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Site-specific relationships between algal biomass and floating photovoltaic solar energy in human-made bodies of water

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Eutrophication and climate-driven warming are degrading aquatic ecosystems by promoting harmful algal and cyanobacterial growth, while global decarbonization efforts are intensifying land-use conflicts for renewable energy. Floating solar photovoltaic (FPV) systems—solar panels installed on human-made waterbodies—offer a potential solution, yet their effects on algae and water quality remain poorly understood. We assessed algal biomass and water quality beneath FPVs and in open water at four FPV-hosting ponds across the United States, spanning a range of FPV coverage levels, trophic states, climates, and bathymetry. Sampling occurred twice daily across all seasons from 2021 to 2022. Results showed minimal overall differences in phycocyanin, chlorophyll-a, dissolved oxygen, pH, conductivity, and temperature between FPV-covered and open-water areas, though some site-specific trends emerged. At one mesotrophic site (4.8% coverage), chlorophyll-a and phycocyanin were significantly lower beneath FPVs in multiple seasons, with up to 80% reductions in chlorophyll-a observed in spring. In contrast, at a eutrophic site (22% coverage), chlorophyll-a was occasionally higher beneath FPVs, while two mesotrophic sites with high coverage (60–71%) showed no consistent differences. Dissolved oxygen and temperature exhibited limited site-specific variations but no consistent trends across FPVs. Overall, within-pond differences in algal biomass and water quality between FPV-covered and open-water areas were largely minimal, underscoring the need for further research with more FPV sites, before–after control–impact designs, and high-frequency monitoring to better understand FPV–algae interactions and potential water quality benefits.

KEYWORDS

floating solar, renewable energy, ecosystem impacts, cyanobacteria, field measurements, water quality, FPV

Introduction

Floating photovoltaic solar energy systems (FPVs) are a rapidly growing renewable energy technology and represent a novel water surface use, altering biotic and abiotic interactions within the host water bodies. In 2022, global FPV capacity reached 5.9 GW, with a 22% annual growth rate since 2018 (IRENA, 2019; Rodríguez-Gallegos et al., 2024). FPV expansion is driven by rising renewable energy demand and the land-sparing potential of FPVs, utilizing existing water bodies for solar energy production (Cagle et al., 2020; Hernandez et al., 2019; World Bank Group et al., 2019). FPVs may also reduce evaporation (Abdelal, 2021; Jin et al., 2023) and algal growth (Abdelal, 2021; Li et al., 2023; Sahu et al., 2016), providing non-energy benefits. Despite these potential co-benefits and a recent increase in field-based research, empirical data on FPVs' impacts on algae and related water quality characteristics remains minimal (Almeida et al., 2022; Bax et al., 2023; Exley et al., 2022; Haas et al., 2020; Rocha et al., 2024). These co-benefits can be contextualized within ecosystem services frameworks (Costanza et al., 1997; Millennium Ecosystem Assessment, 2005). Candidate waterbodies for FPV deployment are commonly human-constructed ponds and small lakes, but can support high aquatic biodiversity and provide critical provisioning and regulating ecosystem services, including water supply, pollution control, and carbon cycling (Biggs et al., 2017; Rocha et al., 2024; Hernandez et al., 2025). Evaluating FPVs through this lens can identify potential multifunctionality in supporting renewable energy goals and conserving aquatic ecosystems.

Once deployed, FPVs can alter physicochemical water quality conditions by affecting temperature, dissolved oxygen (DO), irradiance, and nutrient dynamics that may modulate aquatic ecosystem functioning. Field studies have found FPVs can reduce near-surface temperatures by 0.0–1.4 °C on average (Ilgen et al., 2025; Nobre et al., 2025; Prandini et al., 2025; Ray et al., 2024; Sandrini et al., 2025) and decrease DO by 0.8–1.7 mg/L (Andini et al., 2022; Ilgen et al., 2025; Ray et al., 2024; Ziar et al., 2021), with the strongest effects in summer months, which is coupled with greater insolation. During summer months, FPVs have been found to cool surface waters by 2.8–3.0 °C (Ilgen et al., 2025; Nobre et al., 2025). In small, shallow water bodies, FPVs cool surface waters, shorten stratification periods, and create a shallower mixed depth (Ray et al., 2024; Sandrini et al., 2025; Ziar et al., 2021). Such physical alterations correspond with limnological models of stratification and mixing (Kalff, 2002; Wetzel, 2001), which describe how energy inputs and bathymetry control thermal layers and vertical mixing. Overall, FPV deployment can be viewed as a chronic resource alteration introducing persistent shading and altered surface-atmosphere interactions (Smith et al., 2009). As a novel intervention in aquatic systems, FPVs may alter established patterns of energy flow and matter cycling, leading to shifts in ecosystem function and resilience (Battisti et al., 2016).

