Progress in Energy and Environment

Journal homepage: https://karyailham.com.my/index.php/progee/index
Link to this article:

Vol. 32 Issue 01 (2026) 30-42

Review Article

Impact of Floating Photovoltaic Shading on Light Penetration and Aquatic Primary Productivity

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Abstract

Floating photovoltaic (FPV) systems are gaining global momentum as a space-efficient solution for renewable energy generation, particularly on inland freshwater bodies such as reservoirs, lakes, and ponds. While their engineering and energy performance have been well documented, their ecological impacts, particularly those related to underwater light dynamics remain insufficiently understood. This review examines one key mechanism: the attenuation of photosynthetically active radiation (PAR) by FPV systems and its consequences for aquatic primary productivity. By altering light availability, FPV arrays can suppress the growth of phytoplankton, submerged macrophytes, and benthic algae, with broader implications for oxygen levels, nutrient cycling, and food web structure. We present a conceptual framework that links FPV design and placement to physical light shading, biological responses, and potential system-wide effects. Drawing on evidence from modelling and field studies in reservoirs, natural lakes, and aquaculture ponds, we highlight how ecological outcomes depend on coverage extent, water clarity, and hydrodynamic conditions. While moderate shading may offer benefits in nutrient-rich waters, excessive coverage risks undermining key ecological functions. The review identifies critical knowledge gaps and offers design and policy recommendations to support ecologically informed FPV deployment that balances energy generation with freshwater ecosystem integrity.

Article Info

Received: 30 January 2026
Received in revised form: 18 March 2026
Accepted: 10 April 2026
Available online: 3 May 2026

Keywords

Floating Photovoltaics
Light Attenuation
Aquatic Primary Productivity
Freshwater Ecosystems
Ecological Impacts

1. Introduction

Photovoltaic (PV) technology has become a cornerstone of global renewable energy strategies, converting sunlight directly into electricity through semiconducting materials [1–8]. Floating PV (FPV) systems are rapidly emerging as a promising solution to expand solar energy capacity without consuming terrestrial land [9–12]. Onshore or inland FPV installations, typically sited on the surfaces of reservoirs, lakes, and ponds, offer dual-use advantages by delivering clean electricity while potentially reducing water evaporation and mitigating panel overheating [9,11,13]. Global deployment has accelerated from just over 1.6 GW in 2018 to approximately 7.7 GW by the end of 2023, with nearly 90% of capacity concentrated in Asia. China is one of the leading countries in global FPV installations, followed by Taiwan, India, Israel, Japan, and South Korea [14,15]. Despite well-documented advances in FPV engineering and energy performance, the ecological implications of FPV remain insufficiently studied, particularly in freshwater ecosystems where biological processes are strongly regulated by solar radiation.

One of the most direct and potentially disruptive ecological effects of FPV is light attenuation. Solar panels block photosynthetically active radiation (PAR) from reaching the water surface, altering the underwater light environment [16]. Because light is the primary energy source driving photosynthesis, reductions in light penetration can suppress aquatic primary productivity, which forms the base of freshwater food webs [17,18]. This factor affects key producer groups such as phytoplankton, submerged macrophytes, and benthic algae, all of which require specific light thresholds to sustain growth and oxygen production [19–21].

Light attenuation from FPV is not only a physical alteration but an ecological mechanism with cascading effects. Declines in primary production can reduce dissolved oxygen levels, shift nutrient cycling, and alter species composition throughout aquatic communities. Shading effects vary depending on array coverage, panel spacing, water clarity, and ecosystem type. In small or oligotrophic systems where high light penetration supports sensitive biota, the risk of ecological disruption may be particularly high.

Despite growing concern, environmental assessments of FPV installations rarely quantify the ecological impacts of light. Most focus on water quality or temperature, overlooking the foundational role of underwater light for biological processes [22]. As FPV arrays scale in size and density, the need for mechanism-based ecological guidance becomes urgent. Understanding how FPV-induced shading affects aquatic primary producers is critical to balancing renewable energy goals with ecosystem sustainability.

This review focuses on a single ecological pathway: how light attenuation from FPV affects aquatic primary productivity. It develops a conceptual framework linking FPV system design to underwater light dynamics, biological responses in freshwater producers, and downstream ecological consequences. By isolating this mechanism, we aim to clarify when and where FPV may pose ecological risks.

