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A Systematic Review of Floating Photovoltaic Plant Environmental Impacts

Larissa de Andrade Gonçalves[1], Larissa Faria[1,2], Michael Mannich[3], Marcelo Coelho[3], Jucimara Andreza Rigotti[4], Tobias Bleninger[3] & Jean Ricardo Simões Vitule[1]

[1] Laboratório de Ecologia e Conservação, Departamento de Engenharia Ambiental, Setor de Tecnologia, Universidade Federal do Paraná, Av. Cel. Francisco H. dos Santos 100, Curitiba, PR 81530-000, Brazil

[2] Instituto Água e Terra, R. Engs. Rebouças, 1206, Curitiba, PR 80215-100, Brazil

[3] Departamento de Engenharia Ambiental, Setor de Tecnologia, Universidade Federal do Paraná, Av. Cel. Francisco H. dos Santos 100, Curitiba, PR 81530-000, Brazil

[4] Programa de Pós-Graduação em Engenharia de Recursos Hídricos e Ambiental, Setor de Tecnologia, Universidade Federal do Paraná, Av. Cel. Francisco H. dos Santos 100, Curitiba, PR 81530-000, Brazil

Correspondence: Larissa Faria, Instituto Água e Terra, R. Engs. Rebouças, 1206, Curitiba, PR 80215-100, Brazil. Tel: 55-41-99252-2209. E-mail: larissa.faria@fulbrightmail.org

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Abstract

Solar photovoltaic installations are growing fast worldwide as a renewable alternative for power generation, although, there are some disadvantages of the conventional land-based solar power plants, such as the need of a large land area. Thus, floating photovoltaic power plants (FPV) have emerged as a new solution in solar energy; however, the environmental impacts of such installations are still being investigated. Here, we performed a systematic review to compile reported environmental impacts of FPV installations on water bodies. Twenty-nine papers were retrieved and had data related to environmental impacts of FPV extracted. We looked for any physical, chemical, and biotic parameters that were quantified to evaluate FPV effects (FPV versus a control without FPV). Alterations in parameters were classified as positive or negative impacts according to each study. We found very few studies with primary quantitative data, which does not allow us to draw a general pattern of impacts. The most reported alterations were decreased temperature and evaporation from the water body after FPV installation (~35% of the studies). We found 17 alterations classified as a negative impact, and only six as positive. As FPVs are an emergent energy alternative more investments are needed in studies directly focused on assessing its environmental impacts, particularly making an explicit comparison of FPV installation and a control to disentangle their effects on water quality, phytoplankton and the biota.

Keywords: ecological changes, environmental changes, limnology, photovoltaic power plant, renewable energy, solar energy

1. Introduction

The availability of fossil fuels is continuously decreasing, which implies a reduction in power generation (Kumar, Rashmitha, Naresh, Bangararaju, & Rajagopal, 2013). Fossil fuel burning is a key factor in increasing greenhouse gas emissions, CO_2 being one of the main global warming gases (Zeng, Stringer, & Lv, 2021). In addition, global trends, as well as climate and energy policy goals, push countries to promote renewable energy sources as an alternative to fossil energy (Bieda & Cienciała, 2021). At the United Nations Climate Change Conference (COP 26) held in November 2021, more than 200 countries signed the Glasgow Climate Pact and committed to gradually reduce the use of fossil fuels, listed as the main cause of the climate crisis. Furthermore, the reduction of carbon consumption and the design of new renewable energy technologies are key to achieving the United Nations' Sustainable Development Goals (SDGs). These goals were adopted in 2015 by the UN's member states, aiming to ensure access to affordable, reliable, sustainable, and renewable energy for all (SDG 7) (United Nations, 2015). Therefore, other methods such as solar, wind, and tidal energy should be applied to compensate for the decreasing use of fossil fuels. Particularly, because these come from renewable natural sources that are free and abundantly available worldwide, they have advantages such as low maintenance cost and negligible pollution emission during operation (Kumar et al., 2013).

Solar energy is considered one of the most promising alternative energy sources due to its ubiquity and sustainability (Hosenuzzaman et al., 2015). The world's photovoltaic generation reached a growth record in 2021, increasing by 22% and surpassing 1000 TWh, thus being the second fastest-growing technology within renewable energies (Mugnier, 2022). Moreover, this is the only sustainable energy source with sufficient capacity to meet the entire global energy demand for the foreseeable future (Meng, Hamada, Druffel, Lee, & Rajeshwar, 2020). The total energy from the Sun hitting the Earth every hour is approximately twice the amount of energy used by humans each year (Lee et al., 2020). The most common application for the use of solar energy is through photovoltaic systems. Photovoltaic energy, however, still needs to grow further, with a minimum of 25% per year from 2022 to 2030, to reach the global target of 7400 TWh needed for zero CO_2 emissions (Mugnier, 2022). Given this scenario, great investments are expected worldwide.

Photovoltaic panels that convert sunlight into electricity are one of the most efficient, sustainable, and environmentally friendly products in the field of renewable energy (Hosenuzzaman et al., 2015). However, in order to meet a multi-megawatt scale electricity generation, photovoltaic facilities need to occupy a large space of available land. That requires wide land clearance which can result in deforestation of native ecosystems, leading to habitat loss (Kim, Koide, Ishihama, Kadoya, & Nishihiro, 2021), and various negative impacts to the local biodiversity and ecosystem services (Pimentel Da Silva & Branco, 2018), causing yet restrictions on land use for agriculture (Trapani & Millar, 2013).

