

Investigation of the Effects of Floating Solar Energy Systems on Water Quality and Aquatic Ecosystems: A Literature-Based Assessment

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Abstract – Floating photovoltaic (FPV) systems have recently emerged as a promising renewable energy solution that minimizes land use conflicts while enhancing water resource efficiency. However, their ecological and environmental implications remain poorly understood. This study provides a comprehensive literature-based assessment of the effects of FPV systems on water quality and aquatic ecosystems. Through a systematic review of published research, the study synthesizes current findings regarding physical (temperature, light, evaporation), chemical (oxygen, pH, nutrients), and biological (algae, fish, microorganisms) impacts. The results indicate that FPV systems can significantly reduce evaporation and surface temperature but may also modify light penetration and dissolved oxygen dynamics, influencing aquatic biodiversity. The paper concludes by identifying critical research gaps and suggesting future directions for sustainable FPV design and deployment. Additionally, this study highlights the importance of integrating ecological monitoring and adaptive management strategies into FPV project planning to mitigate potential adverse impacts. The findings underscore the need for interdisciplinary research combining hydrology, ecology, and renewable energy engineering to ensure environmentally responsible FPV system deployment. This review also identifies policy and management considerations essential for balancing renewable energy development with aquatic ecosystem conservation.

Keywords –Floating Photovoltaic Systems, Water Quality, Aquatic Ecosystems, Environmental Sustainability, Renewable Energy.

I. INTRODUCTION

The global demand for energy continues to increase rapidly due to industrialization, urbanization, and population growth, leading to a significant rise in fossil fuel consumption. This trend poses serious challenges to both energy security and environmental sustainability. According to the International Energy Agency (IEA) [1], approximately 60% of global electricity generation still relies on fossil fuels. In response, international climate policies such as the Paris Agreement and the European Green Deal have prioritized the transition toward renewable and low-carbon energy systems. Among these alternatives, solar photovoltaic (PV) energy has emerged as one of the fastest-growing renewable technologies, owing to its high accessibility, technological maturity, and declining production costs.

However, large-scale land-based solar installations require vast areas, which often lead to land-use conflicts, particularly in densely populated or agriculturally productive regions. Issues such as agricultural land loss, habitat fragmentation, and disputes over land ownership have raised concerns about the long-term sustainability of terrestrial PV systems. In this context, Floating Photovoltaic (FPV) systems—also known as floating solar farms—have recently gained attention as an innovative solution that allows renewable energy generation without occupying valuable terrestrial space. FPV systems consist of PV panels mounted on buoyant platforms deployed over water bodies such as reservoirs, lakes, irrigation ponds, and water treatment basins. Beyond their spatial efficiency, FPV systems offer several environmental and operational benefits, including reduced evaporation, lower module temperature (enhancing power efficiency), and potential improvement in water resource management.

From an environmental standpoint, the implications of FPV systems on water quality and aquatic ecosystems are multidimensional. On one hand, FPV installations can reduce water temperature and evaporation rates, limit algal blooms by reducing light penetration, and mitigate eutrophication risks. These effects can enhance water quality and resilience, especially in arid and semi-arid regions where evaporation losses are critical. On the other hand, prolonged shading and alterations in the thermal and light regimes of surface waters may influence dissolved oxygen profiles, nutrient cycling, and biological productivity, potentially affecting aquatic biodiversity and food web dynamics.

Recent studies have provided valuable insights but also highlighted uncertainties regarding FPV–ecosystem interactions. In the context of FPV installations, it has been reported that surface water temperatures typically decline by 1–3°C, while evaporation rates are reduced by up to 20% due to the shading effect [2]. Conversely, modifications in the vertical stratification of dissolved oxygen (DO) were found to be potentially affected by continuous shading, which in turn impacts microbial activity [3]. Furthermore, a suppression of phytoplankton growth in surface layers by FPV installations was demonstrated, suggesting a reduction in eutrophication potential; however, an indirect alteration of species composition and benthic processes could also be induced [4]. These findings collectively indicate that the environmental impacts of FPV systems cannot be generalized; they depend on site-specific factors such as water depth, climatic conditions, panel coverage ratio, and ecosystem sensitivity.

