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Review Article

Semitransparent Floating Photovoltaics for Mitigating Shading Effects in Opaque Floating Solar Systems

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Abstract

Floating photovoltaic (FPV) systems have emerged as a promising solution to expand solar energy deployment without competing for valuable land resources. However, the rapid expansion of conventional FPV systems based on opaque crystalline silicon modules has raised concerns regarding their environmental impacts on aquatic ecosystems, particularly due to excessive shading and altered light penetration. Semitransparent PV technologies offer an alternative approach by enabling partial light transmission while maintaining electricity generation. This review examines semitransparent FPV as a sustainable shading alternative to conventional opaque FPV systems. The design principles of semitransparent PV devices and floating PV systems are first reviewed to establish their technical foundations. Recent studies on semitransparent FPV applications are then discussed, with a focus on light management and interactions with aquatic ecosystems. Evidence suggests that spectrally selective light transmission can support beneficial photosynthetic activity while mitigating adverse ecological impacts associated with excessive shading. The review concludes by outlining key technical challenges and research gaps that must be addressed to enable the sustainable deployment of semitransparent FPV systems.

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1. Introduction

The global transition toward low-carbon energy systems has significantly accelerated the deployment of solar photovoltaic (PV) technologies in many applications [1–3]. While ground-mounted and rooftop PV installations dominate current markets, large-scale solar expansion is increasingly constrained by land availability, competing land use, and social acceptance, particularly in densely populated regions [4]. Floating photovoltaic (FPV) systems have therefore gained increasing attention as an alternative deployment strategy that utilises available water surfaces, including inland waters such as reservoirs, dams, lakes, and ponds, as well as offshore environments such as coastal and marine areas [5-8]. FPV systems offer several advantages beyond land conservation, including reduced module operating temperatures, potential mitigation of water evaporation, and proximity to existing hydropower or water infrastructure. Nevertheless, most commercial FPV installations rely on conventional opaque crystalline silicon modules, which block a substantial portion of incident sunlight. This extensive shading can alter aquatic light regimes, disrupt photosynthesis, affect dissolved oxygen dynamics, and influence biological productivity. As FPV deployment scales up, concerns regarding its long-term ecological implications have become increasingly prominent.

Semitransparent PV present a compelling opportunity to build FPV design from a purely energy-centric solution toward a multifunctional energy–environment system. By selectively transmitting portions of the solar spectrum while harvesting energy from others, semitransparent FPV enable controlled light penetration into water bodies. This capability opens new pathways for balancing electricity generation with ecological sustainability. This review explores the technological foundations, environmental implications, and future potential of semitransparent FPV.

2. Design Principles of Semitransparent PV

Semitransparent PV devices are fundamentally designed to achieve a deliberate balance between optical transparency and electrical energy conversion [9–11]. Unlike conventional opaque PV modules that prioritise maximum photon absorption, ST-PV systems intentionally allow a portion of incident solar radiation to pass through the device. This design philosophy enables multifunctional applications where light transmission is as critical as power generation, such as in building-integrated PVs, agrivoltaics, and FPV systems [12–14].

Several design strategies have been developed to introduce transparency into PV devices. One common approach involves reducing the thickness of the photoactive layer, thereby lowering optical absorption while maintaining charge transport pathways [15]. Another strategy relies on the use of photoactive materials with selective absorption characteristics, where only specific wavelength ranges of the solar spectrum are harvested for electricity generation. In addition, transparent or semi-transparent electrodes, such as ultrathin metals, metal grids, or conductive oxides, are employed to replace conventional opaque contacts. Patterning techniques, including micro- or nano-scale apertures in the active layer, have also been explored to enable controlled light transmission without significantly compromising electrical performance.

A defining characteristic of advanced semitransparent PV systems is spectral selectivity, which refers to the ability of a photovoltaic device to selectively absorb specific wavelength regions of the solar spectrum while transmitting others. Rather than transmitting light indiscriminately, semitransparent PV devices can be designed to selectively absorb wavelength regions that contribute most effectively to charge generation while allowing other portions of the spectrum to pass through. Organic and perovskite PV materials are particularly well-suited for this purpose due to their intrinsically tunable optical absorption. In organic PVs, molecular engineering of donor–acceptor systems enables precise control over absorption bands, while perovskite materials offer band gap tunability through their composition [16–19]. Recent advances in perovskite PV have demonstrated high power conversion efficiencies (PCE), highlighting their strong potential for semitransparent PV applications [20–23]. Spectral selectivity is especially critical for FPV systems, as the transmitted light directly shapes underwater optical conditions. Different wavelength regions affect aquatic photosynthesis, thermal behaviours, and ecological processes in unique ways, thus making wavelength-specific light management a crucial design consideration.