Recently, floating photovoltaic power plants (FPVs) have emerged as a potential solution to the problem of space demand and water scarcity (Trapani & Redón Santafé, 2015). Countries with high population density (e.g, China, India, and Japan) or arid and semi-arid climates (e.g., Australia, Spain, Iran, the US, Chile, India, and Jordan) are making use of FPVs to solve or alleviate these problems (Baradei & Sadeq, 2020). Water availability is not as certain as years or decades ago. Uncertainty has become one of the major challenges in water resources management, and FVPs are playing an important role in these regions (Baradei & Sadeq, 2020). Regarding technical aspects, despite higher deployment costs, FPVs are more efficient in generating electricity than ground-mounted or rooftop installations due to the panel cooling provided by the water below (Redón-Santafé et al., 2014; Azevedo, Freitas, & Silveira, 2021). Also, FVPs can be coupled with hydroelectric power plants to generate energy in dry seasons while still saving water due to reduced evaporation. Coupling FVPs and hydropower plants are better integrated by sharing the existing electric infrastructure. While there are many reasons for the exponential growth in the use of FPVs in the last years, this industry is still developing, and the environmental impacts of these installations are still poorly understood (Baradei & Sadeq, 2020). For instance, the shading caused by the panels reduces water evaporation, temperature, and the growth of some groups of photosynthetic organisms, which can have impacts on herbivores, cascading to other trophic levels and the adjacent terrestrial ecosystems (Redón-Santafé et al., 2014; Azevedo et al., 2021). Especially in closed environments such as lakes the surface cover reduces air-water exchange. Consequently, the dissolved oxygen concentration can be reduced and, hence, lead to biodiversity loss, depending on the water surface covering percentage. Besides reduced CO_2 emissions, there are other observed positive effects, such as panels providing shelter to fish and generating artificial structures in habitat-simplified reservoir zones (Pouran, Lopes, Nogueira, Branco, & Sheng, 2022, Ziar et al., 2021), improved water quality, and habitat preservation as it does not require deforestation or large land areas (Pouran et al., 2022).

The first FPV system was installed in 2007 in Aichi City, Japan, for research purposes and had an output of 20 kWp; followed by the first commercial-scale FPV with 175 kWp installed in California, USA in 2008 (Ziar et al., 2021). Many FPV systems were developed afterwards, mainly in countries with high population density and/or land scarcity. By the end of 2021, the cumulative power generation capacity of FPVs worldwide was estimated at 3 GWp (Masson & Kaizuka, 2021). Between the years 2015 and 2021, 63 new FPVs were built in 19 different countries, 22 of them in China and 12 in Japan, and their power generation potential ranges from 948 kW to 150 000 kW (Ma, Wu, & Su, 2021). In January 2022, the world's largest FPV with a generating capacity of 320 MW was commissioned in Dezhou, Shandong province of China, on a reservoir (Garanovic, 2022).

FPV installations are increasing rapidly worldwide and it is important to know their effects on aquatic ecosystems and its associated functions and services. Without understanding it thoroughly, ecosystem services may be at risk and co-benefit opportunities can be missed. Therefore, this review aims to compile evidence of FPV environmental impacts from the scientific literature to provide a general perspective on this renewable energy type of installation. With that, we identify knowledge gaps that should be addressed in future research to advance the field.

2. Method

We performed a systematic search in the literature following the PRISMA protocol (Château et al., 2019). We searched for studies that provided quantitative data on the effects and environmental changes caused by FPV installations. The search was performed on June 2022, in the Web of Science collection using as keywords "floating photovoltaic" OR "floating solar panel" OR "floating PV" OR "floatovoltaic" AND "effect*" OR "impact*" OR "monitoring" OR "alteration*" OR "water quality". All search fields performed the search by Topic. After identifying the studies, their suitability for our review was assessed through title and abstract reading. Only those that actually cited the occurrence of environmental impacts or changes caused by the installation of FPVs were selected for the next step, which consisted of a full reading of the paper. At this stage, we selected only the studies that presented quantitative data (a measurable increase or decrease in analyzed parameters), however, we also collected qualitative data when available.

Given the low number of papers retrieved in our search, we also included studies that provided secondary data, such as reviews. Thus, the selected papers were classified as primary or secondary evidence data according to the type of study. Studies where data were obtained directly by the authors using their own research instruments (e.g., mathematical models, pilot scale tests, on-site analyses, and case studies) were classified as primary evidence, whereas those which used data already collected and analyzed in previous studies were considered as secondary data (including both literature and systematic reviews).

Specific information about each study was also collected, such as the year and country of publication, the climate of the location according to Köppen-Geiger classification (Peel, Finlayson, & McMahon, 2007) and the type of water body where the FPV is installed, the water body surface area, power plant size, and which biotic and/or physicochemical parameters were investigated. Investigated parameters were classified as physical, chemical, or biotic. Physical parameters were temperature, evaporation, irradiation, total suspended solids (TSS) and total dissolved solids (TDS), diffusivity, electromagnetic field (EMF), and wind speed. Chemical parameters were pH, total N and P, ammoniacal nitrogen (Namn), phosphate, dissolved oxygen (DO), and biochemical demand of oxygen (BOD); while parameters covering all local living beings, and their interaction with the surrounding environment were considered biotic, for example, the biomass of algae and chlorophyll-a (Chl-a).

