiency while maintaining agricultural productivity.

Optimization for specific crops is another key area of research. Different crops have varying light requirements, and research into how ST-SCs can be optimized for specific crop types or environmental conditions could enhance their effectiveness. For example, certain crops may thrive under lower light conditions, while others may require more direct sunlight. By developing ST-SCs with adjustable transparency or light filtering capabilities, they could be tailored to meet the needs of different crops, helping maximize both energy generation and crop yield. Moreover, research into the effects of ST-SCs on plant health, growth rates, and productivity will be crucial for understanding their full potential in agricultural settings.

Finally, it is important to consider the environmental and economic impacts of widespread ST-SC adoption. The long-term benefits of using ST-SCs in agriculture could be substantial, including reduced carbon emissions, lower energy costs, and enhanced resilience against climate change. As these technologies become more affordable and efficient, their environmental benefits could extend to the entire agricultural sector, contributing to a more sustainable and energy-efficient food production system. Economically, farmers could reduce operational costs, improve profitability, and gain energy independence, all while contributing to global sustainability goals.

6. Conclusion

In conclusion ST-SCs offer a promising pathway for integrating renewable energy into agriculture without compromising crop productivity. Their ability to transmit light while generating electricity enables dual land use, supporting both sustainable energy generation and food production. This review has summarized recent advances in ST-SC technologies particularly organic and perovskite-based cells and their applications in greenhouses and open-field agrivoltaics. Studies show that these systems can maintain or enhance crop yields while contributing to clean energy generation. Beyond environmental benefits, ST-SCs can support economic growth through more efficient resource management. By lowering energy costs, optimizing land use, and improving farm resilience, ST-SCs can increase agricultural profitability and reduce reliance on external energy sources. Although challenges in efficiency, stability, and scalability remain, ongoing research and material innovations are steadily addressing these barriers. With continued development, ST-SCs have the potential to play a key role in building sustainable, energy-efficient, and economically resilient agricultural systems.

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