Evaluation of semitransparent PV performance extends beyond conventional metrics such as PCE, open-circuit voltage, and short-circuit current density [24]. Optical parameters, including average visible transmittance (AVT), effective transmittance, and wavelength-dependent transmission profiles, are equally important in assessing device suitability for application-specific requirements [25]. For FPV systems, the relevance of transmitted light is determined not by human visual comfort but by its interaction with aquatic ecosystems. Consequently, the ecological functionality of transmitted light, such as its compatibility with photosynthetic pigment absorption and its influence on water temperature and biological activity, must be considered alongside electrical performance.

In the context of sustainable FPV deployment, the design principles of semitransparent PV represent a shift from purely energy-centric optimisation toward multifunctional system integration. By enabling controlled light transmission, semitransparent PV devices provide a technological foundation for FPV that can generate renewable electricity while maintaining or enhancing ecological balance. This dual-function capability positions semitransparent PV as a key enabling technology for next-generation FPV systems that aim to harmonise energy production with environmental stewardship.

While this multifunctional capability is advantageous, it is important to recognise the inherent performance trade-offs compared to conventional opaque PV systems. Opaque crystalline silicon modules typically achieve high PCE exceeding 27% [26] and are widely used as a commercial type of solar cell. In contrast, semitransparent PV devices intentionally allow partial light transmission, which reduces the number of absorbed photons and consequently lowers the achievable efficiency. Reported PCEs for semitransparent organic and perovskite devices are approximately 14% and 21% [27,28], respectively, although they vary depending on device architecture and transparency level. However, this reduction in power output is accompanied by additional functional benefits, including controlled light transmission, improved thermal regulation, and enhanced compatibility with aquatic ecosystems in FPV applications. As such, semitransparent PV systems should be evaluated not solely based on efficiency, but on their overall system-level performance, where energy generation and environmental functionality are jointly considered.

3. Design Principles of Floating Photovoltaics

FPV systems are engineered solar energy platforms designed to operate on water surfaces, requiring a distinct set of design considerations compared to land-based PV installations. At the system level, FPV typically consists of PV modules mounted on buoyant structures, anchoring and mooring systems to ensure positional stability, electrical infrastructure adapted for humid environments, and access pathways for installation and maintenance [29]. The integration of these components must account for mechanical reliability, environmental exposure, and long-term operational safety.

From a structural perspective, buoyant platforms are commonly fabricated from high-density polyethylene or similar corrosion-resistant materials to withstand prolonged contact with water and exposure to ultraviolet radiation. These platforms must support the weight of PV modules while maintaining sufficient buoyancy and stability under variable water levels, wind loads, and wave action. Anchoring and mooring systems are critical for preventing drift and ensuring system resilience during extreme weather events, particularly in reservoirs, lakes, and near-shore environments where hydrodynamic conditions can change seasonally.

Environmental exposure represents a key challenge in FPV design. High humidity, constant water contact, and potential salinity in coastal or brackish waters accelerate material degradation and corrosion of electrical components. As a result, FPV systems require enhanced encapsulation, corrosion-resistant cabling, and robust electrical insulation. Thermal management is another important consideration, as FPV modules often experience lower operating temperatures due to evaporative cooling from the water surface, which can improve electrical performance. However, thermal gradients and moisture ingress must be carefully managed to avoid long-term reliability issues.

FPV systems inherently engage with aquatic environments, even beyond engineering considerations. By covering portions of the water surface, FPV installations alter incoming solar radiation, air–water heat exchange, and wind-driven mixing. Moderate shading can reduce surface water temperature fluctuations and suppress excessive evaporation, which is particularly beneficial in water-scarce regions. However, excessive or poorly designed shading can disrupt light penetration, reduce photosynthetic activity, and alter dissolved oxygen dynamics, potentially affecting aquatic organisms and ecosystem functioning.