The increasing deployment of FPV systems has consequently given rise to a new interdisciplinary research domain that integrates renewable energy engineering and aquatic ecology—focusing on the energy–ecosystem nexus. This framework emphasizes that the sustainability of energy systems must be assessed not only in terms of carbon reduction potential but also in terms of their influence on ecosystem functions and services, particularly in aquatic environments [5]. For countries such as Turkey, where solar energy potential is high but freshwater resources are limited, FPV systems represent a promising dual-benefit technology. Covering even 1% of the surface area of existing reservoirs with FPV installations could significantly contribute to national electricity generation while reducing evaporation losses [6]. Nonetheless, understanding the environmental sustainability of such systems requires systematic, data-driven assessment.

Therefore, this study aims to provide a comprehensive literature-based evaluation of the effects of floating solar energy systems on water quality parameters and aquatic ecosystems. Through an integrative review of recent experimental and modelling studies, the analysis focuses on the physical, chemical, and biological dimensions of FPV–ecosystem interactions [4, 7]. By synthesizing current knowledge, this work identifies existing research gaps and proposes directions for future interdisciplinary studies, contributing to the sustainable integration of floating solar technology within the broader framework of environmental management.

II. THEORETICAL FRAMEWORK AND METHODOLOGY

A. Theoretical Background

The integration of renewable energy technologies into aquatic environments introduces a complex set of physical, chemical, and biological interactions that require a multidisciplinary analytical framework. The theoretical foundation of this study is based on three interrelated domains: (i) aquatic ecosystem dynamics, (ii) photovoltaic system–environment interactions, and (iii) environmental sustainability assessment.

First, the aquatic ecosystem dynamics component considers the fundamental processes governing thermal stratification, light penetration, gas exchange, and primary production in freshwater bodies [7]. These processes are highly sensitive to surface conditions such as incident solar radiation, wind mixing, and temperature gradients. FPV installations, by modifying light and heat fluxes, have the potential to alter these equilibrium conditions.

Second, the PV system–environment interaction theory draws from environmental physics and hydrodynamic modelling. The placement of solar panels on water surfaces changes the albedo, radiative energy balance, and turbulence at the air–water interface [8]. Reduced light transmission affects photo synthetically active radiation, while localized shading may alter dissolved oxygen and carbon dioxide fluxes through changes in photosynthetic and respiratory activity [9, 10].

Third, environmental sustainability assessment provides a systems-level perspective for evaluating the net ecological outcomes of FPV deployment. This approach incorporates both life-cycle environmental benefits—such as greenhouse gas reduction—and localized ecological trade-offs, including shifts in biodiversity or nutrient cycling [11]. Hence, a comprehensive evaluation of FPV systems requires not only physical and chemical monitoring but also ecological modelling and ecosystem service valuation.

Table 1. Comparison of Floating Photovoltaic (FPV) and Land-based Photovoltaic (LPV) Systems

Parameter	Floating Photovoltaic – (FPV)	Land-based Photovoltaic – (LPV)
Installation Location	Deployed on water surfaces (reservoirs, lakes, hydropower dams)	Installed on terrestrial land surfaces
Cooling Effect	Natural water cooling enhances panel efficiency (by 5–10%)	Limited cooling, efficiency declines with surface heating
Land Use Efficiency	No land occupation; suitable for land-scarce regions	Requires large tracts of land; may compete with agriculture
Evaporation Impact	Reduces evaporation by 20–60%, conserving water resources	No impact on evaporation
Water Quality Influence	Alters light, temperature, and oxygen levels; ecological impacts vary	Negligible direct influence on aquatic systems
Installation and Maintenance Cost	Slightly higher due to floating structures and anchoring systems	Generally lower; easier ground access
Energy Yield	5–15% higher due to lower module temperature and reflectivity	Baseline performance, susceptible to heat losses
Environmental Risks	Potential shading, oxygen depletion, and ecosystem alterations	Land disturbance, soil erosion, and habitat loss
Durability and Stability	Affected by wind, wave action, and biofouling; requires periodic maintenance	Stable under most environmental conditions
Scalability and Integration	Compatible with hydropower, aquaculture, and water management systems	Compatible with agriculture and industrial areas

Source: Compiled from recent studies on FPV–LPV comparative performance (2019–2025).