2. FPV-Induced Alteration of the Aquatic Light Environment

FPV systems alter the aquatic light environment primarily through surface shading, reducing the transmission of solar radiation into the water column. As aquatic ecosystems are structured around light availability, even partial modification of the light regime can affect photosynthesis, thermal dynamics, and habitat suitability for primary producers. This section synthesizes the physical mechanisms by which FPV installations affect underwater light conditions, setting the stage for understanding biological responses.

Figure 1 illustrates an example of FPV on the lake surface and showing how FPV coverage reduces incoming solar radiation, compresses the euphotic zone, and leads to lower oxygen production and diminished aquatic plant growth beneath the panels.

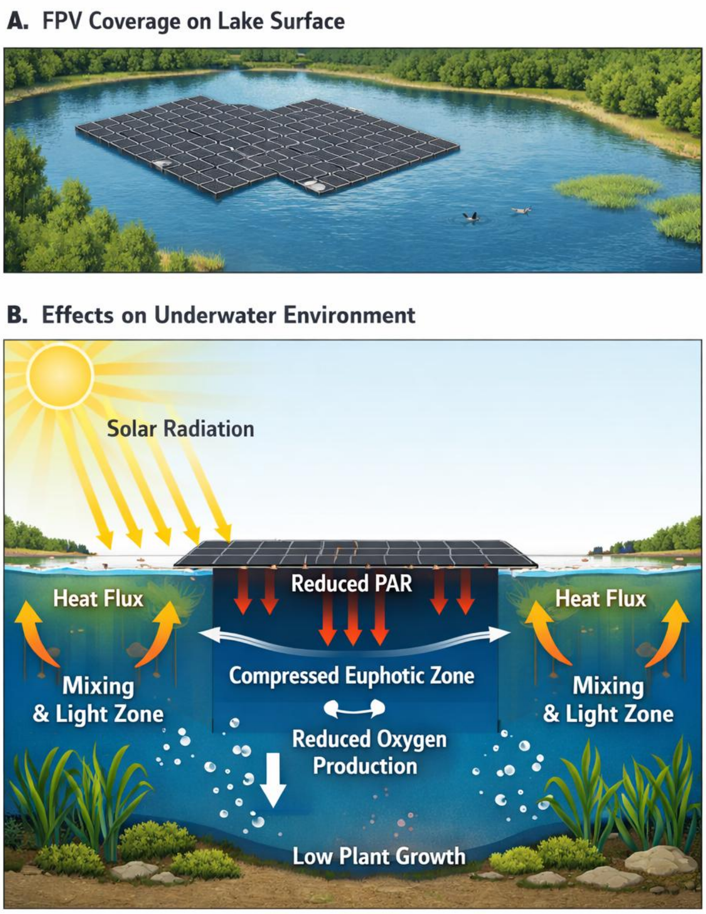

Figure 1. Schematic illustrating of (a) an example of FPV on the lake surface and (b) how FPV systems reduce underwater light penetration, compress vertical light gradients, and alter photosynthetic zones for aquatic primary producers. Reduced PAR under FPV coverage limits light-dependent mixing and oxygen production, particularly in the shaded euphotic layer.

2.1. Surface Coverage and Panel Configuration

The extent of light attenuation in FPV systems is primarily governed by the surface coverage ratio, defined as the proportion of the water surface shaded by photovoltaic modules. In general, increasing coverage leads to greater reductions in incident solar radiation reaching the water surface, although the magnitude of this effect varies depending on system design and environmental conditions [12].

Beyond coverage, panel configuration plays a critical role in determining light penetration and spatial distribution. Factors such as inter-panel spacing, tilt angle, elevation above the water surface, and the presence of gaps or corridors can influence both the intensity and heterogeneity of shading. These design characteristics are particularly important in smaller or shallow aquatic systems, where localized shading can more strongly influence the photic zone and associated biological processes. As such, both coverage extent and structural configuration should be considered jointly when evaluating the potential ecological impacts of FPV deployment.

2.2. Attenuation of Photosynthetically Active Radiation (PAR)

Light attenuation under FPV systems primarily affects the PAR range (400–700 nm), which is essential for aquatic primary producers [23]. PV panels intercept incoming solar radiation, reducing the amount of light transmitted into the water column through a combination of absorption, reflection, and shading effects.

Empirical and modeling studies consistently demonstrate that FPV installations can significantly reduce PAR availability beneath the array, although the degree of attenuation depends on factors such as panel density, configuration, and surface reflectivity [24,25]. Rather than a fixed reduction value, reported attenuation varies widely across systems, reflecting differences in environmental conditions and design parameters.