Small, urban water bodies in particular are highly vulnerable to nutrient loading and climate change-induced warming, increasing the risk of eutrophication and harmful algal blooms (HABs) (Grogan et al., 2023; Winslow et al., 2015). Cytotoxins, released by HABs, pose risks to human and animal health, altering biogeochemical cycling, and creating hypoxic and anoxic conditions (Amorim and Moura, 2021; Lürling et al., 2018; Paerl et al., 2001). These blooms can degrade water quality in FPV-suitable water bodies, such as water treatment reservoirs and irrigation ponds (Joh et al., 2011). Modeling studies suggest FPV shading may mitigate algal growth, offering significant non-energy benefits while the cooling of water may mitigate climate-induced warming (Exley et al., 2022; Haas et al., 2020). Recent field studies have found differing impacts across taxa, finding an increase in cyanobacteria and reduction in green algae (Sandrini et al., 2025). By potentially regulating water temperature and impacting HAB formation and species richness, FPV systems may impact regulating ecosystem services, as defined by the Millennium Ecosystem Assessment framework, underscoring the need to monitor ecological responses to the installation and operation of FPVs (Millennium Ecosystem Assessment, 2005).

FPV-induced shading reduces irradiance and photosynthetically active radiation (PAR) in host water bodies, which in theory, should limit overall algal growth and biomass (Agbeti and Smol, 1995; Bax et al., 2023; Ilgen et al., 2023; Prandini et al., 2025; Zhang et al., 2020). Declines in algal biomass can trigger trophic cascades and disrupt ecosystem resilience, potentially shifting aquatic systems toward alternative stable states (Batt et al., 2015; Beisner et al., 2003; de Tezanos Pinto et al., 2007). Recent modeling by Exley et al. (2022) found chlorophyll-a declines exponentially with FPV coverage, though phytoplankton responses varied by location of the system atop the water body and mixing conditions (Exley et al., 2022). Pilot studies report chlorophyll-a measurements 17.5%–61% lower beneath FPV installations (Abdelal, 2021), and pond-scale studies found lower aquatic plant and algal biomass below FPV installations (Li et al., 2023; Liu et al., 2023; Wang et al., 2022; Ziar et al., 2021); however, more recent studies show varied results in terms of cyanobacteria formation (Sandrini et al., 2025). Few recent studies have evaluated cyanobacteria empirically to date. Decline in primary production, combined with reduced temperature and DO, can alter carbon cycling and may significantly alter aquatic food webs (Vouhe et al., 2025).

Nonlinear interactions among bathymetry, hydrodynamics, and biogeochemical cycling complicate predicting FPV effects, necessitating coupled sampling of physical and biological conditions across water bodies (Richardson et al., 2022). While FPVs generally reduce water temperature, effects vary across sites (Andini et al., 2022; Cagle et al., in review; de Lima et al., 2021; Exley et al., 2021; Wang et al., 2022; Nobre et al., 2025). In small, shallow water bodies with reduced stratification, algal biomass may increase due to limiting competitive pressure from macrophytes (Yamamichi et al., 2018), with nutrient loading further exacerbating algal blooms (Brooks et al., 2016). Despite the modeled potential of FPVs to suppress algae through shading, empirical field data remain limited. Most existing field studies rely on total chlorophyll-a as a general indicator of biological activity, without incorporating more targeted algal metrics such as phycocyanin, which is critical for understanding cyanobacterial responses and evaluating the full ecological implications of FPV deployment (Kim et al., 2019; Li et al., 2023; Liu et al., 2023). A first step toward greater understanding may be conducting site-specific, *in-situ* monitoring that includes both biological and physical parameters to assess relationships among FPVs, algal dynamics, and water chemistry (Andini et al., 2022; Haas et al., 2020).

The global expansion of FPVs across water surfaces is underway. However, our understanding of environmental impacts of FPVs, particularly on algae growth, remains largely theoretical, with a greater emphasis being put on understanding techno-economic considerations of FPVs compared to environmental (Forester et al., 2025). We find a lack of understanding of biological and chemical relationships between FPVs and hosting water bodies, as well as a need for comprehensive studies across a range of depths and locations (Benjamins et al., 2024), in which biological, chemical, and physical aspects of water body dynamics are integrated (Rocha et al., 2024; Oliveira et al., 2024). To address this knowledge gap, we deployed hydrological sensors in four small, urban ponds (<0.005 km^2) with FPVs across the United States and measured water quality throughout the water column below the FPV and in the open water. We performed twice-daily field sampling every season over 1 year to assess how FPVs of various coverage influence *in-situ* algal growth and water quality parameters when deployed atop water bodies with differing bathymetry, climatic regimes, and trophic states. Specifically, we tested the following questions:

i Is there variation between average column measurements for chlorophyll-a, phycocyanin, dissolved oxygen (DO), temperature, and pH beneath the FPV array compared to the open water portion of the water body?
ii Does this variation, if any, shift between morning and afternoon testing intervals for dissolved oxygen (DO), chlorophyll-a, phycocyanin, or other water quality parameters?