Shading characteristics therefore represent a critical design parameter in FPV systems. Key factors include the degree of surface coverage, the spatial arrangement of modules, height above the water surface, and the optical properties of the PV panels. Conventional opaque FPV systems typically provide uniform and non-selective shading, which may be acceptable in certain contexts but can lead to unintended ecological consequences when deployed at large scales or in sensitive water bodies.

The integration of semitransparent PV modules introduces a new level of adaptability into FPV system design. By allowing partial and spectrally selective transmission of sunlight, semitransparent FPV systems can be tailored to local environmental conditions and ecological requirements. Transparency levels can be adjusted through material selection and device architecture, while module spacing and orientation can be optimised to regulate the quantity and quality of transmitted light. This flexibility enables FPV systems to move beyond static shading toward dynamic light management.

From a system design perspective, semitransparent FPV enables a shift from uniform surface coverage to environmentally responsive configurations. For example, higher transparency may be applied in ecologically sensitive zones to sustain aquatic productivity, while lower transparency regions may be designated to maximise energy yield or suppress undesirable biological growth. Such modular and adaptive design strategies offer a pathway for harmonising renewable energy generation with water resource management and ecosystem preservation.

Overall, the design principles of FPV systems are evolving from purely structural and electrical considerations toward integrated energy–environment systems. Incorporating semitransparent PV technologies into FPV design expands the functional role of floating solar installations, enabling them to simultaneously address energy production, environmental impact mitigation, and sustainable water surface utilisation.

4. Semitransparent FPV study in Light Management and Aquatic Ecosystem Impacts

4.1. Spectral Selectivity and Optical Design of Semitransparent PV

Light availability plays a central role in regulating aquatic ecosystem processes, including primary productivity, thermal behaviour, and biogeochemical dynamics. FPV systems modify these processes by altering the intensity and spectral distribution of solar radiation reaching the water surface. Unlike conventional opaque FPV installations that impose uniform shading, semitransparent FPV systems enable controlled and spectrally selective light transmission. Recent research has focused on understanding how semitransparent FPV configurations can manage underwater light environments to reduce ecological disturbance while sustaining PV performance.

Zhang et al. [14] examined common algal pigments involved in photosynthesis, including chlorophyll a, chlorophyll b, and carotenoids (xanthophyll), and showed that their strongest light absorption occurs primarily in the 350–500 nm wavelength range (Figure 1a). By employing semitransparent organic polymer solar cells based on a PTB7-Th donor with both fullerene ($PC_{71}BM$) and non-fullerene (ITIC and PNDI-T5) acceptors, they demonstrated reduced optical absorption within the 370–550 nm region (Figure 1b). This spectral transmission enabled partial penetration of photosynthetically relevant light through the PV device into the underlying water, indicating the potential of such systems to support aquatic photosynthetic activity while generating electricity. Corresponding CIE 1931 chromaticity analysis (Figure 1c) indicates near-neutral colour coordinates close to the white point. Devices using the fullerene acceptors exhibit a neutral to slightly reddish appearance, while those employing non-fullerene acceptors show a bluish tint, attributed to less uniform transmittance in the 400–500 nm wavelength range. Notably, the semitransparent devices achieved PCE ranging from approximately 3% to 9.4%, depending on the thickness of the metal contact.