To evaluate impacts caused by the FPV installation we searched for data from two contrasting situations: a control, where data were simulated/collected before the installation of the FPV or in an area not affected by it; and the FPV, in which data were simulated/collected in an area directly affected by the FPV installation. Data from both situations were then compared to determine whether there was a decrease or an increase (alteration) in the investigated parameter due to the FPV compared to the control. Subsequently, the observed parameter alteration was classified as having a positive or negative impact on the associated biota or water quality. As the classification of positive or negative impact can be subjective and context-dependent, we relied on the interpretation of the authors from the original study. In cases where the classification was not clear or if the same alteration could be interpreted as positive and negative depending on other factors, we classified the alteration as "undefined" impact.

3. Results

The search yielded 360 records which resulted in 29 studies selected for the systematic review after the two-step screening process (Figure 1). Most studies were classified as primary data (55%), despite literature review (n = 11) being the most common study type found. Among primary data studies, mathematical models were the most common (n = 6), followed by pilot scale tests and on-site analysis (n = 4 each), while the least common type found was case study (n = 2). We found two systematic reviews that albeit different approaches, fitted our selection criteria.

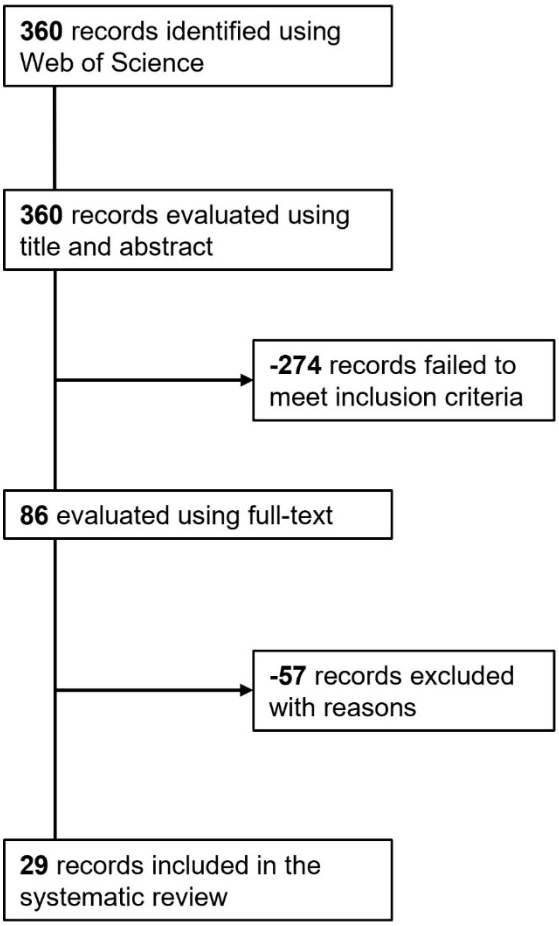

Figure 1. PRISMA flow diagram showing the steps followed to include papers in the systematic review

The first study was published in 2013, and the year with the highest number of publications was 2021 (n = 9) (Figure 2). Considering only studies that provided primary evidence data (n = 16), we found a prevalence of research in regions with climates classified as Warm Summer Mediterranean (Csa) and Seasoned (Cfb) (25% each), and low geographic coverage, as only ten countries have publications about FPV impacts. Only three studies in Subtropical climate with hot summer were found (Cfa) (18.75%), two in Taiwan (on-site analysis and mathematical modeling) (Wang et al., 2022, Château et al., 2019), and a case-study in Portugal (Costa, 2017); two studies in hot desert climate (Bwh) (12.5%) in Jordan (Abdelal, 2021, Al-Widyan, Khasawneh, & Abu-Dalo, 2021); one study in hot summer humid continental climate influenced by monsoons (Dwa) (6.25%) in China (Zhang et al., 2020); one in Humid tropical climate (Af) (6.25%) (Abdelal, 2021); and one in Semiarid (Bsh) in Brazil (6.25%) (Ates, Yilmaz, & Gulgen, 2020).

Regarding the size of the plants and percentage of water body coverage, a wide variation is observed, ranging from 0.01% of the water body covered by the FPV (Costa, 2017) to a complete cover, as in the case of an artificial reservoir in Jordan (Abdelal, 2021). The smallest studied FPV has an area of less than 1 m² (Majumder, Innamorati, Frattolillo, Kumar, & Gatto, 2021) while the largest one occupies an area of 742,902 m² (da Costa & da Silva, 2021). Furthermore, studies were carried out in different water body types, such as reservoirs (80%), aquaculture ponds (13.3%), and coastal regions (6.7%).

