Metal contaminant risk at active floating photovoltaic sites and future research roadmap

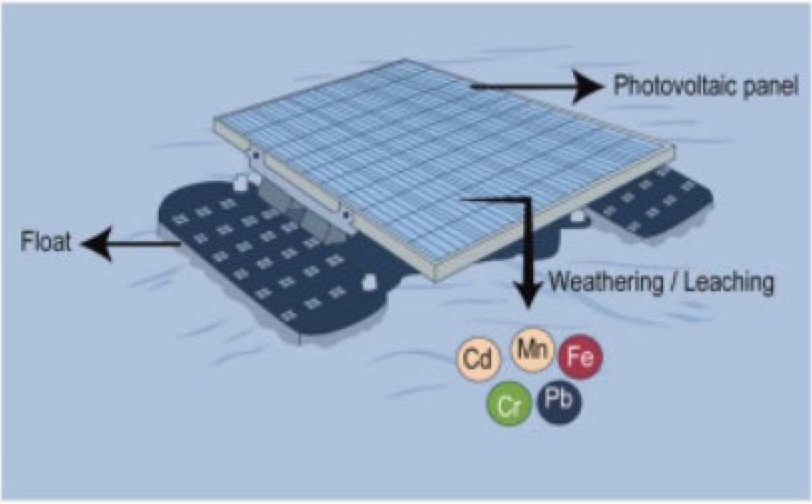
Highlights

- Metal leaching from floating photovoltaic (FPV) is unlikely due to encapsulation.
- A pilot study found metals at FPV sites and Control, suggesting a natural origin.
- Potential pathways of non-FPV metal inputs include overland flow and bird fouling.
- Metal risks and attribution are needed at FPV sites to catalyze FPV development.
- An FPV research roadmap may facilitate FPV-metal leaching studies and consensus.

Abstract

Floating photovoltaics (FPVs) are solar energy systems deployed in aquatic environments, sparing land for other uses. It has been nearly twenty years since photovoltaics were first deployed on water bodies as FPVs. However, the potential for FPVs to contaminate host basins with metals due to some FPV components containing metals is understudied. We conducted a pilot study investigating cadmium (Cd), chromium (Cr), iron (Fe), manganese (Mn), lead (Pb), and tin (Sn) concentrations and their variability at FPV sites in two states in the United States. Next, we contextualized these results using the heavy metal evaluation index (HEI) to understand risks to human health. We found that the predominant metals at the FPV sites were Fe and Mn, and Cd was the least occurring metal. The greatest and least variable metals were Fe and Cd for the study sites. The total mean concentration of metals from the "FPV" and "Open" nodes at the FPV site for SITE 1 (59.92 ppb) was lower than the reference "Control" (76.43 ppb), the latter driven predominantly by the presence of Fe and Mn. The HEI revealed that water at the FPV-host basins have metal concentrations two orders of magnitude below the threshold for low metal pollution (<10), interpreted as safe for drinking. We leveraged these results and those from previous studies to develop an experimental framework and conceptual roadmap to guide future experimental research toward establishing high confidence in metal source attribution at FPV sites.

Graphical abstract



Introduction

Development of renewable energy sources such as solar energy, particularly photovoltaics (PVs), is increasing globally as countries aim to mitigate climate change and achieve the United Nations Sustainable Development Goals (SDG, e.g., SDG 7, Target 7.2). Photovoltaics are installed in many different locations, most abundantly on rooftops and terrestrial land surfaces (Exley et al., 2022). When PVs are installed on land surfaces, they can drive land-use and land-cover change and occupy relatively large amounts of space, presenting trade-offs for agriculture and conservation (Manoj Kumar et al., 2022; Mayville et al., 2020; Lovering et al., 2022). An alternative to land-based PV development is floating photovoltaics (FPVs), which are PV installations typically deployed atop inland water bodies, where PV panels are affixed to floating structures and stablized via anchoring and mooring lines (Mustafa et al., 2021; Wei et al., 2025). Early installations of FPVs began in Japan and the United States in 2007 and 2008, respectively (Forester et al., 2025; Spencer et al., 2019). More than 2.6 GW of FPVs have been installed globally across 28 countries and the market is projected to grow at a compound annual growth rate of 22.5% between 2022 and 2030 (Exley et al., 2022; Koondhar et al., 2024; Arnold et al., 2024; Nobre et al., 2024; Ramanan et al., 2024).

Floating photovoltaics may have additional benefits beyond low-carbon energy generation and land-sparing. Preliminary evidence indicates that FPVs may mitigate evaporative loss in their host basins, especially in arid environments, increase power conversion efficiency via lower PV panel temperatures, and impede algal blooms by reducing photosynthetically active radiation (Spencer et al., 2019; Essak and Ghosh, 2022). Despite the potential benefits of FPVs, some FPV components contain metals that, if released into the host basin, could pose a hazardous risk (Wei et al., 2025; Koondhar et al., 2024; Nobre et al., 2024; Divya et al., 2023). Metal transfer from FPVs to the host basin could occur theoretically via direct pollution and/or leaching events. However, it is unclear if such events are likely to occur and result in hazardous levels of metal influxes in the water of an FPV host basin. Importantly, since the first commerical FPV was deployed in 2008, the FPV sector has evolved, resulting in diverse, innovative designs with enhanced efficiencies and durability, including the ability to withstand harsh environmental and extreme weather conditions (Wei et al., 2025; Gaddam et al., 2021). Further, encapsulation of PV panels with ethylene vinyl acetate (EVA) enhances the structural integrity of PV panels (Gaddam et al., 2021). Therefore, it is possible that FPV-driven metal pollution and/or leaching does not occur or results only from catastrophic FPV failure, for example, from PV corrosion, delamination, or glass breakage—and its subsequent negligence by FPV operators and managers (Aitola et al., 2022; Pinochet et al., 2024; Wu et al., 2023; Ndiaye et al., 2013).