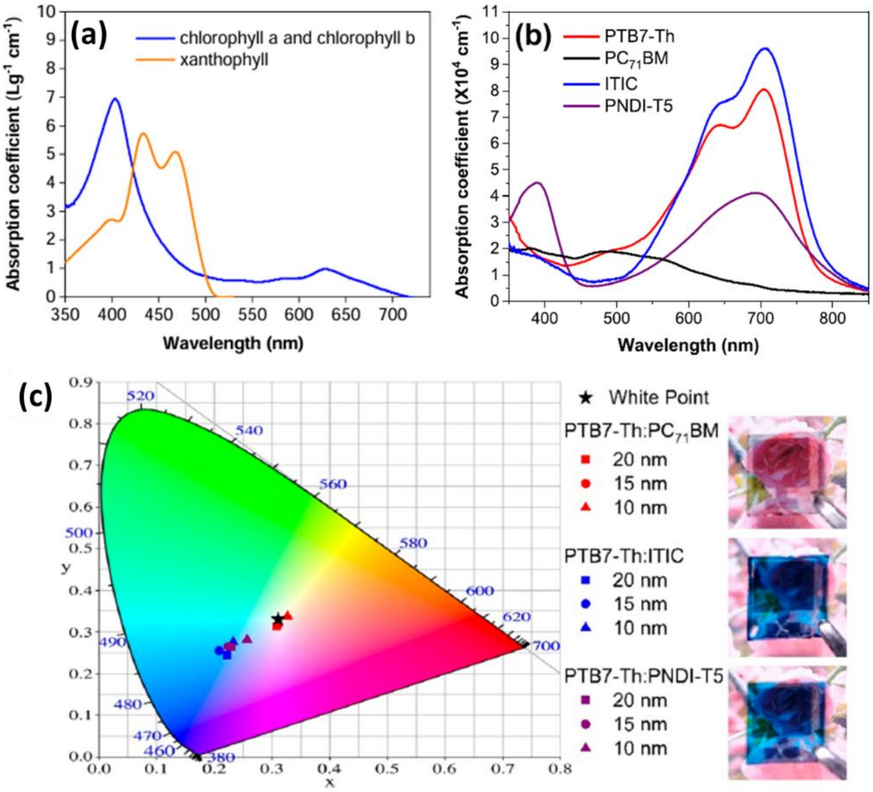

Figure 1. UV-Vis absorption spectra of (a) pigments and (b) organic photoactive materials. (c) CIE 1931 chromaticity and real images of PV devices. Reproduced with permission from [14]. Copyright (2019) American Chemical Society.

4.2. Thermal Regulation and Evaporation Control under Semitransparent PV

The semitransparent PV devices were positioned at tilt angles of 0° and 30° to simulate practical FPV configurations, and their effects on water evaporation rate, photo-thermal conversion efficiency, and surface temperature were systematically evaluated. Figure 2a illustrates the experimental setup used to quantify water evaporation by monitoring mass loss under one-sun illumination with semitransparent PV coverage. In the absence of any cover, freshwater exhibited higher evaporation rates at both tilt angles, whereas evaporation was noticeably reduced when semitransparent PV devices were applied. Infrared imaging and corresponding temperature profiles after 60 minutes of illumination are presented in Figure 2b. Under neat ITO glass coverage, the final water surface temperatures reached 28.7 °C at 0° and 29.1 °C at 30°, approximately 17% lower than that of bare water at 35 °C. In contrast, substantially larger reductions in surface temperature (25–38%) were observed when the three semitransparent PV were used as floating shelters, demonstrating their effectiveness in mitigating water surface heating.

This study reveals an additional functional role of semitransparent PV, highlighting their potential for FPV applications that improve land-use efficiency while simultaneously mitigating water evaporation and conserving water resources.