2.3. Vertical and Spectral Effects

Beyond total PAR reduction, FPV systems may also alter vertical light gradients and the spectral quality of light penetrating the water. Standard solar modules disproportionately block shorter wavelengths (blue and green light), which typically penetrate deeper into freshwater. This leads to a relative shift in the available spectrum, potentially favouring organisms adapted to red or infrared wavelengths. However, data on spectral changes under FPV is limited and requires further study.

Vertical light attenuation under FPV is steeper, meaning that photosynthetically usable light declines rapidly with depth. This compresses the habitable zone for submerged macrophytes and benthic algal mats, especially in clear oligotrophic lakes where these groups dominate primary production.

2.4. Spatial Heterogeneity and Edge Effects

Because most FPV systems do not cover an entire water surface, their impact on light availability is spatially heterogeneous. Areas beneath arrays experience high light attenuation, while adjacent open-water zones may receive unaltered or even enhanced horizontal light scattering. This condition creates patchy light environments, which may differentially affect planktonic versus benthic producers and complicate predictions of ecosystem-level response.

Edge effects also arise where FPV arrays interact with wind and water mixing. Reduced light under the array may coincide with reduced surface turbulence, reinforcing thermal stratification and further limiting the mixing of nutrients and gass driven by light-related processes. These coupled effects can amplify the biological consequences of shading, particularly in warm climates or stratified reservoirs.

To synthesize these physical mechanisms and their ecological implications, a conceptual framework is presented in Figure 2. Figure 2 illustrates the integrated pathway by which FPV system design influences underwater light availability and subsequently affects aquatic primary productivity and ecosystem processes. Specifically, FPV coverage and panel configuration reduce PAR, compress the euphotic zone, and alter vertical light distribution. These physical changes lead to declines in primary producers, including phytoplankton, submerged macrophytes, and benthic algae, which in turn drive downstream effects on dissolved oxygen, nutrient cycling, and overall ecosystem structure. The framework also highlights the role of environmental modifiers such as water clarity, depth, and hydrodynamic conditions in shaping the magnitude of these responses.

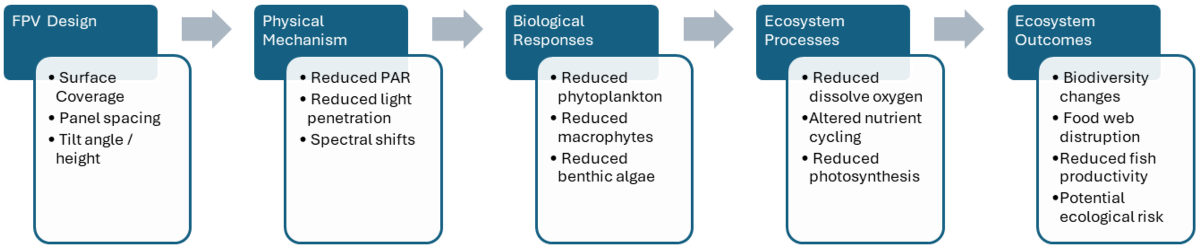

Figure 2. Conceptual framework linking FPV system design to physical mechanism, biological productivity, ecosystem processes, and ecosystem outcomes.

3. Evidence from Existing Studies

3.1. Reservoirs

Reservoirs are a leading candidate for large-scale FPV deployment due to stable water levels, existing energy infrastructure, and compatibility with multipurpose uses such as hydropower, irrigation, or flood control. However, FPV-induced light attenuation may affect reservoir primary productivity, particularly by limiting PAR input to phytoplankton.

Exley et al. [24] conducted a modelling study to examine the potential ecological impacts of FPV systems on a temperate drinking-water reservoir in south-west London (51° 23′27′′ N, 0° 23′32′′ W, surface area: 128 ha), United Kingdom. Using the coupled one-dimensional General Lake Model–Framework for Aquatic Biogeochemical Models (GLM–FABM), the authors simulated a range of FPV coverage levels ranging from 10% to 50%. The results indicated that even moderate shading levels led to a noticeable reduction in PAR throughout the water column, particularly in deeper and more central zones. This light limitation corresponded with a significant decrease in phytoplankton biomass and overall primary productivity. As illustrated in Figure 3a, maximum total chlorophyll a concentrations declined exponentially with increasing FPV coverage, based on mean values over a 5-day model window. The observed changes in algal biomass and community composition were attributed to both the direct reduction in sunlight and to altered water-column mixing due to wind-sheltering effects from the FPV structures. Moreover, the study found that hydrodynamic conditions influenced sensitivity to shading. In faster-flowing sections of the system, phytoplankton experienced compounding stress from both rapid flushing and limited light, making them more susceptible to productivity declines even at lower FPV coverage levels.