Current research on the relationship between FPVs and the environment has primarily focused on how FPVs influence the host basin's hydrodynamics, benthic organism communities, phytoplankton abundance, and water chemistry properties (Exley et al., 2021a, 2021b, 2022; Wei et al., 2025; Haas et al., 2020; Pringle et al., 2017; Benjamins et al., 2024; Frehner et al., 2024; Ouro et al., 2024; Pouran et al., 2022; Gasparatos et al., 2017; Abdelal, 2021; Wang et al., 2022a; Yang et al., 2022; Althuwaini, 2024; Sahu et al., 2016; Al-Widyan et al., 2021; Kumar et al., 2022; Cuce et al., 2022; Andini et al., 2022; Liu et al., 2023). However, few studies have examined potential FPV-driven metal contamination, and far fewer have tested if FPV metal leaching occurs under field conditions (Mathijssen et al., 2020; Wang et al., 2022b). In fact, studies have yet to evaluate the risk of FPV-driven pollution and/or metal leaching to identify the suitability of host basin type, as FPVs are sometimes deployed atop multi-use water bodies that supply drinking water. For example, metal contamination in surface water systems could be assessed by applying established water quality indices, including the heavy metal evaluation index (HEI) (Khadija et al., 2021; Ojekunle et al., 2016; Prasanna et al., 2012; Badeenezhad et al., 2023; Edet and Offiong, 2002; Kumar et al., 2019; Al-Ani Environmental Engineer et al., 1987). Extending metal contamination indices to FPVs and the water they interface with is vital to FPV industry growth and in assessing if certain water body types are more appropriate for FPV development than others.

To address this knowledge gap, we (1) conducted a pilot study that investigated the variability of metal concentrations (i.e., Cd, Cr, Fe, Mn, Pb, and Sn) of FPV host basins under field conditions, and (2) contextualized these results using the HEI. We hypothesized that if metal pollution and/or leaching from FPV development occurs, metal concentrations in the water of FPV host basins, will be greater, on average, than in the water of non-FPV host basins. Secondly, we hypothesized that if water from FPV host basins contains relatively greater metal concentrations, on average, concentrations will not exceed water quality standards as indicated by the HEI. To our knowledge, this is the first effort to design and execute a pilot study to assess baseline metal contamination of water at active FPV sites. We then apply the lessons learned from this pilot study to develop an experimental framework and research roadmap for facilitating and accelerating FPV-metal research. Resolving uncertainties in the potential for FPV-driven metal pollution and/or leaching under real-world operating conditions is crucial as this technology is increasing in capacity across diverse water bodies, including those that support humans and wildlife. Furthermore, as FPV development could be a technological lever to operationalize progress toward SDG 7 (i.e., affordable and clean energy), real or perceived public concerns that FPVs may pose metal risks to water could undermine this progress. If metal pollution and/or leaching from FPV infrastructure to water is a risk to SDG 6 (i.e., clean water and sanitation). Therefore, understanding and anticipating potential harm caused by FPV deployment and operation to their host basins is necessary to achieve SDGs 6 and 7 concomitantly.

2. Methods

2.1. Study area

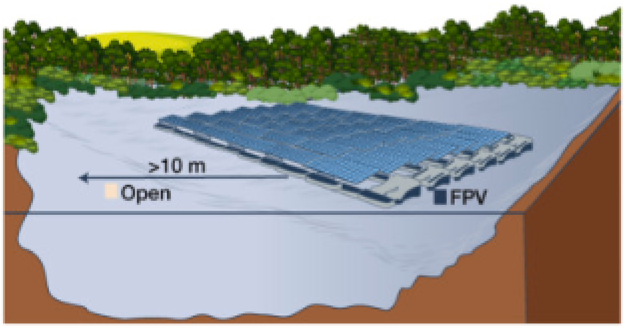
We investigated FPV-metal leaching under field conditions by conducting a pilot study in the summer of 2022 at two FPV sites in two different states in the United States. Our study areas were selected for their unique attributes and ease of access to areas with FPV installations that allowed field-based research operations to be conducted (Table 1). Following best practices, we anonymized the study areas as SITE 1 and SITE 2 (Yip et al., 2016; Miteu, 2024). SITE 1 is in a humid subtropical climate, whereas SITE 2 is in a warm Mediterranean climate. On average, SITE 1 has greater annual precipitation and a greater difference between the highest and lowest temperatures than SITE 2.

Table 1. Technological, hydrological, and spatial attributes of FPV sites used in the pilot study.