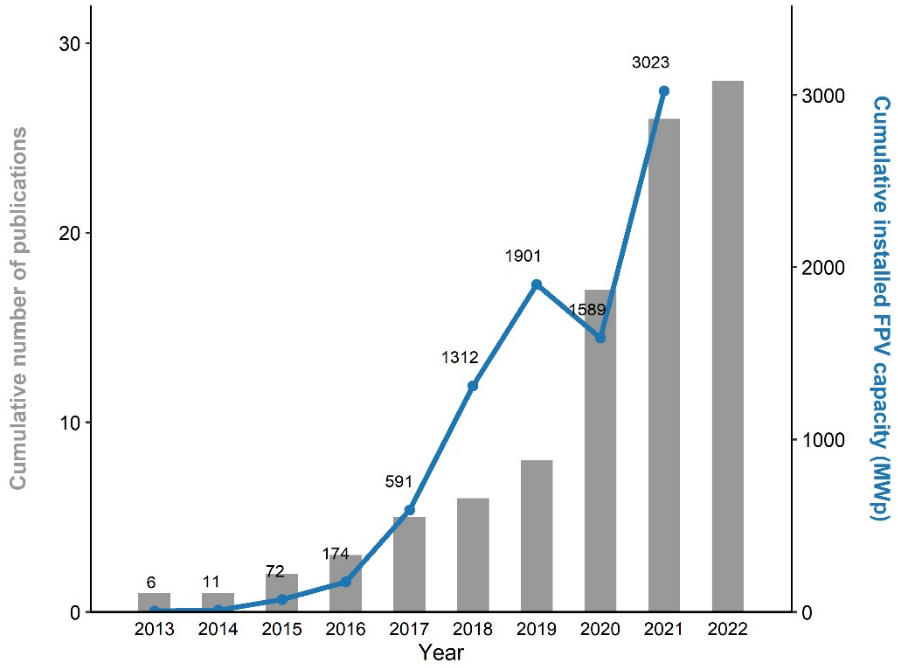

Figure 2. Cumulative number of published papers included in the systematic review (grey bars, left y-axis) compared to the cumulative installed FPV capacity (MWp) worldwide (blue line, right y-axis) according to Masson & Kaizuka (2021). Note the differences in both y-axis scales

Some studies analyzed alterations in more than one type of parameter, however, alterations in physical (n = 17 studies) and chemical parameters (n = 11) were more investigated, whereas biotic alterations were the least studied (n = 8). Regarding physical parameters, temperature, and evaporation are more prevalent, since they were analyzed in 34% and 31% of the studies, respectively, with a decrease in both parameters always being observed in the FPV treatment compared to a control (Figure 3). Irradiation and suspended solids were investigated in approximately 7% of the studies, with decrease in their concentration and incidence also being observed. Finally, parameters such as diffusivity, EMF, TDS, and wind speed are rarely assessed, being present in only 3% of the studies, which corresponds to one paper.

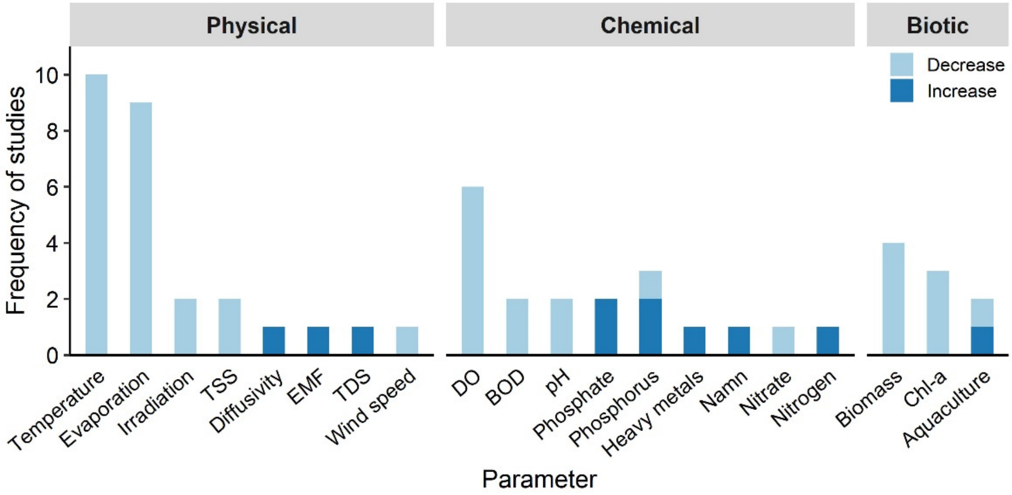

Figure 3. Number of studies that investigated quantitatively physical, chemical and biotic parameter alterations due to the installation of FPVs. Light blue represents a decrease in the measured parameter in the FPV treatment compared to the control (see Methods), while dark blue represents an increase in that parameter

Regarding chemical parameters, the most analyzed was DO (20%), with all studies observing a decrease due to FPVs (Figure 3). BOD and pH were investigated in 7% of the studies, which also found a decrease in these parameters. On the other hand, phosphate was found to increase in 7% of the studies. An increase in phosphorus was found in two studies, but one study found a decrease in this parameter (see Table 1). Other chemical parameters such as heavy metals, Namn, Nitrate, and N were analyzed in only one study each.

The most analyzed biotic parameters were biomass of algae and/or plankton (14%) and chl-a (10%), and FPV installations always resulted in a decrease in these parameters (Figure 3). Finally, two studies analyzed changes in aquaculture production (weight) after the installation of FPVs in culture ponds, finding contradictory results.

Considering quantitative data, we found the occurrence of 11 negative impacts of FPV installations and five positive impacts, whereas seven alterations were classified as undefined (Table 1). Available qualitative data extracted from studies (i.e., perceived alterations caused by FPV installations that were not quantitatively measured) is also presented (Table 2), showing the same pattern with seven negative perceived impacts, two positive and one undefined. The list of reviewed papers with a summary of the data extracted is provided in the Appendix.