Given the vulnerability of small, human-made, and managed water bodies to eutrophication and HABs and the significant implications of water body health for both aquatic and human communities, our investigation aimed to elucidate relationships between FPV systems and algae within the host water body through rigorous field study and analysis.

Methods

Site selection

We performed this study on four FPV installations: Altamonte Springs, Florida (lat. 28°38′34.16″N, lon. 81°23′44.85″W), Windsor, CA (lat. 38°32′22.00″N, lon. 122°48′52.50″W), Orlando, FL (lat. 28°30′09.01″N, lon. 81°25′17.68″W), and Oakville, CA (lat. 38°25′18.90″N, lon. 122°24′30.38″W), respectively, from November, 2021 through November, 2022. We chose these sites to elucidate within pond relationships among FPVs, water body type, and algae (Table 1). All four FPV installations are on managed, human-constructed freshwater bodies, chosen based on pre-existing FPV installations and data collection accessibility for both FPV systems and water body parameters, such as construction diagrams and bathymetry. All study sites are classified as shallow, small water bodies (<5 m greatest depth). Research partnerships were established with the Town of Altamonte Springs, the Orlando Utilities Commission (Orlando, FL), Far Niente Winery (Oakville, CA), and the FPV floatation device company Ciel et Terre (Petaluma, CA). These collaborations facilitated logistical support and access to FPV site data, including deployment specifications for floatation equipment, panel type, and water body coverage percentages.

High FPV coverage location (60%): Altamonte Springs, Florida, USA

Installed in 2020 and grid-connected in January 2023, the Altamonte Springs FPV system (960 kWp) covers 60% of the pond's surface (Table 1). Altamonte Springs is located in a tropical climate with 158 cm of precipitation during the study year. Constructed in 2015, this unlined secondary water treatment pond receives input from a local river and stormwater runoff and is connected to a primary receiving pond located 10 m to the south. The shoreline features an actively managed vegetated littoral zone. The pond supports a variety of aquatic and semi-aquatic species, including sunfish, water snakes, river otters, and multiple resident bird species.

Medium FPV coverage location (25%): Windsor, California, USA

Installed in 2020, the Windsor FPV system (1,780 kWp) covers 22% of the surface of a lined, elevated water treatment pond and is the largest system in this study. Located in a Mediterranean climate, this site received 74 cm of precipitation during the study year. The pond receives treated irrigation water from nearby agriculture with historically high nutrient loads. Four surface aerators are positioned between the shore and the FPV system, near the inflow and outflow locations. Cyanobacterial blooms were visible during all sampling seasons.

Low FPV coverage location (5%): Orlando, Florida, USA

The Orlando Utilities Commission's Gardenia Facility features a small (33 kWp) FPV system, which was installed and became operational in 2017, doubled in size in 2020 (64 kWp), and covers less than 5% of the stormwater pond's surface (Table 1). Located in a tropical climate, this pond received 62 cm of precipitation during the study year. The unlined pond receives stormwater runoff from surrounding urban areas. Throughout the study, anaerobic decay near the outflow was evident from odor and visible decomposing organic matter. The FPV system is anchored 5 m from the inflow on the pond's west shore. The pond supports sunfish, minnows, turtles, amphibians, and river otters.

High aeration/high FPV coverage location (71%): Oakville, California, USA

The Oakville FPV system (206 kWp) has operated since 2008, covering 70% of an unlined vineyard irrigation pond (Table 1). This location, situated in a Mediterranean climate,

TABLE 1 Water body and floating photovoltaic (FPV) system characteristics of the four FPV systems examined in this study.

	Altamonte Springs, Florida	Windsor, California	Orlando, Florida	Oakville, California
Water body surface area (m^2)	13,500	71,125	11,773	4,652
Maximum water body depth (m)	2.8	3.5	2.1	3.3
Active Aeration	No	Yes	No	Yes
Water body Type	Water Treatment Pond	Water Treatment Pond	Stormwater runoff pond	Irrigation pond
Water body coverage by FPV ratio (%)	60	22	4.8	71
Nameplate capacity of FPV system (kWp)	960	1,780	31.5 in 2017; 64 kW in 2020	206
Age of FPV system (years)	4	5	8	17
Trophic State	Mesotrophic	Eutrophic	Mesotrophic	Mesotrophic

Trophic states are based on lake fertility and were assigned qualitatively. Definitions for the trophic state classifications are as follows: (1) Mesotrophic: Medium amount of nutrients, moderately clear water, some algal blooms in late summer, oxygen depletion at bottom of lake as biomass decomposes. (2) Eutrophic: Nutrient rich, highly productive plant growth, shallow lakes, seasonally deficient in oxygen, may lead to fish kills (Carlson, 1997).

received 43 cm of precipitation during the study year. The pond receives treated irrigation water from the local municipality. Two industrial-grade aerators provide continuous aeration, running multiple times daily. Although notable fish populations are absent, frogs, turtles, and aquatic invertebrates are present.