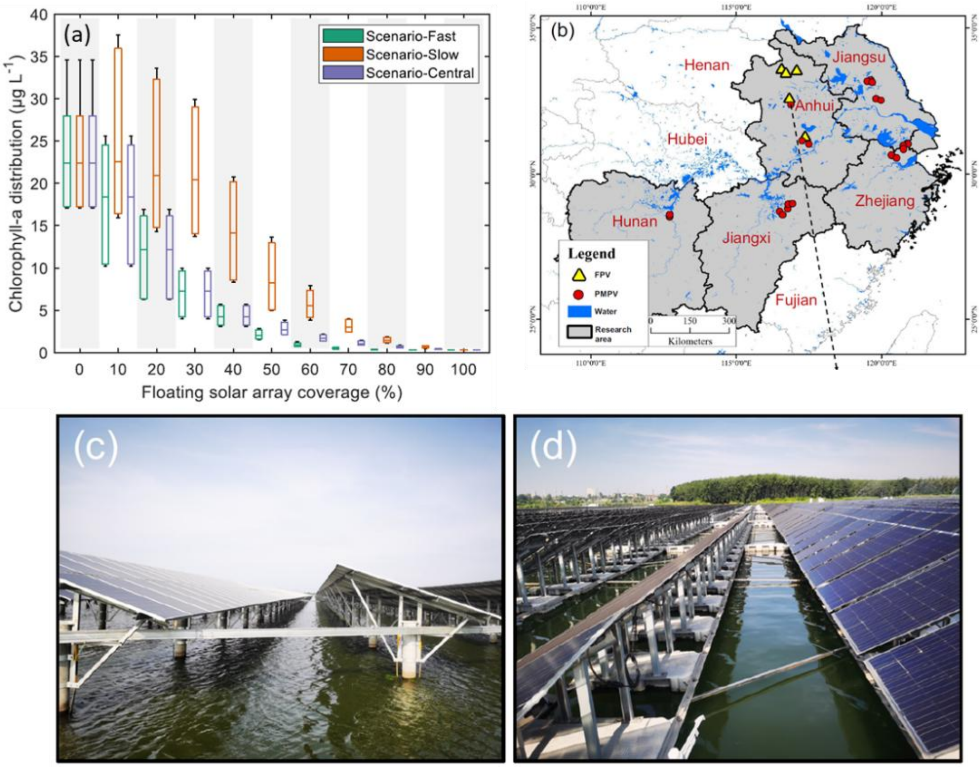

Figure 3. (a) Total chlorophyll a versus FPV coverage. Reproduced under CC-BY [24], Copyright (2022) The Authors. (b) Locations of the 26 waterbodies with FPV systems sampled in this study, including (c) five floating photovoltaic (FPV) systems and (d) 21 pile-mounted photovoltaic (PMPV) systems. Reproduced under CC-BY [25] Copyright (2024) The Authors.

Recent empirical work by Yang et al. [25] provided valuable large-scale field-based evidence on how FPV affects ecological dynamics in reservoir systems. Their study assessed 26 FPV installations across the upper Yangtze River Basin, China during winter and summer, examining variation in light, primary producers, and zooplankton communities under differing FPV coverage levels (Figure 3b-d). Figure 4 illustrates seasonal changes in biodiversity metrics, species richness, density, Shannon–Weiner diversity index, and Pielou evenness for three plankton groups: phytoplankton (top row), microzooplankton (middle row) and macrozooplankton (bottom row), across different sampling zones in relation to FPV coverage. The zones are PA (panel area under FPV), NPA (non-panel area within FPV site), and CA (control area without FPV). The left side of the dashed line shows summer data, the right shows winter. The results show that plankton communities in shaded areas (PA) consistently exhibited lower species richness and density than those in the unshaded control (CA), particularly during the summer. This pattern is most evident in phytoplankton richness and density, where a significant drop is observed under FPV panels likely a direct response to reduced light availability and subsequent declines in primary productivity. These patterns extend to both microzooplankton and macrozooplankton, suggesting potential food-web effects stemming from suppressed autotrophic production. Similarly, the Shannon–Weiner diversity index and Pielou's evenness also declined under FPV coverage in summer months, suggesting a community shift toward fewer, possibly more light-tolerant or opportunistic species and reduced ecological complexity. In winter, although light levels are generally lower, some recovery or less pronounced differences were noted, reflecting seasonal shifts in biological activity and environmental buffering.