Table 1. Quantitative environmental effects of FPV installations, organized by type of parameter investigated and their classification as positive or negative according to the reviewed studies

Alteration/Impact	Impact classification	References
Physical parameters		
Decreased water temperature	Negative	Wang et al. (2022), Château et al. (2019), Abdelal (2021), Ates et al. (2020), Majumder et al. (2021), da Costa & da Silva (2021), Haas et al. (2020), Sahu, Yadav, & Sudhakar (2016)
Reduced evaporation from the water body	Positive	Kumar et al. (2013), Abdelal (2021), Al-Widyan et al. (2021), Ates et al. (2020), Majumder et al. (2021), da Costa & da Silva (2021), Haas et al. (2020), Costa (2017), Scavo, Tina, Gagliano, Merlo, & Bizzarri (2020), Zhang et al. (2020)
Decreased sunlight incidence (albedo)	Negative	Karpouzoglou, Vlaswinkel, & Van Der Molen (2020), Mathijssen et al. (2020)
Changes in turbulent diffusivity and turbidity of water	Undefined	Karpouzoglou et al. (2020)
Electromagnetic field induction in water by cabling	Negative	Costa (2017)
Reduction of wind forcing on the water surface	Undefined	Karpouzoglou et al. (2020)
Chemical parameters		
Decrease in DO concentration	Negative	Wang et al. (2022), Château et al. (2019), Al-Widyan et al. (2021), Andini, Suwartha, Setiawan, & Ma'arif (2022), de Lima, Paxinou, Boogaard, Akkerman, & Lin (2021), Costa (2017)
Decrease in BOD	Positive	Wang et al. (2022), Château et al. (2019)
pH reduction	Negative	Wang et al. (2022), Al-Widyan et al. (2021)

pH increase	Undefined	Baradei & Sadeq (2020)
Alkalinity increase	Undefined	Baradei & Sadeq (2020)
Increasedorthophosphate/phosphate (PO_4^{3}-) concentration	Undefined	Wang et al. (2022)
Increased orthophosphate/phosphate (PO_4^{3}-) concentration	Negative	Wang et al. (2022), Al-Widyan et al. (2021)
Increase in P concentration	Negative	Al-Widyan et al. (2021)
Decrease in P concentration	Positive	Abdelal (2021)
Degradation/leaching of plastic and heavy metals from the constituent materials of floating structures	Negative	Mathijssen et al. (2020)
Increase in Namn concentration	Undefined	Wang et al. (2022)
Decrease in nitrate (NO3-) concentration	Undefined	Karpouzoglou et al. (2020)
Increase in N concentration	Negative	Château et al. (2019)
Biotic parameters		
Decrease in algae biomass	Positive	da Costa & da Silva (2021), Sahu et al. (2016), Karpouzoglou et al. (2020)
Decrease in phytoplankton biomass	Negative	Haas et al. (2020)
Decreased chl-a concentration	Undefined	Château et al. (2019), Andini et al. (2022), Haas et al. (2020)
Reduced growth of aquatic plants	Undefined	Ziar et al. (2021)
Reduced aquaculture production (weight)	Negative	Château et al. (2019)
Increased aquaculture production (weight)	Positive	Wang et al. (2022)

Table 2. Qualitative environmental effects of FPV installations found in our review, organized by type of parameter investigated and their classification as positive or negative according to the reviewed studies

Alteration/Impact	Impact classification	References
Physical parameters		
Noise and air pollution during construction of FPV	Negative	Gorjian et al. (2021)
Visual pollution	Negative	Gorjian et al. (2021)
Microclimate alteration	Negative	Costa (2017)
Chemical parameters		
Water contamination during the maintenance and cleaning of panels	Negative	Gorjian et al. (2021)
Biotic parameters		
Reduction of eutrophication	Positive	Haas et al. (2020), Gorjian et al. (2021)
Fish mortality	Negative	Exley et al. (2021)
Reduced predation of fish by birds	Undefined	Ahn et al. (2021)
Biofouling on FPV panels	Negative	Ziar et al. (2021), de Lima et al. (2021)
Collision of birds and insects with panels	Negative	Pimentel Da Silva & Branco (2018)
Attraction of birds to nest and rest	Positive	de Lima et al. (2021), Gorjian et al. (2021)

4. Discussion

Through this systematic review, it can be observed that the environmental impacts resulting from the installation of FPVs are still a recent topic and little quantitatively studied. Most of the studies found are literature reviews and mathematical models, and fewer are on-site or case studies and pilot scale tests. Furthermore, we did not find any study applying the Before-After Control-Impact (BACI) methodology, which is recommended to reveal impacts caused by major environmental disturbances (Armstrong, Page, Thackeray, Hernandez, & Jones, 2020), such as the installation of FPVs. It was also possible to verify that this theme has been gaining more space recently, since the last two years presented a tendency of growth in publications. We recognize that our search is limited to the chosen database (Web of Science) and that only papers published in English or Portuguese were included. Searches covering other languages, such as Mandarin, Japanese, or Korean, could have yielded more results, given the great advancement that FPV has been gaining in Asian countries (Ma, Wu, & Su, 2021). Overall, due to the low number of papers found on the topic, more studies in different climates and water bodies, targeting more organisms, and using a varied array of methodologies are needed. In this context, the results found here corroborate with data extracted systematically and with empirical evidence that has already been proposed by a previous study (Exley et al., 2021).