Field sampling

Beginning in Fall, 2021, we performed *in-situ* water quality measurements at each water body using two YSI Pro-DSS multiparameter probes (YSI, a xylem brand, Yellow Springs, Ohio). Using these probes, we measured phycocyanin (relative fluorescence unit [RFU]), chlorophyll-α (RFU), pH, conductivity ($\mu s\,cm^{-1}$), dissolved oxygen (% saturation), and water temperature (°C). Phycocyanin is an accessory pigment found in cyanobacteria and an indicator of harmful cyanobacteria growth (Beal and Block, 2022). Chlorophyll-a is a pigment present in all algal species and thus can be used as a proxy measurement to assess algal growth dynamics (Pápista et al., 2002). Similar sensor equipment and methodologies have been used in recent water quality studies to measure phycocyanin and chlorophyll-a (Hohman et al., 2021; McKercher et al., 2022; Mwanake et al., 2023; Ortiz and Wilkinson, 2021; Xiong et al., 2022). We calibrated sensors before each seasonal campaign and removed outliers in pigment data before analysis.

We sampled at increments ≤20 cm throughout the water column at four randomized locations beneath the FPV ($n = 4$) and three in the open water at depths similar to those beneath the array ($n = 3$). Sampling occurred in the morning (≤2 h before sunrise) and afternoon (≤2 h before sunset) for four consecutive days each season (i.e., winter 2022, spring 2022, summer 2022, fall 2021). If inclement weather postponed sampling, we repeated the entire sampling day for consistency. Morning and afternoon sampling sessions were conducted in an attempt to capture diurnal variation in phytoplanktonic dynamics as cyanobacteria and other phytoplankton presence is typically higher during high light hours vs. early morning hours.

Data analysis

For each seasonal field campaign, we calculated mean values for all parameters at 0.2 m depth intervals, classified by morning and afternoon sampling, and computed standard deviations. Average total water column values were also calculated. Given dissimilar sample sizes, we statistically compared differences in the total water column values between FPV and open locations for each parameter using Welch's t-tests. Welch's t-test was chosen as opposed to a paired t-test given the difference in variance and sampling amounts between the FPV and open water locations. P-values <0.05 were considered statistically significant. When $P < 0.05$, the means of sampling seasons were further analyzed for variance within sensor accuracy ranges and standard deviations. We also considered ecological relevance, noting that statistically significant differences, such as in phycocyanin, between FPV and open water, might not always reflect meaningful shifts in aquatic systems owing to FPV, especially if both values were below 1 RFU unit.

Results

Phycocyanin

Phycocyanin concentrations varied widely across water bodies. All sites except Windsor had negligible concentrations (<2.0 RFU) throughout all sampling seasons and at all measured depths, including summer (Figure 1, Appendix 14). Windsor demonstrated high phycocyanin levels (>20 RFU) in spring and summer, with visible cyanobacteria blooms. However, there was no significant difference in phycocyanin between depths below the FPV and open water, nor between morning and afternoon samples across the four study seasons (Figure 1; Appendix 14). At Altamonte Springs and Oakville, no differences were observed between FPV and open water. At Altamonte Springs, phycocyanin was slightly lower during afternoon near-benthos depths beneath the FPV in winter, spring, and summer, but these differences (<1 RFU) must be contextualized in terms of impact on cyanobacteria biomass (Figure 1). The OUC site, with low FPV coverage, showed