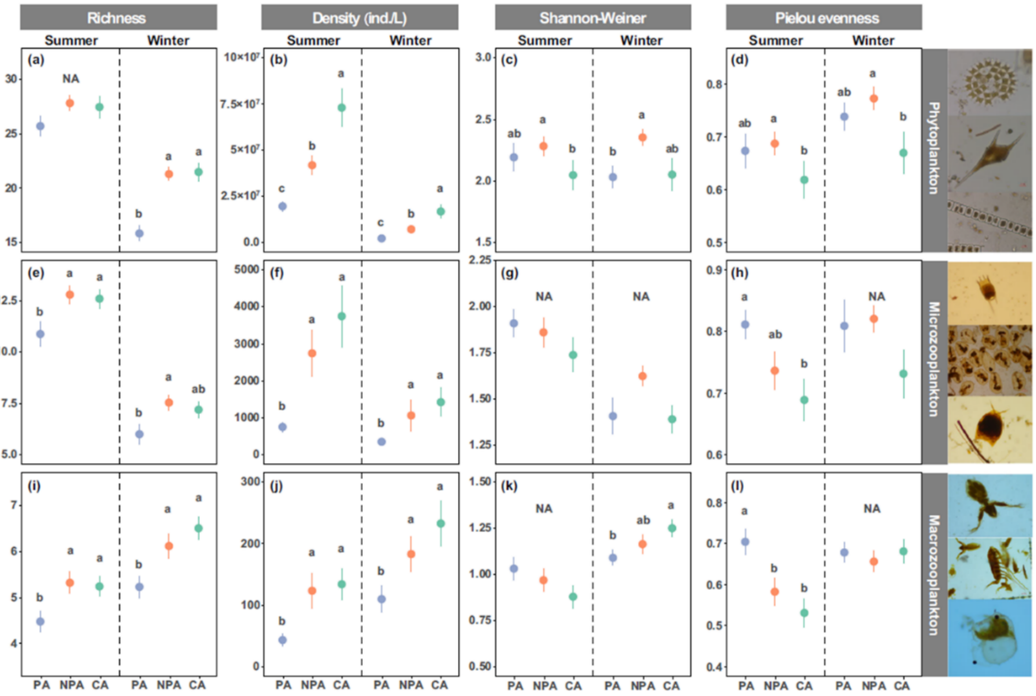

Figure 4. Variation in phytoplankton, microzooplankton and microzooplankton community indices and individual density in the three types of areas sampled in summer and winter. Reproduced under CC-BY **[25]** Copyright (2024) The Authors.

3.2. Lakes

Natural lakes are often more ecologically sensitive to surface shading than reservoirs, particularly when they are shallow, oligotrophic, or support extensive submerged vegetation. Light attenuation from floating structures can compress the photic zone and alter the balance between benthic and pelagic primary producers. In these systems, even moderate FPV coverage may lead to substantial shifts in productivity and community structure.

Nobre et al. [26] conducted a whole-lake study across six small lakes in France, comparing three FPV-covered lakes to three reference systems. The FPV lakes experienced a mean surface cooling of 1.2°C, and up to 3°C in summer, due to shading. Although lower temperatures could reduce thermal stress during heatwaves, the cooling also reduced vertical mixing, potentially affecting dissolved oxygen and productivity. The authors caution that cooling beneath FPV arrays might enhance greenhouse gas release from sediments in some lakes, thereby introducing biogeochemical trade-offs.

Eglin et al. [27] offer a broad overview of how FPV systems may impact lake ecosystems, drawing on insights from a national seminar in France that brought together scientists, authorities, NGOs, and industry stakeholders. While physical effects such as reduced light penetration and altered water temperature are increasingly reported, the authors emphasize that biological impacts such as changes in primary productivity, species composition, and food web dynamics remain poorly understood. The study highlights concerns that FPV shading can disrupt light availability and thermal mixing, potentially affecting oxygen levels and aquatic life. It also points out that the physical structures of FPV systems may unintentionally support invasive species or alter habitat use by native species. To improve understanding and guide sustainable FPV deployment, the authors call for long-term ecological monitoring using standard approaches such as Before-After-Control-Impact (BACI) designs. They stress the need for more research across multiple trophic levels using functional ecological indicators. The paper concludes by proposing a draft eco-design guide for FPV developers, focusing on project planning, ecological safeguards, and adaptive management. Overall, it lays the groundwork for better integrating biodiversity protection into future FPV planning and policy.