As shown in Table 1, FPV systems provide notable advantages over LPV systems in terms of energy efficiency, land-use optimization, and water conservation. The natural cooling effect of water improves power output by approximately 5–10%, while surface shading can reduce evaporation by up to 60%. These

characteristics make FPV systems particularly suitable for regions facing land scarcity and high evaporation rates. However, FPV installations also introduce unique ecological and operational challenges. By altering light penetration, water temperature, and oxygen dynamics, they can influence aquatic biodiversity and biogeochemical cycles. Additionally, higher installation and maintenance costs due to floating platforms and anchoring structures must be considered. Therefore, FPV deployment should follow a balanced approach that maximizes renewable energy benefits while minimizing ecological disruption.

B. Conceptual Framework

The conceptual model guiding this research (Figure 1) illustrates the interdependencies among the key components affected by FPV systems: solar radiation, thermal regime, water chemistry, and biological community structure. FPV arrays reduce solar irradiance reaching the water surface, which consequently affects temperature distribution and light-dependent biological processes. This cascade influences primary productivity, dissolved oxygen concentration, and ultimately the health of aquatic organisms [12].

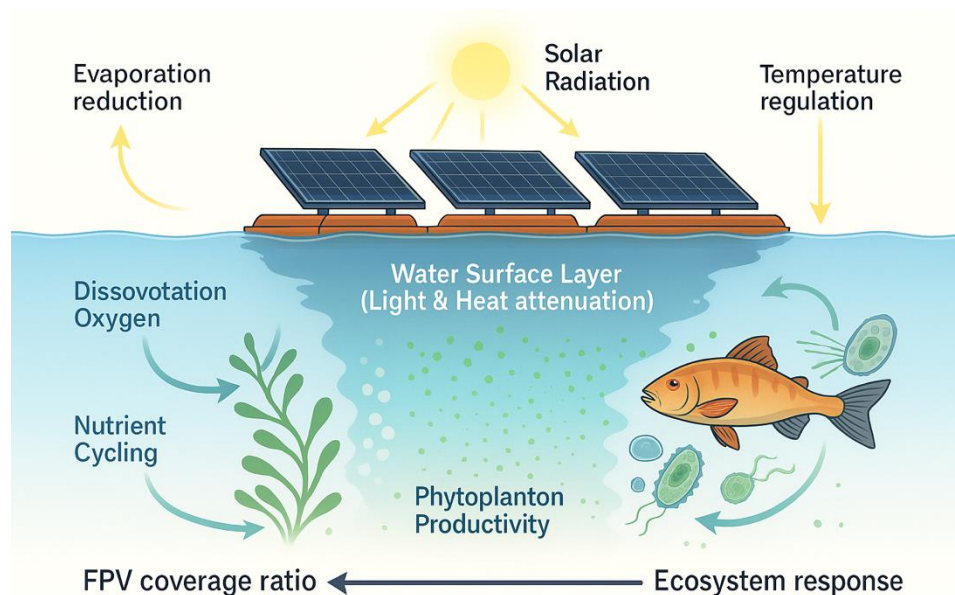


Figure 1: A schematic representation showing how floating photovoltaic systems influence light, heat, and nutrient dynamics within aquatic environments.