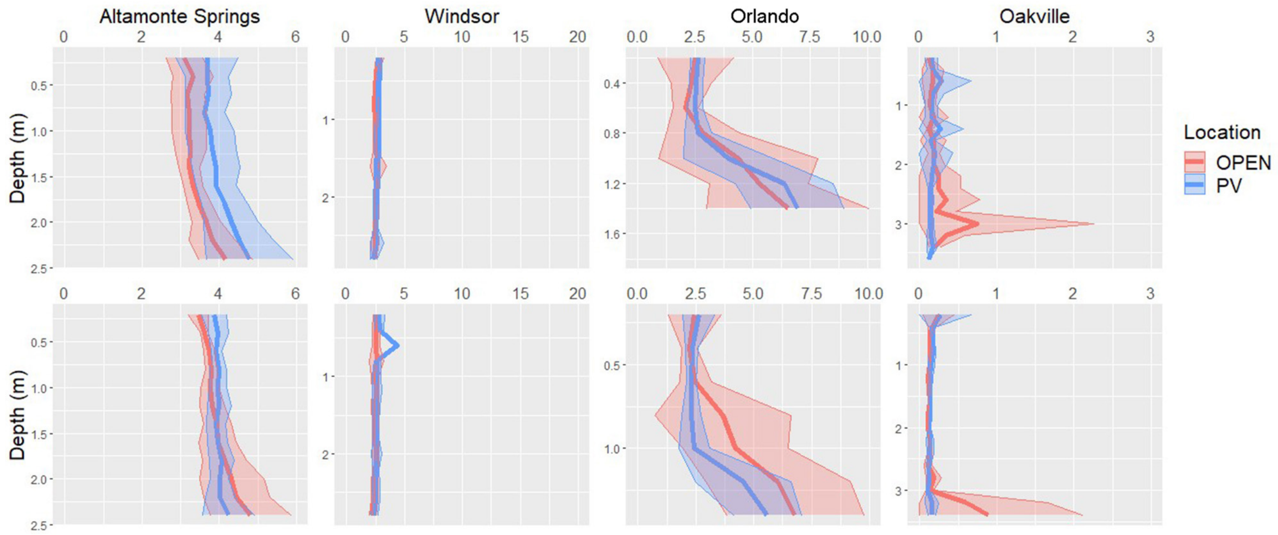

FIGURE 1
Phycocyanin levels (relative fluorescence unit) in the open water ("OPEN", **red**) and under the floating photovoltaic ("FPV", **blue**) installations. Data show morning ("AM") and afternoon ("PM") sampling periods during the summer 2022 study across all four FPV-hosting locations ("Altamonte Springs" in Altamonte Springs, FL; "Windsor" in Windsor, CA; the Orlando Utilities Commission ("OUC"), in Orlando, FL; and "Oakville" in Oakville, CA). **Lines** represent means. **Shading** represents 95% confidence intervals.

statistically significant ($p<0.05$) reduced phycocyanin beneath the FPV during winter, spring, and fall (Appendix 14).

Chlorophyll-a

Chlorophyll-a concentrations (RFU) were similar between FPV and open water across two of the four sites, with significant differences observed at the low-coverage OUC location (Figure 2, Appendix 13). Specifically, at OUC, significant reductions in chlorophyll-a were observed beneath the FPV in the winter, spring, and fall, with up to 80% reduction in spring at near-surface depths. While chlorophyll-a at OUC was low throughout the sampling year (<5 RFU), the spring decrease in chlorophyll-a was statistically significant. Six of the eight seasonal samplings demonstrated less chlorophyll-a beneath the FPV. The OUC site also had noticeable assemblages of macrophytes dominated by the invasive *Hydrilla sp.* (Hydrocharitaceae). The Windsor site showed the opposite trend, with increased chlorophyll-a beneath the FPV installation during winter and fall but no significant changes in spring or summer (Figure 2, Appendix 13). Additionally, Windsor had the highest chlorophyll-a (>20 RFU) observed at any site. At Altamonte Springs and Oakville, no discernible trends were identified during any season in the sampling year.

Water quality results

pH and conductivity

No significant trends in pH or conductivity were measured beneath the FPV and in open water at any of the sites (Appendices 9, 10). At Windsor, a statistically significant difference in pH ($p<0.05$) between the FPV and Openwater body locations was observed during the morning summer sampling, with the average mean difference exceeding sensor accuracy range (Appendix 10). The OUC site showed significant differences in pH during the afternoon spring and morning winter samplings; however, these differences are also greater than sensor accuracy. Windsor was far more alkaline and had higher pH values (8.4–10.0) than the other FPV sites.

Dissolved oxygen and temperature

No discernable dissolved oxygen (DO) trends between the FPV and open locations were found at the Altamonte Springs and Oakville locations (Appendix 11). At Windsor, DO was significantly lower ($p \leq 0.05$) beneath the FPV in the top 1 m depth during the morning sampling across all seasons. By the afternoon sampling time, DO trends were similar between the FPV and open water. Sampling at the OUC location indicated mixed results: significantly lower DO in the morning and afternoon sampling below the FPV in the spring, with less pronounced differences in winter, summer, and fall. No significant differences in water temperature between FPV and open water at any depth or time of day were observed at any of the four FPV sites (Appendix 12). Windsor demonstrated a significant difference between X and Y during the afternoon fall sampling campaign, with higher temperatures beneath the FPV.