Ilgen et al. [28] identified several key findings regarding the ecological impacts of floating photovoltaic (FPV) systems on Lake Neusiedl, a large shallow lake (Figure 5a). Their modelling revealed that increasing FPV coverage significantly alters the lake's thermal structure, with surface waters cooling due to reduced solar input and bottom waters warming from decreased wind-driven mixing. These changes intensified thermal stratification, especially at higher FPV coverage levels. Figure 5b shows that the vertical mixing suppression reduced oxygen replenishment at the bottom and restricted nutrient upward transport of nutrients, potentially constraining primary productivity. Light attenuation caused by the FPV panels further diminished net primary production, with effects becoming pronounced beyond 40% surface coverage. Given the lake’s shallow morphology, the ecosystem was highly sensitive to changes in light and heat flux. The authors suggest limiting FPV coverage to below 40% to mitigate risks to oxygen dynamics and autotrophic processes, emphasizing the importance of considering lake-specific features such as depth and wind exposure when planning FPV deployments.

3.3. Aquaculture Ponds

Aquaculture ponds have become attractive sites for FPV deployment due to their typically small surface area, high solar exposure, and reduced land-use conflicts. In many cases, the co-location of fish or shrimp farming with solar arrays referred to as “aquavoltaics” is promoted as a synergistic system. However, these ponds are biologically active, and FPV-induced light attenuation may influence water quality and productivity, with implications for both algal dynamics and aquaculture yield.

Château et al. [29] investigated the ecological effects of FPV systems on aquaculture ponds by combining field observations and dynamic modelling in a commercial milkfish (Chanos chanos) pond in Taiwan (Figure 6a). The objective was to evaluate how different levels of FPV shading affect key water quality parameters such as temperature, dissolved oxygen (DO), biological oxygen demand (BOD), and fish growth under various aeration scenarios. The study used empirical data from two adjacent ponds, one partially shaded by FPV and the other unshaded, to calibrate simulation models. The findings showed that shading reduced daytime DO levels, largely because lower light availability limited photosynthesis. Figure 6b presents the ecological impacts under 20%, 40%, and 60% FPV coverage for both winter and summer. As panel coverage increased, reductions were observed in water temperature, DO, BOD, chlorophyll a, suspended solids, and fish biomass, while concentrations of nitrogen and phosphorus, particularly toxic ammoniacal nitrogen (NH3-N) increased. Figure 6c illustrates a trade-off between energy production and fish yield. While energy output rose with greater FPV coverage, fish production declined by around 10% in winter and 5% in summer at 60% coverage. The decline was attributed to lower DO and cooler water temperatures, which suppress milkfish feeding activity.

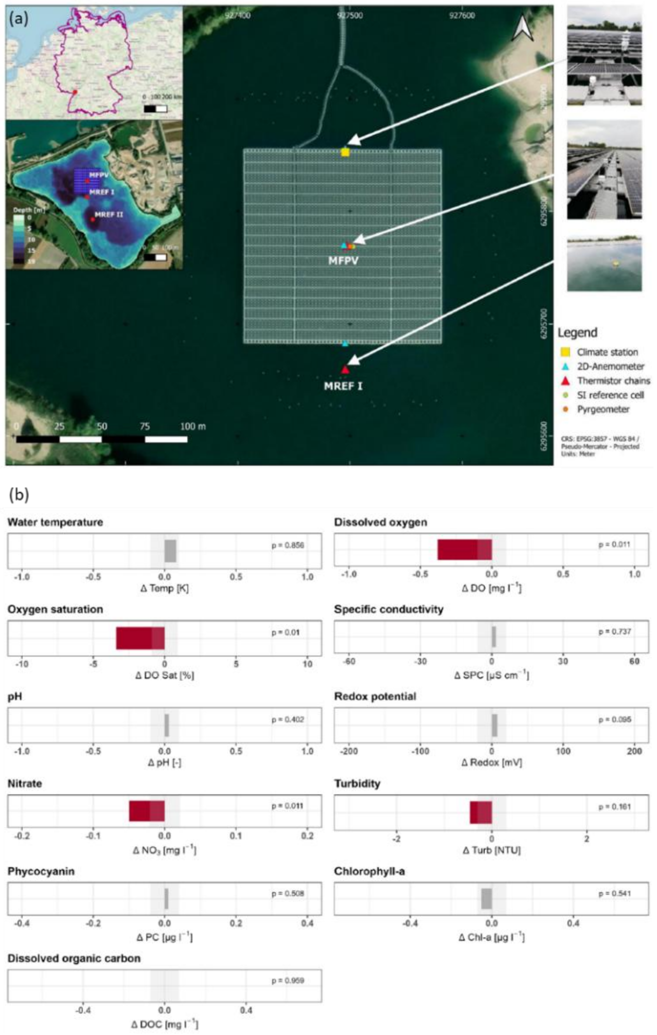

Figure 5. (a) Location of the studied gravel pit lake in Germany. (b) Deviations of the measured parameter. The grey shaded area represents measurement uncertainty. Red bars indicate deviation that exceed the measurement uncertainty. Reproduced under CC-BY-ND [28] Copyright (2025) The Authors.