The number of studies on the environmental impacts of FPV is growing, however, it does not keep pace with the installation of new plants (Azevedo, Freitas, & Silveira, 2021). In addition, few countries have publications on the subject, which results in scarce evidence of impact for each climate region. As the observed impact can vary with climate, it is important to have more studies in different climate regions to obtain a general understanding. There is also great variability of FPV coverage. One can hypothesize that the total impact will vary according to the FPV total coverage, however, we do not have enough evidence to say whether the impact is directly proportional to the size of the FPV. Currently, there are few studies on this subject. The first was performed by (Baradei & Sadeq, 2020) on Sheikh Zayed Canal in Egypt. The results showed that DO, algae concentration, nutrients, and phosphorus had a considerable decrease with an increase in coverage, while ammonia and pH increased. There could be benefits for water quality, in the case of FPVs over public supply reservoirs, but also losses in primary production and hence in the overall ecosystem. As most studies investigated installations in artificial environments, impacts of FPV in natural aquatic ecosystems such as lakes and rivers are largely unknown. Nonetheless, this was expected given the general proposal of coupling FPVs with hydroelectric or drinking water reservoirs or mining pits (Almeida et al., 2022). Researching the impacts of FPVs in natural aquatic ecosystems, such as lakes and rivers, is urgent to offer a more comprehensive understanding of its potential ecological effects. Finally, few studies analyzed the same parameters, so it is difficult to draw a general pattern of alterations caused by FPV installations, especially in water quality parameters since their impacts are dependent on the type of water body use. Despite that, we summarized the observed effects obtained by the studies, discussing them in more detail below.

The most reported alteration after FPV installations is the decrease in water temperature due to the surface cover and the consequent shading of the water body. The FPV cover acts as a physical barrier, attenuating solar radiation and reducing the heating of the water surface (Armstrong et al., 2020). The rate of water temperature fluctuation in covered regions is lower, and temperature differences of up to 4.9°C have been found between ponds covered and uncovered by FPV (Wang et al., 2022). A study performed in Germany on data recorded at the FPV system of Lake Maiwald, also found lower variability in covered regions (Ilgen, Schindler, Wieland, & Lange, 2023). However, it was found that the 2% coverage system hardly causes any changes to the thermal characteristics and stratification of Lake Maiwald, except for a greater capacity of heat storage (Ilgen et al., 2023). Additionally, more recently it was found a water temperature increase of 0.5^0C on average beneath the floating panels compared to an open water control (Yang, Chua, Irvine, Nguyen, & Low, 2022). Contradictory results depends on the installation type of the solar panels, as their strong heating may heat up the water below. Furthermore, the effect of coverage should also be investigated in regions close to the borders of the FPV, such as daily variations and related processes as evaporation and oxygen availability.

Because of shading and reduction of wind stress, the surface water temperature is expected to decrease, and consequently, a decrease in evaporation rates occurs, which comes to be the second most reported alteration (Armstrong et al., 2020). The reduced water loss through evaporation can be a positive impact in water-scarce areas (Armstrong et al., 2020), being advantageous in artificial reservoirs that store water for public supply or agricultural irrigation, with the co-benefit of water conservation and sustainable energy generation. In addition, FPV will maintain power generation even during periods of drought (Gadzanku, Mirletz, Lee, Daw, & Warren, 2021). However, since water temperature has a great influence on the structure and function of the aquatic ecosystem and light levels and evaporation are directly related to microclimate, the reduction in related parameters is considered a negative impact (Costa, 2017; Cathcart & Wheaton, 1987). For instance, if the facility is deployed in the marine environment, shading caused by the FPV may cause negative impacts on organisms that require sunlight to grow, such as coral reefs and seagrasses (Rogers, Benham, Beavis, Hendry, & Jackson, 2016). To mitigate such impacts, gaps between rows of photovoltaic panels should be planned so that total blocking of light input does not occur (Sahu, Yadav, & Sudhakar, 2016). In this regard, the influence of different types of modules should be investigated. Additionally, a monitoring program should be proposed to investigate changes in primary (phytoplankton) and secondary (zooplankton and benthic macroinvertebrates) productivity of the ecosystem, preferably applying the BACI methodology to account for spatial and temporal variation (Underwood, 1991).

Completely blocking light input and reducing the area exposed to air diffusion can result in other negative impacts, such as reduced photosynthesis and depleted oxygen levels (Pimentel Da Silva & Branco, 2018). In on-site analysis studies, a reduction of around 20% in DO concentration was found at locations covered with FPV (Wang et al., 2022; Andini et al., 2022), a higher value than that predicted by mathematical models (Château et al., 2019). A reduction of 2 mg/L on average on DO was found in another study (Yang et al., 2022). When DO concentrations decrease, there is the possibility of an anoxic environment for aquatic fauna (Exley et al., 2021). In a comparative study of ice-covered lakes, oxygen depletion is the most important factor determining the onset of fish mortality (Ellis & Stefan, 1989). Thus, this is an impact that negatively affects the aquatic ecosystem, and can lead to the death of aquatic fauna, causing great imbalance in the entire trophic web. To compensate for the effects of decreasing DO, aerators commonly used in aquaculture tanks can be installed, to oxygenate the water.

Decreased DO concentration can directly affect the metabolism of fish, interfering in their growth rates. This effect is most pronounced when the water temperature is below the ideal temperature for the organism, which can be the case under the panels. In cultures of milkfish (*Chanos chanos*), over a five month, a 10% reduction in growth was predicted in winter and 5% in summer under a scenario of 60% of covered water surface (Château et al., 2019). In contrast, a coverage of 40% of the water body can be considered as being optimal for the cultivation of this species, according to results found in the literature demonstrating higher milkfish production in ponds covered by FPVs (Wang et al., 2022). Low irradiance in water bodies due to the FPV coverage also leads to decreased growth of photosynthetic beings, such as aquatic plants and algae. Whereas this alteration can have positive effects such as reduced eutrophication and concentration of algae toxins (da Costa & da Silva, 2021), reduced algal growth and inhibition of their photosynthesis, can lead to decreased chl-a (Abdelal, 2021) and water pH (Sahu et al., 2016). The decreased chl-a concentration is mainly due to the shading effect of the floating panels, reducing the photosynthetic active radiation. The algae growth is limited by light conditions and DO production is reduced, implying lower DO concentrations (Yang et al., 2022). pH affects the metabolism of several aquatic species, thus this alteration can be significant for aquatic fauna. In addition, pH directly influences the water quality, since this parameter has a significant impact on the nutrient's availability and chemical conversions in aquatic ecosystems, relative to the number of oxidation states of nitrogen and phosphorus (Ellis & Stefan, 1989).