Attribute	**SITE 1**	**SITE 2**
Age of FPV installation as of 2022 (years)	1	3
Type of PV panel used for installation	Monocrystalline silicon	Monocrystalline silicon
Number of PV panels in installation	2,430	4,959
Managed water inputs	Yes	Yes
Water body type	Water treatment holding pond	Post-water treatment holding pond
Water depth (m)	2.3	3.5
Water body perimeter (m)	478	1,086
Water body surface area (m^2)	12,396	69,452
Water body volume (m^3)	28,511	243,082
Surface area of FPV installation (m^2)	552	16,184
Percent of water surface covered (%)	4.45	23.30

2.2. Sample collection and sampling procedures

We adapted our pilot study to a similar experimental design for floating vegetation islands in urban water bodies (Zhao et al., 2012; Tanner and Headley, 2011). To minimize contamination from possible sources of metals, we followed standardized water sampling protocols as outlined by the United States Environmental Protection Agency (Telliard, 1996). Using a swing sampler, we collected a total of 15 water samples from two FPV sites (SITE 1 and SITE 2) and one Control site located near SITE 1. At each FPV site, we collected water at two distinct nodes, >10 m away from the FPV ("Open" node) and <0.5 m directly beneath the FPV ("FPV" node). Water samples were taken within the pond of the Control site ("Control" node). We collected three water samples at randomized spots for each node ("Open" n=3; "FPV" n=3; and "Control" n=3; Fig. 1). To minimize disturbing the water column and the sediment, we collected samples from a kayak or the FPV structure, moving slowly and with caution.



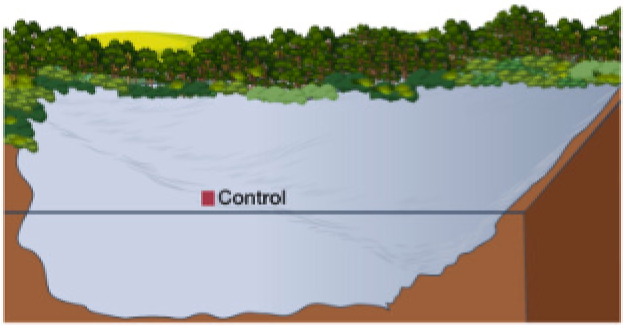


Fig. 1. Water samples were taken from the floating photovoltaic solar energy (FPV) and control sites. Each FPV site had an "Open" node located over 10 m from the FPV array and an "FPV" node less than 0.5 m beneath the FPV infrastructure. Samples were taken within the pond of the Control site ("Control" node).

2.3. Sample preparation, storage, and analytical methods

Water samples were filtered on-site using a 0.45 μm acrodisc filter that was coupled with a sanitized 50 mL syringe. The filtered samples were then transferred to a pre-acidified 125 mL high-density polyethylene (HDPE) bottle with metal-grade nitric acid and sealed in a plastic bag. Both sample bottles and bags were pre-labeled and then placed on ice. The samples were transferred to the laboratory within seven days and stored in a refrigerator. After the completion of the field sampling season (one month), we analyzed the water samples for a suite of 32 metals. We tested for metal contaminants that are commonly found in commercial PV panels and have public health implications (e.g., Cd, Cr, Fe, Mn, Pb, and Sn) (Divya et al., 2023; Pastuszak and Węgierek, 2022; Jaishankar et al., 2014). The metal analysis of the water samples was conducted using Inductively Coupled Plasma Mass Spectrometry (ICP-MS) at the University of California Davis Interdisciplinary Center for Inductively Coupled Plasma Mass Spectrometry using standardized methods (Zhao et al., 2012; Tanner and Headley, 2011).

2.4. Evaluating the metal pollution index at floating photovoltaic sites

We evaluated the metal concentrations detected at the FPV sites using the HEI. As a quantitative index, the HEI can be used to determine if the detected metal concentrations are within permissible drinking water limits (Equation (1)). H_{max} refers to the permissible metal contaminant level in drinking water, and H_c refers to the average concentration of the metal from the "FPV" and "Open" nodes in parts per billion. We determined the suitability of water samples at the FPV sites using permissible metal contaminant levels and secondary maximum contaminant levels (Khadija et al., 2021; Ojekunle et al., 2016; Prasanna et al., 2012; Badeenezhad et al., 2023; Edet and Offiong, 2002; Kumar et al., 2019; Al-Ani Environmental Engineer et al., 1987). Additionally, we defined the water quality of the FPV host basin to have (1) low pollution when HEI <10, (2) moderate pollution when HEI = 10–20, and (3) high pollution for HEI >20 (Kumar et al., 2019).

$$HEI = \sum_{i=1}^{n} H_c / H_{max} \qquad \text{Equation (1)}$$

3. Results

3.1. Descriptive and statistical analysis

We found varying metal concentrations at all FPV and control sites (SITE 1, SITE 2, and control) and every sampling node within each site ("Open," "FPV," and "Control"). Across all the sites, Fe and Mn had the highest concentrations, while Cd had the lowest concentrations (Table 2). Within the FPV sites, heterogeneity was high across all ponds, and there were no consistent trends for the metal concentrations. For instance, while some of the metals, such as Fe and Sn, appeared to be at higher concentrations at the "FPV" than the "Open" nodes at SITE 1, the reverse trend was observed at SITE 2. Relative variability of metal concentrations was consistent across both SITE 1 and SITE 2. Across the FPV sites, the greatest and least variable metals were Fe (55.29±18.39 ppb) and Cd (0.01±0.00 ppb) for SITE 1 and Fe (6.82±3.30 ppb) and Cd (0.05±0.01 ppb) for SITE 2. Between SITE 1 and the Control site, the total mean metal concentration of "Control" (76.43 ppb) was higher than SITE 1 (59.92 ppb), driven predominantly by the presence of Fe and Mn.

Table 2. Metal concentrations in parts per billion (ppb) of water at the floating photovoltaic study sites, collected in summer 2022.