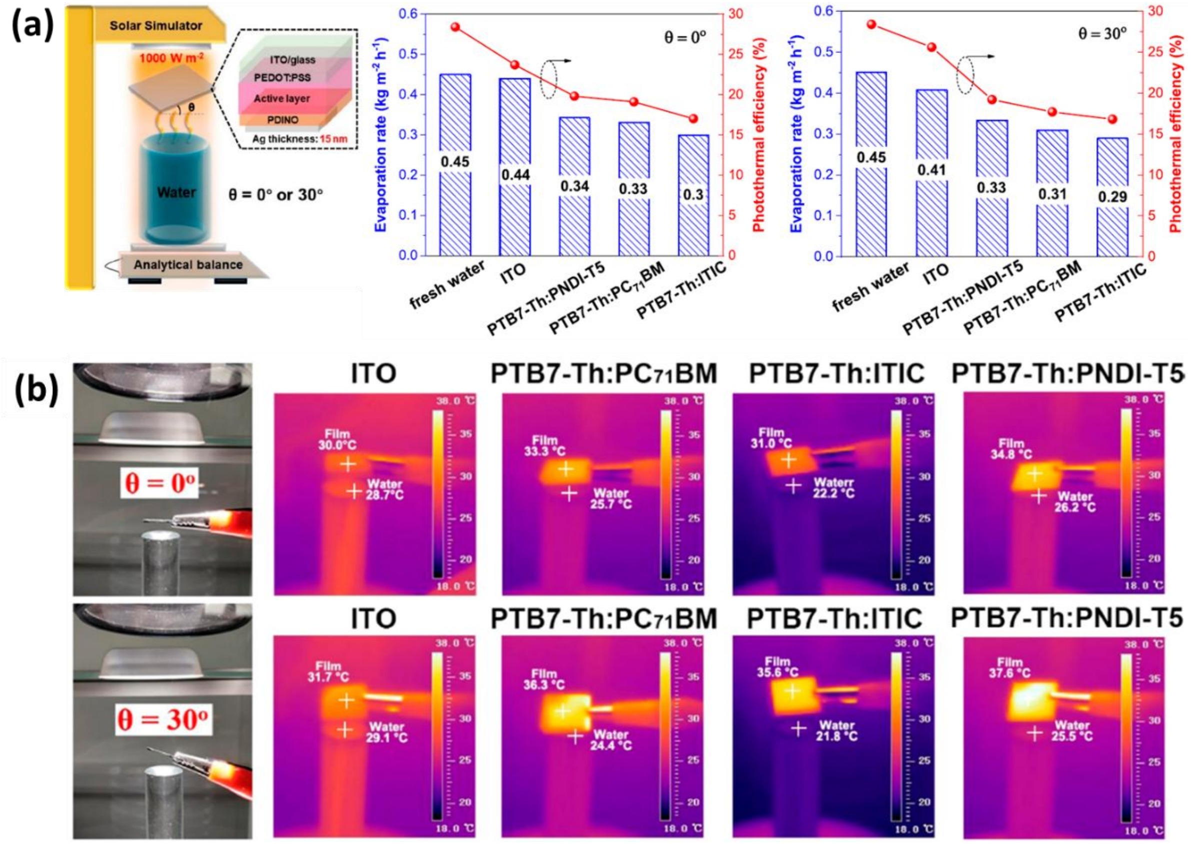

Figure 2. (a) Schematic illustration of the experimental setup used for water evaporation and surface temperature measurements, together with the corresponding water evaporation rates and photo-thermal conversion efficiencies under one-sun illumination at tilt angles of 0° and 30°. (b) Digital photographs, infrared (IR) images, and temperature profiles of the water surface obtained at tilt angles of 0° and 30° after illumination. Reproduced with permission from [14]. Copyright (2019) American Chemical Society.

4.3. Effects of Semitransparent FPV on Algal Growth and Photosynthetic Performance

In a subsequent study, Zhang et al. [30] further advanced semitransparent FPV research by employing a ternary organic photoactive system consisting of a polymer donor (PBDB-TF) blended with a non-fullerene small-molecule acceptor (Y6) and a fullerene acceptor (PC71BM). The authors systematically compared conventional device architectures (ITO/PEDOT:PSS/active layer/PDINO/Ag) with inverted configurations (ITO/ZnO/active layer/MoO3/Ag), including an inverted design incorporating a transparent electrode. These device optimisations yielded improved performance, with PCE ranging from 9.2% to 13% and average visible transmittance values of approximately 18–21%, representing a notable enhancement over their earlier work. In addition to PV performance, the study demonstrated substantial reductions in water evaporation and surface heating under semitransparent PV coverage relative to uncovered water surfaces.

A key contribution of this work is the explicit investigation of biological responses, focusing on the growth and photosynthetic activity of Chlorella (Chlorophyta), a representative freshwater green microalgae (Figure 3a). Algal cultures were first grown to the exponential phase before being exposed to large-area photovoltaic coverage, and growth behaviour was monitored over a 24-h period (Figure 3b). The results showed that the highest cell concentrations occurred under fully exposed conditions, whereas opaque photovoltaic coverage resulted in pronounced growth suppression, indicating strong light limitation. Semitransparent photovoltaic devices produced intermediate growth rates, reflecting moderated light availability (Figure 3c). Chlorophyll fluorescence analysis further revealed that the maximum quantum efficiency of photosystem II (Fv/Fm) was lowest in the uncovered control, indicating photoinhibition under high irradiance, while semitransparent devices alleviated this effect by partially filtering incident light, resulting in improved Fv/Fm values of approximately 0.62–0.68 (Figure 3d). These findings demonstrate that semitransparent PV systems can mitigate photoinhibition and regulate algal photosynthesis through controlled light transmission, in contrast to the excessive shading imposed by opaque PV modules.