Discussion

This study investigates the impact of FPV installations on the spatial distribution of water quality parameters at four FPV installations across the United States through twice-daily, seasonal spot sampling campaigns of algal indicators and major water

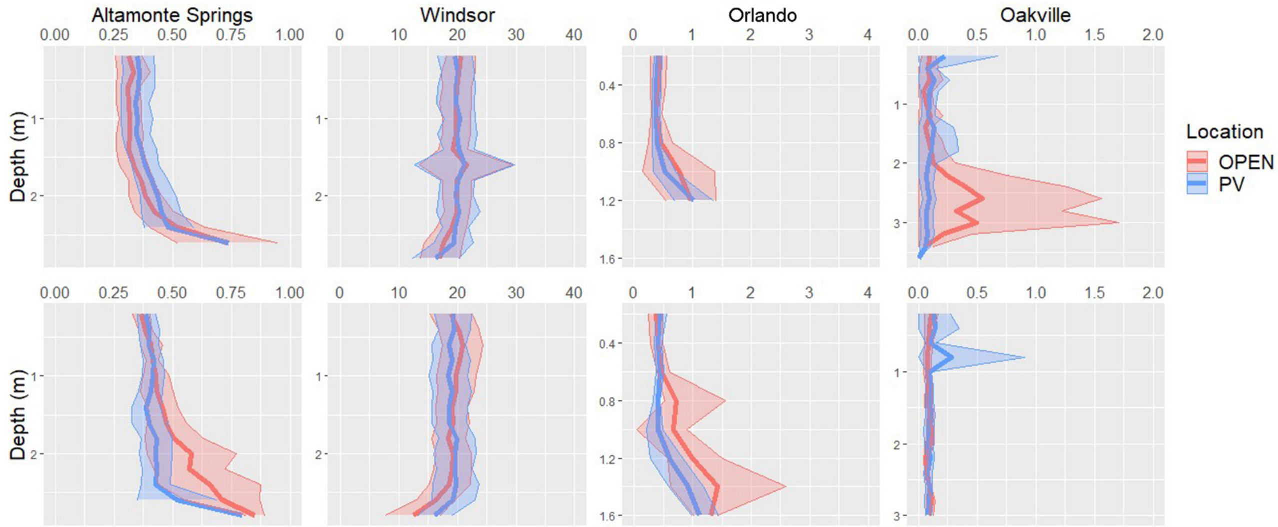

FIGURE 2
Chlorophyll-a levels (relative fluorescence unit [RFU]) in the open water ("OPEN", **red**) and under the floating photovoltaic ("FPV", **blue**) installations. Data show morning ("AM") and afternoon ("PM") sampling periods duringacross the summer 2022 study across all four FPV-hosting locations ("Altamonte Springs" in Altamonte Springs, FL; "Windsor" in Windsor, CA; the Orlando Utilities Commission ("OUC"), in Orlando, FL; and "Oakville" in Oakville, CA). **Lines** represent means. **Shading** represents *x* standard deviation/95% confidence intervals.

quality parameters beneath the FPV and in open water. Previous *in-situ* water quality case studies have typically focused on a single FPV pond and have yielded contradictory findings regarding the relationship between FPV installations and key parameters like algal indicators, dissolved oxygen, and water temperature, which demonstrates the importance of variable local conditions on aquatic ecosystems (de Lima et al., 2021; Wang et al., 2022). In this study, we analyzed four water bodies hosting FPV installations in a standardized manner, where each site embodied distinct surface coverage ratios.

Our analysis shows that, in this sampling year, FPV installations did not create noticeable heterogeneity in water quality compared to non-covered areas of the same water body, nor did they affect localized differences in algal growth, as evidenced by the lack of discernible trends in chlorophyll-a and phycocyanin. The negligible effect on algal growth suggests a promising lack of ecological disturbance from FPV deployment; however, the limited sampling of the spot sampling technique may have missed any major temporal variations associated with FPV and future studies could further explore these phenomena via a continuous-monitoring campaign.

Water quality parameters

The absence of discernible cooling effects from floating photovoltaic (FPV) installations in this spot-sampling study contrasts with findings from other field studies, which observed temperature reductions beneath the FPV compared to open water (Ilgen et al., 2025; Nobre et al., 2025; Ray et al., 2024). Specifically, at Altamonte Springs, OUC, and Oakville, the author team conducted a parallel study of continuous temperature and DO monitoring and found an overall cooling trend beneath the FPV (Cagle et al., in review). This discrepancy in FPV temperature impacts—between the findings of this study and those of other field studies on the same water bodies and beyond—may stem from differences in sampling timing. Continuous monitoring studies on the same water bodies indicate the largest shifts in water temperatures tend to occur between 15:00 and 16:00 at the sites in this spot sampling campaign, which does not align with the morning and afternoon spot sampling schedule (Cagle et al., in review). Additionally, sampling only occurred across a single year. Interannual variation may have a significant influence on the effect and magnitude of effect of FPV systems.