Metal	FPV Node (ppb)	Open Node (ppb)	Mean (FPV+Open Nodes) (ppb)	Std dev. (ppb)	Control Node (ppb)
SITE 1					
Cd	0.01	0.01	0.01	0.00	0.01
Cr	0.35	0.29	0.32	0.04	0.17
Fe	68.29	42.28	55.29	18.39	70.23
Mn	4.36	3.63	4.00	0.52	5.80
Pb	0.30	0.24	0.27	0.04	0.21
Sn	0.03	0.02	0.03	0.01	0.01
Sum	–	–	59.92	–	76.43
SITE 2					
Cd	0.04	0.05	0.05	0.01	–
Cr	0.27	0.39	0.33	0.08	–
Fe	4.48	9.15	6.82	3.30	–
Mn	2.24	0.96	1.60	0.91	–
Pb	0.53	0.09	0.31	0.31	–
Sn	0.08	0.11	0.10	0.02	–
Sum	–	–	9.21	–	–

3.2. Evaluating the metal pollution index at floating photovoltaic sites

The H_c values for Cd, Cr, Fe, Mn, Pb, and Sn for the "Open" and "FPV" nodes at SITE 1 and SITE 2 were lower than the H_{max} values. Furthermore, the calculated HEI value was higher for SITE 1 than SITE 2. However, SITE 1 (0.23) and Site 2 (0.11) have HEI values less than 10, indicating low metal pollution at both FPV sites (Table 3)(Kumar et al., 2019).

Table 3. Heavy metal evaluation index (HEI) results describing water quality at the floating photovoltaic study sites. Pollution levels for HEI are low (<10), moderate (10–20), and high (>20).

Metal	Average metal concentration from "FPV" and "Open" nodes: H_c (ppb)	Permissible metal contaminant: H_{max} (ppb)	H_c/H_{max}
SITE 1			
Cd	0.01	5	0.00
Cr	0.32	100	0.00
Fe	55.29	300	0.18
Mn	4.00	300	0.01
Pb	0.27	15	0.02
Sn	0.03	2	0.01
HEI: 0.23			
Metal pollution index: Low			
SITE 2			
Cd	0.05	5	0.01
Cr	0.33	100	0.00
Fe	6.82	300	0.02
Mn	1.60	300	0.01
Pb	0.31	15	0.02
Sn	0.10	2	0.05
HEI: 0.11			
Metal pollution index: Low			

4. Discussion

4.1. Interpretation and implications of the pilot study

Previous studies have underscored the importance of evaluating potential leachates from FPVs, particularly as this technology is increasingly deployed in aquatic environments (de Lima et al., 2021; Bhattacharya et al., 2024; Nain and Kumar, 2020; Kwak et al., 2020). As a first step in assessing possible FPV-related metal contamination under real-world conditions, we conducted a pilot study at two different active FPVs located in the United States. Across all sampling nodes ("Open," "FPV," and "Control"), metal concentrations were low, suggesting minimal metal pollution in our study areas. Notably, HEI was two orders of magnitude below the threshold for low pollution at FPV SITES 1 and 2. Further, we detected several metals, including Fe and Mn, at the Control node, where no FPV infrastructure was present. These findings suggest that some detected metals are likely of natural origin or stem from background sources unrelated to FPV infrastructure (Elder, 1988; Zhou et al., 2020). These metals may originate from a range of exogenous sources such as atmospheric deposition, overland flow, groundwater intrusion, sewage effluent, or upstream flow (Tchounwou et al., 2012). Thus, incorporating a Control is not only prudent but essential when evaluating FPV-associated metal contamination, as it provides critical context for distinguishing FPV-related impacts from non-FPV sources of metals. Moreover, these findings highlight the importance of considering site-specific factors, such as climate, land use, and hydrology, which may also contribute to variations in metal concentrations across FPV host basins.

We observed differences in metal concentrations between the two FPV installations (SITE 1 and SITE 2), suggesting that FPV-related metal contamination could be site-specific and influenced by distinct site-specific conditions, such as differences in FPV and host basin characteristics (Armstrong et al., 2020). For instance, SITE 1 has about 50% less PV panels, 20% of the water body surface area (m^2), 20% lower FPV coverage, and 12% of the water volume (m^3) compared to SITE 2 (Table 1). Assuming that the PV panels have the potential to "leach" metals, the number of PV panels could correlate with the amount of metals being introduced into the FPV host basin. Our assumption is based on the idea that the amount of solute and the volume of solvent can impact the concentration of a solution. Therefore, the ratio of available metals at SITE 1 to the volume of its host basin may influence the detected metal concentration. Alternatively, a difference in water chemistry properties between the two FPV sites can influence the behavoir of metals in the water column, potentially impacting metal concentration and, hence, their detection (Zhang et al., 2023; Saravanan et al., 2024). Likewise, exogenous environmental conditions can influence metal contamination, impacting differences in metal concentrations between FPV sites.