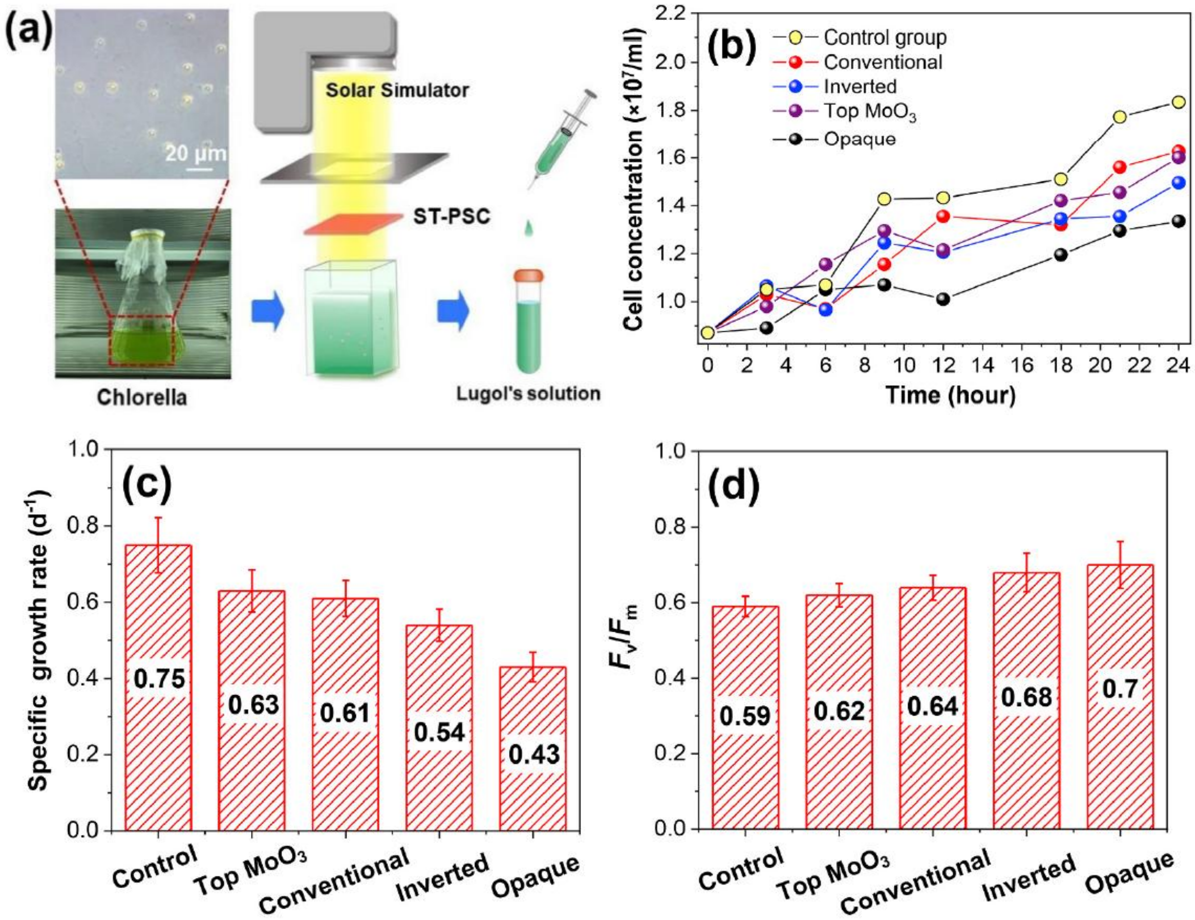

Figure 3. (a) Schematic illustration of the experimental setup used to evaluate Chlorella proliferation; (b) temporal variation in Chlorella cell concentration during 24 h of illumination; (c) calculated specific growth rates; and (d) maximum quantum efficiency of photosystem II (Fv/Fm) of Chlorella under different experimental conditions. Reproduced with permission from [30]. Copyright 2020 Elsevier.

4.4. Species-Dependent Ecological Responses under Spectrally Filtered Light

In a similar group study, Yin et al. [31] further expanded the environmental relevance of semitransparent FPV systems by demonstrating their applicability across multiple algal groups with distinct pigment compositions. In their study, they synthesised terpolymer (PBDB-TF-T10) as donor and combined it with Y6 acceptor. Semitransparent devices achieving PCE of approximately 11.2% while maintaining

AVT above 20% through controlled thinning of the metallic electrode. A key contribution of this work was the explicit mapping of device transmission spectra against the absorption profiles of major photosynthetic pigments. Using four representative microalgae, which are green algae Chlorella, dinoflagellates Amphidinium carterae, diatoms P. tricornutum and blue-algae Synechococcus, they demonstrated that algal responses to semitransparent FPV filtering were species-dependent and governed by wavelength-specific light availability (Figure 4).