We observed reduced DO concentrations beneath FPV installations at the OUC site in the afternoon across seasons, aligning with prior studies attributing decreased DO to reduced wind mixing and photosynthesis inhibition from shading (Cagle et al., in review; de Lima et al., 2021; Liu et al., 2023; Yang et al., 2022; Ilgen et al., 2025; Ray et al., 2024). These findings also align with traditional hydrological dynamics that state dissolved oxygen is governed by light availability and mixing, both of which are altered by FPV (Wetzel, 2001). However, the other three sites showed no consistent DO trends, likely due to mechanical and surface aeration (Oakville and Windsor, respectively) and natural diel mixing conditions. Conductivity and pH measurements remained homogeneous across FPV and open-water areas, consistent with well-mixed conditions and previous reports of minimal or no significant change in these parameters (Li et al., 2023; Liu et al., 2023).

Algae indicators

One of the main putative benefits of FPVs is reduced algae growth. In this study, Windsor was the only location demonstrating a high concentration of phycocyanin; however, no trends indicated the uneven distribution of cyanobacteria across sampling time and season. While certain seasons had singular occurrences in which averaged values were less beneath the FPV than the open water body (Appendix 11), the measured phycocyanin beneath the FPV and open water body were near-zero, indicating these findings are of little significance toward water body health and ecosystem function. For example, the OUC location trended toward lower phycocyanin below the FPV across most sampling seasons, aligning with the decreased DO trend over the same sampling periods. However, the recorded phycocyanin at OUC was so low (<2 RFU) that the impact of FPV on major cyanobacteria-driven episodes, such as HABs, could not be determined.

Similar to phycocyanin, there was no consistent trend in chlorophyll-a concentrations beneath the FPV across all sites and seasons. The OUC location demonstrated analogous trends to phycocyanin in which lesser chlorophyll-a concentrations were identified below the FPV installation, aligning and potentially explaining the decreased DO beneath the FPV. Li et al. (2023) found a similar trend in chlorophyll-a in FPV and non-FPV zones; however, the lack of reduced chlorophyll-a concentrations below the other three FPV installations contradicts modeling outcomes (Exley et al., 2022; Haas et al., 2020). Liu et al. (2023) observed a slight reduction in chlorophyll-a below FPV, demonstrating the variable impacts of FPV on algae. The depth and time of day of sampling can impact photosynthetic pigment readings, with maximum concentrations at the surface in the morning and shifting to 0.5 m depth in the afternoon. Nevertheless, our sampling regime captured morning and afternoon conditions with at least 1 m depth in the water column (Wolny et al., 2020). Importantly, algae growth varies annually in intensity and timing of growth (Brown et al., 2024), indicating the potential for alternative results if the same sampling protocol were applied in a different year. Thus, highlighting the need for continuous monitoring of algae and cyanobacteria biomass pre- and post-FPV deployment.

This study represents one of the first to collect field-based measurements of phycocyanin in FPV-hosting waters and assess the potential impact of FPV on cyanobacteria with other initial studies finding no difference in phycocyanin as well (Ilgen et al., 2025). Previous research has focused on modeling and field study of green algae, finding a reduction in chlorophyll-a beneath FPV (Exley et al., 2022; Haas et al., 2020; Li et al., 2023; Wang et al., 2022). Conversely, there is an absence of modeling and empirical field data on the impact of FPVs on cyanobacteria. Characterizing phycocyanin concentration in FPV ponds is critical because cyanobacterial HAB events pose a direct risk to the aquatic ecosystem and public health (Amorim and Moura, 2021; Grattan et al., 2016; Lürling et al., 2018; Melaram and Lopez-Dueñas, 2022; Paerl et al., 2001). Rising water temperatures owing to climate change not only favor cyanobacterial dominance but also create feedback loops where blooms further exacerbate warming through reduced water clarity and altered heat dynamics (Grogan et al., 2023; Paerl, 2023; Winslow et al., 2015). Although we observed no consistent FPV-driven changes in phycocyanin across our four shallow, polymictic sites, future water quality monitoring should prioritize phycocyanin metrics given the rising risk and recurrence of HABs in these vulnerable systems. While we observed limited evidence of FPV impact in these four shallow, polymictic water bodies, future water quality sampling campaigns should incorporate phycocyanin due to the well-documented impacts of HABs.

Implications for future FPV development

While limited in the frequency of sampling, this study illustrates how FPV installations may have minimal discernible impacts on water quality and algal biomass in shallow, polymictic water bodies, regardless of FPV coverage intensity or biological complexity. Despite varying biological activity, aeration mechanisms, and FPV surface coverage across four sites (Table 1), parameters like dissolved oxygen, chlorophyll-a, and phycocyanin showed no consistent trends beneath FPV arrays. This contrasts with studies suggesting FPV coverage influences water quality and algae (Li et al., 2023; Sandrini et al., 2025), but aligns with a few recent FPV field studies that found little to no impact (Bax et al., 2023; Ziar et al., 2021). Minor algal reductions were occasionally observed across sampling times and seasons, but were functionally negligible due to low baseline concentrations. The consistent factor across all sites was the polymictic nature of the water bodies, characterized by frequent mixing that equalizes stratification and homogenizes physicochemical parameters.