Exogenous environmental factors modulate the evaporation and precipitation of water in a host basin to influence metal concentrations (Singh et al., 2024; Briffa et al., 2020; Basallote et al., 2019). Particularly, while we measured metal concentrations at our study sites, the absolute metal measurements may not indicate how changes in water volume by dilution and evaporation affect the composition (and volume) in the basin, causing either an apparent increase or decrease in metal concentrations. A prime example is how, in the dry seasons in arid environments, a decrease in basin water volume with lower inflow and higher evaporation may increase metal concentration (Singh et al., 2024; Briffa et al., 2020; Basallote et al., 2019). Moreover, the input of rain or more diluted water into the basin (mixing) can decrease the metal concentrations. Specifically, an increase in water volume through precipitation and overland flow may carry metals into these ponds, alter redox conditions within the sediments, and alter metal release rates (Milazzo et al., 2014). The effect of evaporation on increasing metal concentration is progressive and time-dependent. At the same time, dilution (or mixing) is mostly event-based, associated with precipitation, snow melting, or even infilling of the basin. In addition, temperature changes resulting from seasonal changes may modulate chemical reactions in an aquatic system, affecting the chemistry of metals and altering their concentrations in the ponds (Iordache et al., 2022).

Integrating the heavy metal evaluation index (HEI) into assessments of FPV-related metal contamination is helpful to ensure that emerging renewable technologies do not pose unintended risks to human health. Concerns surrounding metal use in FPV infrastructure are heightened by the fact that these systems are deployed directly on water bodies that serve as vital resources for drinking, irrigation, and recreation (Bošnjaković et al., 2023; Nobre et al., 2023). Yet, current uncertainties around the sources and potential impacts of FPV-associated metals may hinder widespread adoption and public trust (Mirletz et al., 2023; Eisenson et al.). Without robust, site-specific data and health-based thresholds like HEI, the sustainability of FPV installations, despite their promise for large-scale renewable energy production, remains unclear. As global energy transitions accelerate, decision-makers need clear evidence that clean energy deployment will not compromise water quality. Therefore, incorporating HEI into policy frameworks can help safeguard public health, support Sustainable Development Goals 6 and 7, and guide responsible FPV development, deployment, and operation (Kumar, 2022; Wang, 2009).

4.2. Refining floating photovoltaic field studies

Despite detecting low levels of metal pollution at FPV sites in two distinct regions, our findings highlight critical potential pitfalls in current research on FPV-related metal contamination. In particular, the ability to accurately attribute metal concentrations to FPV infrastructure is hindered by three major limitations: (1) the absence of "before" or pre-installation baseline data, (2) a lack of systematic testing of different metal sources and their fluxes through the FPV–aquatic interface, and (3) the absence of standardized methodologies for data collection and reporting (Fig. 2). These gaps collectively obscure definitive conclusions about FPV impacts on water quality and risk assessment. To address these challenges, we developed a conceptual framework informed by our pilot study, a small-scale, exploratory assessment of feasibility for *in-situ* FPV metal monitoring (Leon et al., 2011). This framework identifies key research needs and guides the design of robust, hypothesis-driven studies on FPV-driven impacts on water quality. Ultimately, advancing this area of research will require coordinated, interdisciplinary efforts that integrate pre-deployment baseline data, systematic and repeated testing over time, and rigorous, standardized methods for sampling, analysis, and reporting to ensure comparability across studies and sites.

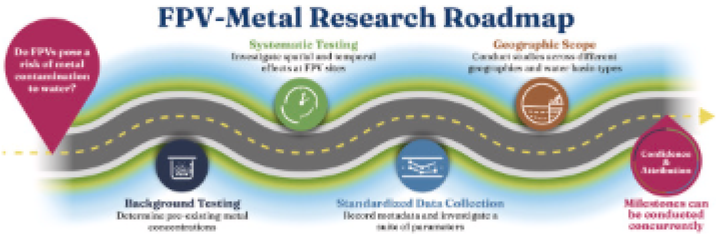


Fig. 2. A conceptual research roadmap to attain confidence and attribution of potential risks associated with metals and floating photovoltaic solar energy.

4.2.1. Lack of background testing and assessment of metals

An aquatic environment is predisposed to metals from exogenous and endogenous sources, and thus, assessing the water chemistry properties and metal concentrations at prospective FPV sites is critical to establishing a pre-installation baseline for future reference conditions. Specifically, the pre-installation baseline is useful to compare metal concentrations from pre-and post-FPV deployment and, importantly, assess whether metals in the water, post-FPV installation, originate either from the FPV installations or pre-existing metal conditions. In the case of our pilot study, the lack of a pre-installation baseline made it difficult to determine if the FPV installation altered the metal dynamics at the FPV sites. As such, we were unsuccessful in attributing the detected metals, albeit very low in concentration, to the presence or absence of the FPV infrastructure. Therefore, for future FPV deployment, we may want to establish guidelines or protocols to include a metal assessment of prospective host basins. This background assessment should also include the determination of a suite of other physico-chemical conditions, given the interactions between such conditions and metal partitioning in water and sediments (Zhang et al., 2023; Saravanan et al., 2024). On the other hand, to determine the metal sources at existing FPV sites, we can use a combination of water quality monitoring, geological analysis, chemical tracers, and statistical models to evaluate if detected metals originate from the FPV installations (Wu et al., 2021; Fadlillah et al., 2023). Incorporating layers of assessment prior to FPV deployment will enhance future investigations that seek to understand the impacts of new FPV installations on "background" metal dynamics and correctly attribute such changes.

4.2.2. Lack of systematic testing

Studies can adopt systematic testing approaches that examine all potential sources of metal inputs to determine if FPVs contribute to metal contamination in aquatic ecosystems. Attribution to FPVs cannot be made in isolation without accounting for endogenous and exogenous sources of metals. Endogenous sources include the consideration of spatial and temporal dynamics within the FPV host basin, while exogenous sources, while also spatiotemporally dynamic, range from bird fouling and atmospheric deposition to overland runoff. Addressing these potential metal pathways enables the systematic elimination of confounding variables and can support the accurate assessment of metal concentrations, or lack thereof, to FPV deployment and operation.