Wang et al. [30] investigated the ecological impacts of FPV systems on aquaculture ponds, focusing on water quality, plankton communities, and nutrient dynamics. Conducted in the Yangtze River Delta region of China, the research compares ecological indicators across four types of areas in two adjacent fishponds: permanently shaded (PA), non-permanently shaded (NPA), control (CA), and non-panel area (NPA). The findings reveal that FPV shading significantly reduced phytoplankton richness and density, particularly in permanently shaded zones, where chlorophyll a and oxygen levels were also lower.

Zooplankton communities (both micro- and macrozooplankton) exhibited similar patterns, showing reduced diversity and evenness under shaded conditions.

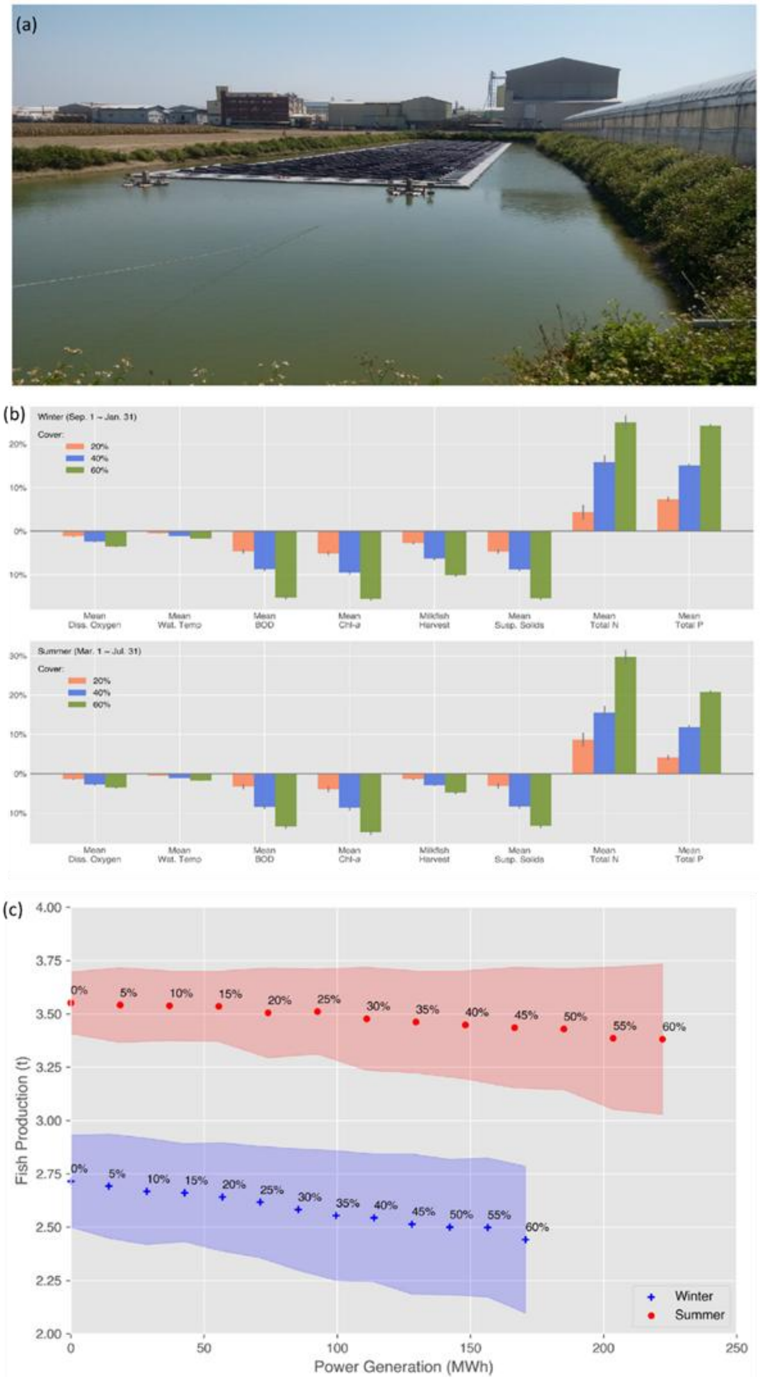

Figure 6. (a) 40% FPV cover pond. (b) Average ecosystem changes under 20% (orange), 40% (blue), 60% (green) covers, in winter (upper panel) and summer (lower panel). (c) Fish-Energy production frontier in winter (blue) and summer (red). The percentage cover is added above the simulated points. Reproduce with permission from **[29]** Copyright (2019) Elsevier B.V.