C. Methodological Approach

This study adopts a systematic literature review methodology to identify, analyse, and synthesize existing scientific knowledge concerning the effects of floating solar systems on water quality and aquatic ecosystems. The approach follows the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) framework to ensure transparency and reproducibility. A comprehensive search was conducted across Scopus, Web of Science, and ScienceDirect, covering publications from 2010 to 2025.

Inclusion criteria were limited to peer-reviewed journal articles, conference papers, and technical reports providing quantitative or qualitative data related to the environmental implications of FPV systems. Studies focusing solely on economic or mechanical aspects of FPV technology were excluded. A representative set of studies that met these criteria was selected for detailed analysis and classification based on the nature of their environmental assessments. Selected studies were categorized according to three main impact domains:

- **Physical impacts** — changes in water temperature, evaporation rate, and irradiance distribution;
- **Chemical impacts** — alterations in dissolved oxygen, pH, and nutrient concentrations;
- **Biological impacts** — effects on algae, plankton, fish, and microbial communities.

Each article was analysed for study location, experimental setup (e.g., coverage ratio, panel type), duration, and key outcomes. Comparative synthesis was performed to identify consistent patterns, contradictions, and knowledge gaps.

D. Analytical Framework

The analysis integrates both qualitative synthesis and quantitative trend evaluation from the reviewed literature. For instance, reported reductions in surface temperature and evaporation were compiled to derive an approximate range of FPV-induced modulation across different climatic zones. Similarly, studies reporting variations in dissolved oxygen and chlorophyll concentrations were compared to assess ecosystem responses under different FPV configurations.

This analytical framework enables the identification of threshold conditions under which FPV systems may transition from environmentally beneficial to potentially adverse. Such insights contribute to establishing environmental design guidelines for FPV installations, including optimal coverage ratios, array spacing, and monitoring parameters to ensure ecological compatibility.

III. RESULTS AND DISCUSSION

The implementation of FPV systems has demonstrated notable impacts on the physical, chemical, and biological parameters of aquatic environments. Results from recent experimental and modelling studies indicate that FPV installations can significantly modify the local microclimate, hydrodynamic balance, and ecological processes in freshwater bodies. The extent of these effects depends primarily on the coverage ratio, design configuration, and site-specific characteristics such as water depth, wind patterns, and nutrient availability.

A. Effects on Water Temperature and Thermal Stratification

FPV arrays act as partial surface covers that intercept incoming solar radiation, leading to a measurable reduction in surface water temperature. For instance, field data from pilot-scale reservoirs show temperature decreases of up to 1–3°C beneath dense FPV coverage compared to open water areas. This reduction in solar energy input alters the vertical temperature profile, often stabilizing the thermal stratification and slowing the rate of surface mixing. Such temperature regulation may provide benefits in hot and arid regions by reducing evaporation losses, yet prolonged cooling may suppress natural convection processes necessary for oxygen and nutrient redistribution.

B. Evaporation Reduction and Water Conservation

The physical shading provided by FPV panels can substantially mitigate evaporative losses. Several hydrological models estimate evaporation reductions ranging from 20% to 60%, depending on the panel density and local climatic conditions. This effect is particularly valuable in water-scarce regions, contributing to water resource conservation and improving reservoir management efficiency. However, excessive surface coverage (>60%) may disrupt gas exchange and light penetration, which are essential for sustaining aquatic life.

C. Light Attenuation and Primary Productivity

The attenuation of light intensity beneath FPV arrays influences the photosynthetic activity of phytoplankton and submerged vegetation. Reduced light availability limits primary productivity in the shaded zones, potentially shifting the ecosystem toward a heterotrophic balance. Controlled mesocosm studies have shown a 30–50% decline in chlorophyll-a concentration under partial FPV shading. While this may help prevent eutrophication in nutrient-rich reservoirs, it could also affect the trophic dynamics and the availability of food sources for higher organisms. This effect can also vary seasonally, with stronger attenuation observed during summer months due to higher solar angles.