Understanding the natural dynamics of a water body is essential for disentangling FPV-related effects from background variability. Metal concentrations in aquatic systems are not static, as spatial properties of the host water body and temporal variation can influence their availability and mobility (Yuan et al., 2022). Factors such as water body morphology, hydrodynamic circulation, sediment composition, and water chemistry may vary across locations, potentially driving differences in metal concentrations near and far from FPV installations (Singh et al., 2024). Seasonal changes (i.e., fluctuations in water levels, temperature, and redox conditions) can further affect metal transport, release, and sequestration in the water column and sediment (Iordache et al., 2022; Lazăr et al., 2024). To accurately assess the influence of FPVs, studies must account for this spatio temporal variability through well-designed sampling frameworks that include transects radiating from FPV structures across different points of the FPV host basin and measurements across multiple seasons. Further, water and sediments from these transects can be characterized to better understand metal dynamics in the dissolved phase and the sediment. While internal dynamics within the FPV host basin are complex, external, exogenous sources may introduce additional and often confounding metal inputs that must also be evaluated.

Multiple exogenous pathways can deliver metals into FPV host basins, complicating efforts to isolate FPV-related impacts (Singh et al., 2024; Iordache et al., 2022). Bird fouling, atmospheric deposition, and overland flow all have the potential to transport metals into a system (Fig. 3). Wildlife, especially birds that can roost or nest on FPV components, may introduce metals through their fecal deposition, which may be enriched with bioaccumulated contaminants (Forester et al., 2025; Rosa-Clot, 2020; Eeva et al., 2020). Identifying these sources of metals is vital if we are to discern the unique contributions of FPVs and evaluate their contributions to overall metal budgets at FPV sites.

sites.

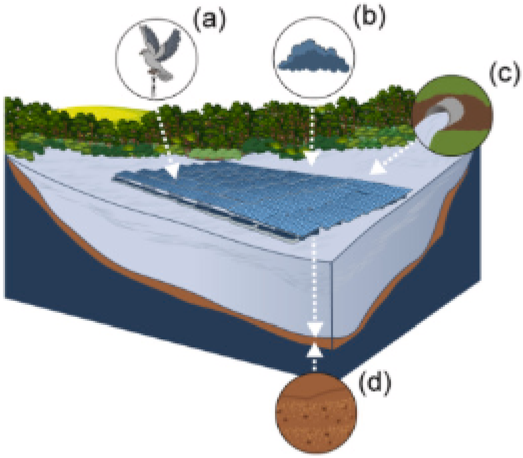


Fig. 3. Proposed conceptual model of potential pathways of metal inputs into floating photovoltaic solar energy host basins: (a) bird fouling, (b) atmospheric deposition, (c) overland flow, and (d) sediments in the host basin.

Because of how FPV host basins can receive water from different sources, we can use stable isotopes of hydrogen (δD) and oxygen ($\delta^{18}O$) to trace the origin and the processes that change the composition (and volume) of water that will affect the metal (and solute) concentrations (and composition) in FPV-host basins (Williams et al., 1997; Williams and Williams, 1997; Thaw et al., 2021; Ana et al., 2014). For instance, dilution from water inputs such as precipitation, river water, or groundwater during anthropogenic regulation of water levels in FPV host basins can change the $\delta^{18}O$ and δD and metal (and solute) concentrations (Mukesh Kumar et al., 2020; Yang et al., 2019). Suppose there is a difference in $\delta^{18}O$ and δD of the water in the host basin and that of the input source; the change in the volume and isotopes can be characterized by mixing ratios and evaluated by isotopic mixing modeling (Ward et al., 2011; Donald et al., 2005). Furthermore, due to the unique isotopic signatures relative to the isotopic signatures of the sources and the mixture, diverse water types (if any) in the host basin can be quantified (Donald et al., 2003, 2005). Consequently, this can be used to elucidate factors such as geological and anthropogenic controls of water to make predictions about the origin, evolution, and transport needed to interpret the sources and changes in metal in FPV host basins.

Similarly, evaporation causes changes in the isotopic composition of water, and the $\delta^{18}O$ and δD of water molecules can be used as tracers of evaporation (Williams et al., 1997; Williams and Williams, 1997; Schlegel et al., 2023). Variations in $\delta^{18}O$ and δD are such that the relationship between them is characterized by a linear fit to the data known as the global meteoric water line (GMWL) (Williams et al., 1997; Williams and Williams, 1997; Schlegel et al., 2023; Stewart and Stewart, 1975; Craig and Craig, 1961). During evaporation, lighter isotopes of hydrogen (H) and oxygen (^{16}O) are preferentially transferred to the vapor phase, and heavier isotopes (D and ^{18}O) accumulate and are enriched in residual water (Williams et al., 1997; Nelson Eby and Eby, 2003). The enrichment of the heavy water isotopes is characterized by a new linear relationship (evaporation line) for $\delta^{18}O$ vs. δD with a lower slope that intersects the GMWL (Williams et al., 1997). Because of the energetics of evaporation, more hydrogen is transferred to the vapor phase than the heavier oxygen isotopes and can be characterized by the d-excess parameter (Williams et al., 1997; Nelson Eby and Eby, 2003). Hence, we expect a negative relationship between the d-excess and solutes, which characterize solute enrichment from evaporation (Letshele et al., 2022; Huang et al., 2012). This relationship between $\delta^{18}O$ vs. δD and select solutes vs. d-excess, including metals, can be used to characterize the effects of evaporation on the solute behavior in FPV-hosting basins. Importantly, this may be useful for determining whether water input, evaporation, or dilution is responsible for the high, low, or seasonally increasing or decreasing metal concentrations at FPV sites without misattributing the FPVs as the source of changes in metal concentrations (Ana et al., 2014; Yiliang et al., 2021).