There are some qualitatively reported positive impacts of FPVs on aquatic life. For example, panels can provide shelter for fish that are preyed by birds. Species of various fish, including juveniles, predators, and endangered species, have been observed under the structure of FPVs (Ahn et al., 2021). The FPV structure may also function as a nesting site and shelter for birds. Nests have been found between the panels and the floating structure (Ziar et al., 2021), and birds have also been observed and heard around the FPV, suggesting that they use this space actively (de Lima et al., 2021). On the other hand, the presence of the structure can cause negative impacts on local avifauna due to direct collision with the floating panels, in addition to the attraction of insects because of the glare emitted (Costa, 2017). To minimize this impact, it is recommended to evaluate which species of birds are present in the proposed area, before the installation of the FPVs. The floating structure may also serve as an artificial substrate for colonization by fouling organisms, which also tends to attract more mobile species such as crabs, lobsters, and fish (Svane & Petersen, 2001). Nevertheless, the floating structure also allows the establishment of invasive alien species (Costa, 2017). These may compete with native species, which are important for ecosystem balance, and therefore this impact is considered negative (Tyrrell & Byers, 2007). Biofouling can also cause direct damage to panels, thus a periodic monitoring should be conducted through underwater photos and filming of the floating blocks to assure that biofouling will not affect the performance of the FPV and/or influence the hydrodynamic loading (Jusoh & Wolfram, 1996).

We acknowledge that the classification of impacts as negative or positive is challenging, as the same alteration can have positive and negative outcomes at the same time (e.g., the effects caused by non-native species can be regarded as benefits or costs depending on the analyzed context; Vitule & Pelicice, 2023). For example, reduced chl-a concentration due to FPV installations (Château et al., 2019, Andini et al., 2022) can be considered positive as it reflects a decrease in the excessive proliferation of algae that causes eutrophication, resulting in improved water quality. On the other hand, it also indicates decreased primary productivity in the water body that cascades through the food chain, negatively affecting the aquatic community. Additionally, the new radiation characteristics may select some phytoplankton species, what requires more investigations. Here, relying on the authors' interpretation, we found a greater number of negative impacts that can be caused by FPV installations on water bodies. These impacts cannot be left aside, and more investigative studies are needed to predict and effectively mitigate them. The most prominent alterations caused by FPV installations are the decrease in water temperature under the panels and the reduced evaporation. How these changes will affect the biota directly and indirectly through reduced photosynthesis and consequently alterations in pH and DO concentration, for example, are yet questions that should be further investigated. Additionally, changes in water temperature and reduced wind mixing, alters the water column stability and substances transport in the water body. Despite that, there are also some potential benefits of FPVs, such as reduced eutrophication and increased habitat complexity in generally poorly structured reservoirs. Some of the negative impacts of FPV can be minimized with the correct design and sizing of the plant, and choosing the right site for installation, according to physical characteristics as depth, distance from margins, as well as water quality characteristics of the water body.

Finally, constant monitoring is needed to adjust strategies that aim to compensate potential negative effects of FPVs. For instance, if the plant is located in water supply reservoirs, sampling should be periodically performed to assess the water quality and thus check for the presence of metals and other compounds. As preventive measures, research should be conducted on leaching tests and/or the monitoring of the materials of the floating structures, to assess the probability of degradation and contamination of the water body prior to the installation of the plant (Gadzanku et al., 2021). This monitoring should also be continuous, as seasonal effects can occur, and long-term leaching can give rise to the release of other compounds (Mathijssen et al., 2020). Additionally, good practices must be taken to avoid contamination of the water body during the cleaning and maintenance of FPVs, avoiding chemical materials that contaminate and pollute the water (Gorjian et al., 2021).

It is recommended that future studies ideally apply the asymmetrical BACI methodology (i.e. replicated measurements) over longitudinal gradients and long-term periods for a more complete understanding of the impacts that can be attributed to FPV installations (Underwood, 1991; Stewart-Oaten & Bence, 2001), since this study design accounts for the spatial and temporal variability in observed effects, generating more robust evidence that enables effective management planning (Underwood, 1991). In cases where a FPV is already installed, the BACI methodology can be adapted, using areas of similar size and characteristics to the location where the FPV is installed as a proxy; or even obtaining relevant data from models (Queiroz, Lima, Ribeiro, Pereira, & Santos, 2006).

There is still a great need and an opportunity for the scientific community to investigate the impacts of FPV on water bodies. This finding is critical as many FPV installations have been emerging in recent years. This review presents important data to guide the direction of future empirical studies to increase knowledge on the subject. We strongly encourage multidisciplinary collaboration between ecologists, engineers, limnologists, and policymakers in order to develop comprehensive assessments addressing both the technical feasibility and ecological impacts of FPV installations. It is evident that more studies are needed mainly on chemical and biotic effects, once changes in water quality parameters also impacts the composition of aquatic communities. Moreover, research should emphasize documenting key characteristics of FPV installations, including size, coverage percentage, and the type of water body, along with the monitoring methods used. This will aid in comparative analyses across studies and assist in discovering consistent trends. Regarding the 29 studies analyzed in this review, there is an indication of potential alterations that FPV causes on water quality and the biotic environment. However, with little quantitative evidence, it is difficult to describe a pattern of impacts and to assess whether they will be positive or negative for water bodies.