4. Knowledge Gaps and Limitations

Although empirical and modelling studies consistently show that FPV systems can reduce aquatic primary productivity via light attenuation, substantial knowledge gaps remain. These limitations span ecosystem variability, study design, ecological parameters, and long-term observation, and they must be addressed to inform responsible FPV expansion.

4.1. Limited Ecosystem Diversity

To date, most field studies focus on tropical and subtropical regions, especially Asia and South America, where FPV adoption is advancing rapidly. However, few studies assess impacts in temperate or boreal systems, where seasonal stratification, ice cover, and different light regimes may alter ecological responses. Similarly, oligotrophic lakes, particularly those with deep photic zones and benthic primary production, remain underrepresented in the literature, despite being especially vulnerable to shading.

4.2. Lack of Long-Term Monitoring

Most existing data derive from short-term experiments or snapshot surveys, which may not capture seasonal or interannual variability in productivity. Long-term shading may lead to cumulative effects, such as sediment anoxia, changes in nutrient cycling, or gradual shifts in macrophyte community structure. Without multi-year datasets, it is difficult to assess whether FPV-induced light limitation leads to ecological thresholds or irreversible shifts in ecosystem state.

4.3. Absence of Functional Thresholds

Few studies define quantitative thresholds for acceptable FPV coverage in relation to biological impacts. For instance, coverage levels above 40% are often flagged as risky, but these values vary with system depth, mixing regime, and water clarity. Current guidelines rarely integrate biological metrics, such as minimum chlorophyll concentrations or oxygen saturation required for fish habitat, into FPV siting or permitting decisions.

4.4. Oversimplification of Light Dynamics

Many models and assessments treat shading as a uniform or binary variable, ignoring the complexity of light transmission, reflection, and spectral shifts beneath different FPV designs. In reality, panel spacing, angle, height, and movement all affect the spatial heterogeneity of light and may create microhabitats with variable biological outcomes. More detailed radiative transfer modelling and in situ light profiling are needed to refine ecological predictions.

4.5. Underexplored Food Web and Biogeochemical Effects

While phytoplankton and macrophyte responses are increasingly studied, there is limited research on secondary impacts, such as changes in zooplankton, benthic invertebrates, microbial communities, and nutrient fluxes, remains limited. For instance, declines in algal productivity may reduce food availability for herbivores, while lower oxygen production could alter nitrification or phosphorus release from sediments. These effects could affect water quality and fish production, even in systems where algal biomass remains relatively stable.

While several key factors influencing FPV-induced ecological impacts can be identified, the development of a generalized decision framework remains challenging due to the limited availability of standardized, cross-system datasets. Ecological responses to FPV shading are highly context-dependent, varying with water optical properties, hydrodynamic conditions, and system design. Future research should focus on establishing validated thresholds and decision-support tools through coordinated multi-site studies and long-term monitoring.

5. Conclusion

FPV systems offer a promising solution to clean energy expansion, yet their ecological implications particularly through light attenuation remain insufficiently resolved. This review focused on a single but foundational mechanism: how FPV-induced shading alters underwater light availability and suppresses aquatic primary productivity. Evidence from reservoirs, lakes, and aquaculture ponds consistently shows that reductions in PAR affect ecosystem biodiversity, with downstream consequences for oxygen dynamics and food webs. As FPV deployment accelerates globally, integrating ecological light requirements into system design and impact assessment will be essential for protecting freshwater ecosystem integrity. Continued research should aim to close critical knowledge gaps, particularly in diverse and understudied aquatic environments. A focused understanding of light–productivity relationships will support more balanced, evidence-based FPV implementation in the context of sustainable energy and environmental stewardship.

Acknowledgements

Authors acknowledge support provided by the Geran Translasi UKM (TR-UKM), grant number UKM-TR2024-09, funded by Universiti Kebangsaan Malaysia (UKM).

Declaration of Conflict of Interest

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

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