In effect, drawing accurate conclusions about the role of FPV infrastructure in aquatic metal contamination requires more than simple point comparisons, as it demands comprehensive system-based approaches. Studies must be grounded in robust baseline data collected before FPV deployment and must integrate all potential sources of metal contamination into their experimental designs. This includes spatially explicit monitoring, seasonal sampling, hydrological tracing, and consideration of ecological interactions such as wildlife activity. Without this level of resolution, any attribution of metal contamination to FPVs remains speculative. Establishing systematic testing methods for metal assessment across FPV sites in different geographic locations will not only improve data comparability but also help safeguard against misguided conclusions and unintended consequences. Ultimately, addressing these methodological gaps will support evidence-based decision-making and ensure that FPV technologies are deployed in a manner that protects both energy generation goals and the integrity of aquatic ecosystems.

4.2.3. Lack of standardization of data collection and analysis

Floating photovoltaic installations and their host basins differ in terms of attributes, such as the percent coverage of the water by FPV infrastructure, the design of the FPV footprint, the age of the FPV, and the host basin volume (e.g., pond versus reservoir). These differences arise because of the modularity of FPV infrastructure, diversity of potential FPV host basins, which are further influenced by technological and economic factors (Forester et al., 2025; Friel et al., 2019; C et al., 2024; Alexander et al., 2020; Gadzanku et al., 2021). However, as FPVs are increasingly deployed across the globe and there is the need to anticipate potential FPV-metal pollution and/or leaching risks, it is important that among-study differences in sampling design (locations, frequency, parameters measured, the presence or absence of "control" sites, and pre-installation data) are documented. In fact, documenting these and other critical attributes (metadata) is important, as they may influence observed metal leaching fluxes (if any) and the fate of the metals (either dissolved in the water or accumulated in sediments). By adopting a standardized approach for data collection and analysis, the FPV research community would be better placed to discern trends related to scaling (e.g., how critical leaching fluxes, concentrations, and ratios relate to FPV coverage). An understanding of scaling may inform acceptable limits for metal leaching and concentrations based upon ecosystem impact that are integrated into the design and development of FPVs and that consider host basin volume to ensure that water quality regulations are met while also supporting the generation of electricity (Fig. 4). In effect, standardized documentation of such host basins and FPV attributes during data collection, analysis, and reporting will pave the way for comparative studies that will further our understanding of the relationship between FPVs and water quality.

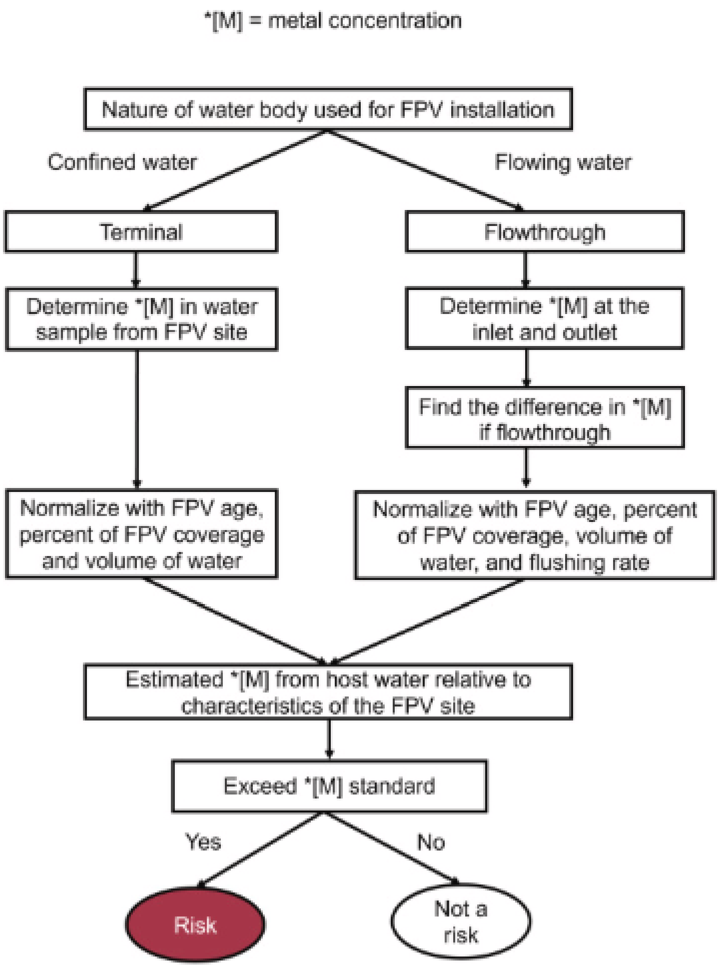


Fig. 4. A proposed conceptual workflow to determine standardized metal concentrations in a water body serving as a host basin for floating photovoltaic solar energy infrastructure.