Consistent with earlier findings [30], green algae Chlorella, which primarily contains chlorophyll a and b, exhibited the highest cell densities under fully exposed conditions, while opaque photovoltaic coverage caused pronounced growth suppression due to severe light limitation. Semitransparent photovoltaic filtering resulted in intermediate growth rates, reflecting moderated light availability. Similar trends were observed for A. carterae and P. tricornutum, both of which contain chlorophyll and accessory pigments such as β-carotene or fucoxanthin, and showed reduced photoinhibition under semitransparent coverage compared to full exposure. In contrast, the cyanobacterium Synechococcus, which utilises chlorophyll a together with phycobiliproteins, exhibited a markedly different response. The lowest growth and photosynthetic efficiency were observed under full light exposure, indicating strong photoinhibition, while semitransparent photovoltaic coverage produced the highest growth rates with negligible photoinhibitory effects. This behaviour reflects the lower optimal light requirement of Synechococcus compared to eukaryotic microalgae. The findings showed that semitransparent FPV systems can sustain or regulate algal growth depending on spectral alignment and light intensity, highlighting the inadequacy of uniform shading strategies. This study positioned semitransparent FPV as a potential tool for adaptive aquatic ecosystem management, where optical design can be tailored to local ecological conditions rather than applied uniformly.

5. Challenges and Research Gaps

Despite the growing body of evidence supporting the environmental and functional advantages of semitransparent FPV systems, several technical and implementation challenges continue to hinder their large-scale deployment. Material stability remains a primary concern, particularly for organic and perovskite-based semitransparent PV technologies that are inherently sensitive to moisture, oxygen ingress, ultraviolet radiation, and thermal cycling [32,33]. Floating environments impose more severe operating conditions than land-based installations due to constant exposure to high humidity, water splashing, and salinity [34,35]. These factors accelerate the degradation of active layers, electrodes, and interfacial materials, potentially shortening operational lifetimes. However, some studies also found FPV have better lifetime even with 10% higher humidity over water bodies with just 1.6°C lowered temperature [36]. These contrasting findings suggest that environmental conditions may have both beneficial and adverse influences, depending on system design and materials. Although encapsulation strategies have advanced in laboratory settings, the development of durable, lightweight, and cost-effective solutions tailored for long-term floating applications remains an important area for further research. In addition, achieving an optimal balance between optical transparency and PCE remains a design trade-off, particularly when scaling up from small-area devices to large FPV arrays [31]. System-level challenges, including mechanical durability, anchoring stability, and electrical safety in wet environments, further complicate deployment and require integrated engineering solutions.

Beyond technical challenges, significant research gaps remain in understanding the long-term environmental impacts of semitransparent FPV systems under real-world conditions. Most existing studies are limited to laboratory-scale experiments or short-term outdoor tests, often conducted under controlled and simplified conditions. There is a clear lack of longitudinal field studies that evaluate ecological responses over seasonal cycles, accounting for natural variability in solar irradiance, temperature, nutrient availability, and hydrodynamic conditions. Moreover, current biological assessments frequently focus on single model organisms, such as selected microalgae, without fully capturing ecosystem-level interactions involving multiple trophic levels. The cumulative impacts of partial shading over large water surface areas, particularly in reservoirs, aquaculture systems, and near-shore environments, remain poorly understood. Standardised evaluation frameworks and environmental performance indicators for semitransparent FPV systems are also lacking, making cross-study comparisons difficult. Addressing these gaps will require interdisciplinary research combining PV engineering, aquatic ecology, and environmental monitoring to establish evidence-based design guidelines and regulatory frameworks for sustainable semitransparent FPV deployment.