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Appendix

List of papers included in the systematic review and a summary of data extracted from each one

Reference	*Study type*	*Country*	*Climate*	*Water body type*	*Water body surface area (m^2)*	*FPV size (m^2)*	*Percent of water surface area covered by the FPV (%)*	*Investigated parameters*
Kumar et al. (2013)	Literature review	-	-	-	-	-	-	-
Pimentel Da Silva & Branco (2018)	Literature review	-	-	-	-	-	-	-
Ziar et al. (2021)	Pilot-scale testing	Netherlands	Seasoned (Cfb)	Reservoir	18,524 - 22,639	-	-	Plant Biomass, T, Irradiation
Wang et al. (2022)	*On-site* analysis	Taiwan	Subtropical climate, with hot summer (Cfa)	Aquaculture pond	800 and 3000	320 and 1200	40%	T, DO, pH, TDS, SS, Namn, BOD, P, Orthophosphate, Total Photosynthetic Pigments, Phytoplankton Biomass, Final Production
Château et al. (2019)	Mathematical modeling	Taiwan	Subtropical climate, with hot summer (Cfa)	Aquaculture pond	4,000	1,600 - 2400	40 - 60%	DO, T, BOD, Chl-a, SS, M, N, P, Aquaculture production (weight)
Abdelal (2021)	Pilot-scale testing	Jordan	Hot desert climate (desert) (Bwh)	Reservoir	4	4	100%	T, Evaporation
Al-Widyan et al. (2021)	Pilot-scale testing	Jordan	Hot desert climate (desert) (Bwh)	Reservoir	2.56	0.77 - 1.28	30 - 50%	Evaporation, pH, DO, orthophosphate,
Ates et al. (2020)	Mathematical modeling (ecological)	Turkey	Warm Summer Mediterranean (Csa)	Reservoir	-	-	-	T, Evaporation, Wind speed
Majumder et al. (2021)	*On-site* analysis	Italy	Warm Summer Mediterranean (Csa)	Reservoir	4	0.68	17%	T, Evaporation
da Costa & da Silva (2021)	Mathematical modeling	Brazil	Semiarid (Bsh)	Reservoir	3,095,424.20	742,901.8	24%	Evaporation

Andini et al. (2022)	*On-site* analysis	Indonesia	Humid tropical climate (Af)	Reservoir	52,996	170	0.32%	T, Chl-a, DO, TDS, P
de Lima et al. (2021)	*On-site* analysis	Netherlands	Seasoned (Cfb)	Reservoir	608,333	182.500	30%	T, DO
Haas et al. (2020)	Mathematical modeling	Chile	Warm Summer Mediterranean (Csa)	Reservoir	39,000,000	0 - 39,000	0 - 0.1%	Evaporation, Chl-a
Sahu et al. (2016)	Literature review	-	-	-	-	-	-	-
Costa (2017)	Case study	Portugal	Subtropical climate with hot summer (Cfa)	Reservoir	22,120,000	2,250	0,01%	Evaporation, Electromagnetic field, DO, Microclimate
Scavo et al. (2020)	Mathematical modeling	Italy	Warm Summer Mediterranean (Csa)	Reservoir	2,700	81	70%	T, Evaporation
Zhang et al. (2020)	Pilot-scale testing	China	Hot summer humid continental climate influenced by monsoons (Dwa)	-	-	-	-	T, Evaporation, Algae
Karpouzoglou et al. (2020)	Mathematical modeling	Netherlands	Seasoned (Cfb)	Coastal sea	-	-	-	Nitrate, Phosphate, Irradiation, SS, Diffusivity
Ahn et al. (2021)	Literature review	-	-	-	-	-	-	-
Gorjian et al. (2021)	Literature review	-	-	-	-	-	-	-
Gadzanku et al. (2021)	Systematc review	-	-	-	-	-	-	-
Mathijssen et al. (2020)	Case study	Netherlands	Seasoned (Cfb)	Reservoir	72,000	8,000	11.1%	Leaching of heavy metals
Liber et al. (2020)	Literature review	-	-	-	-	-	-	-
Grippo, Hayse, & O'Connor (2015)	Literature review	-	-	-	-	-	-	-
McKay (2013)	Literature review	-	-	-	-	-	-	-
Pimentel Da Silva, Magrini, & Branco (2020)	Literature review	-	-	-	-	-	-	-
Prinsloo (2017)	Literature review	-	-	-	-	-	-	-
Song, Yadav, & Liang (2018)	Literature review	-	-	-	-	-	-	-
Exley et al. (2021)	Systematic review	-	-	-	-	-	-	-

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Authors contributions

LAA was responsible for data curation, formal analysis, visualization and writing-original draft preparation draft. Dr. LF was responsible for data curation, formal analysis, visualization, writing-original draft preparation, review&editing. Prof. MM worked with writing-original draft preparation, review&editing. Dr. JAR worked on writing-original draft preparation, review&editing. Prof. TB helped with writing-original draft preparation, review&editing. Prof. JRSV was responsible for conceptualization, methodology, supervision, and writing-review&editing. All authors read and approved the final manuscript. All authors contributed equally to the study in each contribution item.

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Competing interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Obtained.

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The data that support the findings of this study are available on request from the corresponding author. The data are not publicly available due to privacy or ethical restrictions.

Data sharing statement

No additional data are available.

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