4.3. Key findings on floating photovoltaic metal contamination

We summarize the key findings from our pilot study on FPV-metal contamination as follows:

(1) FPV components such as PV panels are encapsulated, and it is likely that in the absence of catastrophic failure and negligence, they may not leach metals into the water.

(2) Metals found at FPV sites may not be of FPV origin, as we found metals in a pond without FPV components (Control site).

(3) Understanding the relationship between metal contamination and FPV development requires a robust and systematic approach.

(4) Several factors can influence the availability, distribution, and mobility of metals in an FPV host basin. These factors remain unresolved, affecting our understanding of FPVs' impact on water chemistry.

5. Conclusions

In general, the limited nature of the pilot study— particularly the small sample size —may have restricted our ability to generalize findings about the broader extent of metal contamination from FPVs. Specifically, our pilot study lacked sufficient power as it did not go beyond descriptive statistical analysis to include sensitivity analysis to explain the contribution of different sources to the detected metal concentrations in water. However, we have demonstrated from our pilot study that there is low metal contamination in host basins of FPVs operating under field conditions. We articulated that uncertainties in our understanding of FPV-driven impacts on water quality and a lack of scientific consensus on the absence of metal contamination risks may curb FPV development if risks and attribution are scientifically unfounded. To overcome these uncertainties, which are critical to informing of the pace and scale of FPV development, we proposed a systematic approach informed by the pilot study for investigating FPV metal contamination under field conditions. Importantly, investigations that span across various functional water body types, hosting different FPV materials, and across unique geographies will be required to reach a consensus (Table 4).

Table 4. Recommended actions to be incorporated into future FPV metal contamination studies.

Limitation	Actionable Recommendations
Lack of background testing	1. Analyze metals and physicochemical parameters before (i) FPV installation and (ii) immediately after FPV installation. 2. Obtain water quality parameters before (i) FPV installation and (ii) immediately after FPV installation.
Lack of systematic testing	1. Incorporate longer-term monitoring to assess possible degradation and leaching over time. 2. Test for seasonal variations (wet and dry, fall, winter, spring, and summer). 3. Test for spatial and depth variations. 4. If possible, test for obvious metal inputs. 5. Undertake controlled mesocosm studies where PV panels are (i) intentionally degraded to ascertain the potential magnitude and composition of metal contamination, and (ii) monitored for a longer term (if resources permit, years) to assess possible degradation and leaching rates over time.
Lack of standardized data collection and analysis	1. Randomized sample collection. 2. Increase sample size and distribution. 3. Establish an acceptable control (a site without FPV components, which is similar in key climatic, morphometric, physicochemical, and ecological properties). 4. Incorporate other relevant chemical analyses, for instance, water isotopes, to explain metal fluxes at FPV sites. 5. If possible, incorporate sediment and water analyses.

Despite the fact that we investigated FPV-metal leaching at FPV sites, we limited our pilot study to Cd, Cr, Fe, Mn, Pb, and Sn, albeit there are other suites of metals that could have been investigated. From a broader perspective, solar cells that are used for the fabrication of PVs consist of different metal compositions due to intentional or unintentional metal additions during the manufacturing process associated with various PV technologies (Hofstetter et al., 2009; Hajjiah et al., 2020; Sugiura and Nakano, 2022). Accordingly, there are at least four types of photovoltaic generations, with each type embodying a unique metal compositions and potential metal toxicities (e.g., In, Pb, Te, Ti, and Zn) (Pastuszak and Węgierek, 2022). Furthermore, since PV installations are often developed in natural and semi-natural environments, it underscores the need to expand the breadth of research questions in relation to potential PV contamination of the environment based on PV generations (Mirletz et al., 2023; Ren et al., 2022; Scarpulla et al., 2023; Mirabi et al., 2021; Sailor et al., 2021; Belloni et al., 2024; Dual-Use Photovoltaic Technologies). For example, certain semiconductor materials such as perovskites, copper indium gallium diselenide (CIGS), and cadmium telluride (CdTe), which are used for PV systems, may contain hazardous metals, and research is needed to ascertain that they they pose minimal risk of introducing hazardous materials into the environment. For instance, future research could examine whether rainfall, particularly acid rain, affects PV systems and allay public concerns related to metal contamination of surrounding soil, surface water, and groundwater. Furthermore, research targets can employ numerical analysis of fluid dynamics to predict how fluids move and interact with FPVs and other types of PV infrastructure under various conditions to evaluate the extent to which such fluids may accumulate and penetrate PV panels and under what conditions. Ultimately, future research is needed to understand and anticipate the extent of multifarious environmental interactions (chemical and biological) that may exist between PV-related infrastructure and their host environment.

CRediT authorship contribution statement

Moreen Akomea-Ampeh: Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Eliot A. Atekwana:** Visualization, Supervision, Resources, Methodology, Conceptualization. **Elliott P. Steele:** Writing – review & editing, Visualization. **Alex E. Cagle:** Writing – review & editing, Data curation. **Alona Armstrong:** Writing – review & editing, Funding acquisition. **Stephen J. Thackeray:** Writing – review & editing. **Steven Sadro:** Writing – review & editing, Funding acquisition. **Olusola O. Ololade:** Writing – review & editing. **Olatubosun A. Fasipe:** Writing – review & editing. **Rebecca R. Hernandez:** Writing – review & editing, Visualization, Supervision, Resources, Funding acquisition, Conceptualization.

Declaration of competing interest

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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Data availability

The data that has been used is confidential.