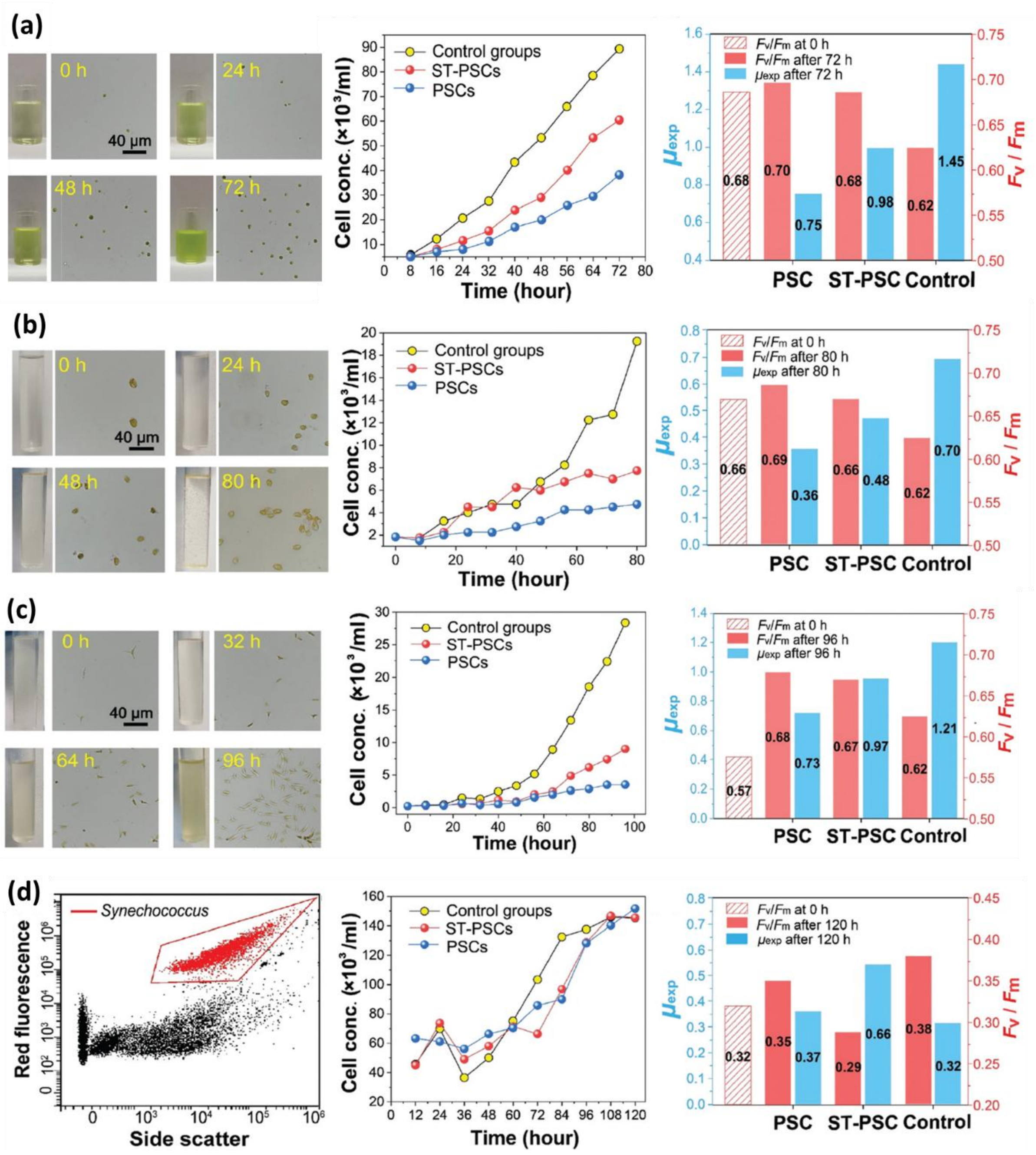

Figure 4. Digital photographs of culture solutions and cells, growth curves and summary of μexp and Fv/Fm of (a) Green algae Chlorella, (b) Dinoflagellate A. carterae, (c) Marine diatom P. tricornutum and (d) Blue-algae Synechococcus. Reproduced with permission from [31]. Copyright (2021), Royal Science Chemistry.

6. Conclusion

Semitransparent PV introduce a transformative approach to FPV systems by enabling simultaneous energy generation and ecological stewardship. Through selective light transmission and adaptable system design, semitransparent FPV technologies address key limitations of conventional opaque installations. While technical and environmental challenges remain, ongoing advances in materials engineering and system integration suggest a strong potential for semitransparent FPV systems to contribute meaningfully to sustainable energy and water management. Continued research and regionally contextualised deployment strategies will be essential to fully realise their benefits.

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Declaration of Conflict of Interest

The author declared no conflict of interest with any other party on the publication of the current work.

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