A parallel study at three of the four sites found that the FPV system reduced surface temperatures by >1 °C and regulated diel fluctuations, alongside reduced Schmidt stability (indicative of limited stratification (Cagle et al., in review; Kirillin and Shatwell, 2016). While thermal changes can influence cyanobacteria biomass (Dantas et al., 2011), no corresponding shifts were observed—likely because the water bodies were already unstratified. Consistent mixing homogenizes temperature, nutrients, and other physiochemical water quality parameters (Andersen et al., 2017; Holgerson et al., 2022), potentially mediating localized FPV effects. Ultimately, the study highlights the suitability of polymictic water bodies for FPV deployment, as their inherent mixing dynamics may minimize FPV disturbance on algae and water quality.

FPV as a land sparing and low environmental emissions alternative

Across the United States, the renewable energy transition is driving increasing demand for land at the expense of natural and working lands, presenting a need for renewable energy solutions with minimal environmental impact. Ground-mounted photovoltaic (GPV) systems represent the most widely deployed solar technology; however, they can drive negative environmental impacts, including ecosystem disturbance, biodiversity loss, and land utilization at the expense of agriculture (Condon et al., 2025; Levin et al., 2023; Hernandez et al., 2015, 2019). Our study demonstrates that FPV may have minimal effects on water quality and algal biomass, presenting a clear advantage over GPV's documented negative impacts. Furthermore, FPV systems are 2.3 times more land-use efficient than GPV (Cagle et al., 2020; van de Ven et al., 2021). These combined land-sparing and environmental advantages demonstrate how FPVs can help integrate renewable energy into existing human made water bodies with positive impacts, especially in regions where land conservation is a priority. Additional long-term monitoring and pre-post construction research is required to validate these preliminary environmental trends observed for FPVs.

Furthermore, FPV systems are responsible for fewer environmental emissions than other renewable energy technologies. FPVs produces an estimated 2.61 g CO_2-eq kWh^{-1} of environmental emissions, which is significantly less than the 12.7–13.91 g CO_2-eq kWh^{-1} for onshore and offshore wind farms and less than the 50 g CO_2-eq kWh^{-1} of emissions for terrestrial solar (Marashli et al., 2022; Ray et al., 2024). Replacing 1 unit of wind or terrestrial solar with FPVs in future renewable energy development planning can save up to 11.3 and 20–47 g CO_2-eq kWh^{-1}, respectively, and 502–936 g CO_2-eq kWh^{-1} replacing 1 unit of fossil fuel-fired systems (Marashli et al., 2022). Life cycle assessment of these renewable energy technologies further highlights the untapped potential of FPV as a key technology in the clean energy transition that can provide renewable energy generation with the least environmental cost.

This study's findings demonstrate the complex, interplay between hydrological and biogeochemical mechanisms in a given water body. Our findings indicate limited, albeit site-specific differences in phycocyanin, chlorophyll-a, pH, conductivity, dissolved oxygen, and water temperature exist between areas beneath FPVs and in the open water across this sample of shallow, well-mixed water bodies. Specifically, the lack of clear, observable trends across all water bodies demonstrates the importance of integrating continuous, pre- and post-FPV deployment monitoring of water quality and biological conditions to provide insights into the response of water body dynamics over the lifespan of FPV installations. Future research should focus on high-frequency, long-term monitoring to fingerprint FPV impacts on water quality and algal biomass to better inform FPV system design and operation. Overall, this study demonstrates that FPV installations in shallow, well-mixed water bodies produce negligible impacts on water quality and algae. These findings help address common environmental concerns about FPV and support the technology's role as a sustainable renewable energy solution.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary material, further inquiries can be directed to the corresponding author.

Author contributions

AC: Writing – review & editing, Writing – original draft, Formal analysis, Conceptualization, Investigation, Methodology. BN: Writing – review & editing, Writing – original draft, Formal analysis. AA: Supervision, Validation, Writing – review & editing, Conceptualization. SS: Conceptualization, Writing – review & editing. GP: Writing – review & editing. MD: Writing – review & editing. RH: Methodology, Conceptualization, Investigation, Supervision, Funding acquisition, Writing – review & editing, Resources, Writing – original draft.

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Conflict of interest

GP and MD were employed by Innovation of Enel Green Power S.p.A.

The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/frwa.2025.1614008/full#supplementary-material

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