D. Dissolved Oxygen Dynamics and Biogeochemical Cycling

Changes in temperature and photosynthetic rates directly affect DO concentrations. Reduced surface turbulence beneath FPV structures may lower DO diffusion, while decreased primary production reduces

oxygen generation. Observations indicate a spatial DO gradient of up to 2 mg/L between shaded and unshaded areas. Furthermore, sediment biogeochemical processes may be altered due to reduced light and temperature fluctuations, influencing nutrient regeneration and microbial activity. These effects are more pronounced in stagnant or eutrophic waters where oxygen demand is already high.

E. Ecological and Biodiversity Implications

FPV-induced modifications in the aquatic environment can affect community composition, favouring species adapted to lower light and cooler conditions. For example, certain benthic organisms and cyanobacteria exhibit increased relative abundance under shaded conditions, while photophilic species may decline. The long-term ecological balance thus depends on maintaining a sustainable FPV coverage ratio, generally recommended below 40% of the water surface to preserve ecological resilience and biotic diversity.

F. Integrated Environmental and Energy Perspective

From an integrated sustainability viewpoint, FPV systems offer a dual benefit: renewable energy generation and environmental management. When properly designed, FPV installations can help mitigate water loss, stabilize temperature regimes, and reduce algal blooms. Nonetheless, overexpansion without ecological consideration may introduce new environmental stresses. Therefore, the optimization of FPV system design must involve multi-criteria assessments that include hydrodynamic modelling, ecological monitoring, and adaptive management frameworks.

IV. CONCLUSION AND FUTURE WORK

This study presents a comprehensive literature-based assessment of the environmental implications of FPV systems on water quality and aquatic ecosystems. The synthesis of existing research demonstrates that FPV installations can yield both beneficial and adverse outcomes depending on their scale, configuration, and the ecological sensitivity of the hosting water bodies.

From a physical perspective, FPV arrays effectively reduce water surface temperature and evaporation rates, contributing to improved thermal stability and water resource conservation—particularly valuable in arid and semi-arid regions. Chemically, however, these systems alter oxygen exchange and biogeochemical processes due to shading and reduced turbulence at the air–water interface. Biologically, FPV deployment can suppress excessive algal growth and mitigate eutrophication risks but may also shift the structure of aquatic communities by modifying light and nutrient dynamics.

Overall, the review indicates that the net environmental impact of FPV systems depends on finding a critical balance between energy generation efficiency and ecosystem health. Optimal design parameters, such as coverage ratio, module spacing, and anchoring depth, must be adapted to local hydrological and ecological conditions. Implementing adaptive management frameworks and environmental monitoring programs will be essential to ensure that FPV expansion aligns with sustainability objectives.

Future research should move beyond short-term, small-scale observations and focus on long-term, integrative studies that combine in situ monitoring with numerical modelling and remote sensing. Coupled hydrodynamic–biogeochemical models could help quantify the nonlinear interactions among radiation, temperature, and oxygen fluxes under FPV coverage. Additionally, the development of standardized environmental impact assessment (EIA) protocols specific to FPV systems is urgently needed to support policymaking and sustainable deployment. Future deployment strategies should incorporate environmental policy instruments, such as EIA and adaptive management frameworks, as mandatory prerequisites for FPV licensing.

Another promising direction lies in the integration of FPV with complementary technologies, such as floating wetlands, aquaculture systems, or hybrid hydro-solar plants. Such multifunctional configurations may enhance both energy and ecological outcomes, transforming artificial reservoirs into productive, resilient ecosystems. Future studies should also explore circular design concepts, including recyclable materials and low-impact anchoring mechanisms, to further reduce the ecological footprint of FPV installations.

In conclusion, FPV systems represent a frontier technology within the renewable energy transition—capable of delivering substantial energy and water co-benefits if implemented responsibly. A holistic, interdisciplinary approach that combines engineering innovation with ecological stewardship will be critical to achieving the full potential of floating solar energy systems in advancing global sustainability goals. Integrating FPV systems with real-time monitoring sensors could provide continuous data to evaluate ecosystem responses, enabling proactive management.

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