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Leaching of Solar Panel Components and Its Impact on Freshwater Biodiversity

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Abstract

Solar photovoltaic technology is the most important pillars of global renewable energy transition. The expansion of solar installations decreases greenhouse gas emissions and reduce dependence on fossil fuels. This change is crucial to combating climate change, but real sustainability means considering more than just energy generation — we need to think about the full life cycle of solar panels, including the end of their usable life.

Solar panels typically last 20 to 30 years. Photovoltaic modules contain trace amounts of potentially harmful metals such as cadmium, lead, chromium, nickel and silver. In case of mechanical failure, flooding or unregulated recycling, these materials may leach into neighbouring ecosystems including freshwater bodies.

Research indicates that metal release from solar panels is influenced by several factors, including panel composition, ageing, pH, temperature, and hydrological conditions. Exposure to these contaminants has been associated with oxidative stress, developmental abnormalities, reproductive effects, and behavioural changes in a range of aquatic organisms, including algae, zooplankton, benthic invertebrates, fish, and amphibians. Many heavy metals are persistent, accumulate in organisms, and their movement through aquatic food webs increase their effects at higher trophic levels because of biomagnification.

This review highlights the need to include freshwater ecotoxicological risk assessment within broader solar life-cycle sustainability frameworks. Responsible management of solar panels at the end of their service life is essential to ensure that the shift towards renewable energy not only helps address climate change but also safeguards the health and integrity of aquatic ecosystems.

Keywords: Photovoltaic waste; Freshwater ecotoxicology; Heavy metal leaching; Aquatic biodiversity; Bioaccumulation; Renewable energy sustainability.

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1. Introduction

Solar energy has become the primary substitute for fossil fuel energy and is contributing to the reduction of greenhouse gas emissions. The lifecycle of solar panels may involve environmental hazards, including the extraction of raw materials, their production, use and disposal. (Nain and Kumar, 2020).

Freshwater ecosystems are particularly vulnerable due to their connectivity and the critical ecosystem services

they provide, such as water purification and nutrient cycling and due to their role as "sinks" for terrestrial runoff (Mulvaney, 2023).

This paper provides an analysis of how PV-derived leachates- specifically those containing Pb and Cd- affect freshwater biodiversity.

1.1 Composition of Solar Panels

Table No 1: Constituent Materials of Solar Panels

Component	Percentage (%)	Material Type	Environmental Concern
Glass	70–75	Silica-based	Low
Aluminium Frame	10–15	Metal	Moderate (mining impact)
Polymers	5–10	Encapsulants/back sheet	Non-biodegradable
Silicon	3–5	Semiconductor	Low
Trace Metals	<1	Cd, Pb, Cr, Ni, Ag	High toxicity

(International Energy Agency-IEA, 2022)

1.2 Leaching Mechanisms

Leaching is the process through which soluble substances are released from solid materials into surrounding liquids, such as water.

Weathering: Metals and other chemicals are released into the environment because of rainfall, UV radiation, temperature fluctuations, and physical wear (Weckend et al., 2016- IRENA Report).

Mechanical Damage: Transportation, installation, or disposal causes physical damage, increasing the surface area and exposing internal components.

Improper Disposal: Leachates infiltrate the soil and groundwater during landfilling or uncontrolled dumping without containment measures (Nain and Kumar, 2022).

Chemical Interactions: The solubility and mobility of metals increases in acidic or alkaline conditions (Weckend et al., 2016- IRENA Report).

1.3 Freshwater Contamination

Bioavailability: The rate of absorption of metals by aquatic organisms is influenced by their chemical speciation. For example, dissolved metal ions are more bioavailable than particulate-bound forms (Luoma & Rainbow, 2008).

Sediment Accumulation: Metals adsorb onto sediments, and create reservoirs of contamination that can persist long-term (Luoma & Rainbow, 2008).

Spatial Distribution: Contamination gradients show peak concentrations adjacent to pollution sources, and diminish downstream but affect a wide range of areas (Chapman et al., 1998).

1.4 Ecotoxicological Effects

Exposure to leached contaminants can adversely affect aquatic organisms at different biological levels.

Physiological Disruptions: Heavy metals interfere with enzymatic functions, ion regulation, and oxidative stress responses (Jaishankar et al., 2014).

Growth and Reproduction: Prolonged exposure can result in stunted growth, reduced capacity to reproduce, and developmental abnormalities (Newman, 2019).

Mortality: Acute toxicity can cause mortality in sensitive species such as *Daphnia magna* and fish embryos (Brun et al., 2016; OECD, 2004).

Bioaccumulation and Biomagnification: Metals impact higher trophic levels and biodiversity because of progressive accumulation and biomagnification in organisms (Luoma & Rainbow, 2008).

These effects disrupt the ecosystem structure and function, reduces resilience and the availability of essential ecosystem services.

1.5 Regulatory and Management Practices

Environmental policies governing solar panel waste management differ across regions worldwide.

Some of the key challenges include:

- Lack of Specific Guidelines
- Enforcement Gaps
- Recycling Limitations
- Emerging Approaches
- International cooperation (European Parliament & Council, 2012)

2. Experimental Approaches Reported in Previous Studies

2.1 Sample Collection

- Water samples from wastewater discharge channels at photovoltaic manufacturing facilities.

- Landfill leachate samples from the disposal sites of solar module waste.

- Water and sediment samples from rivers and lakes receiving drainage from disposal sites.

2.2 Leachate Extraction

Toxicity Characteristic Leaching Procedure (TCLP): Acidic extraction fluids are used to recreate landfill conditions for end-of-life solar waste to assess the release and mobility of contaminants (U.S. EPA, 1992; Nain & Kumar, 2022).

Synthetic Precipitation Leaching Procedure (SPLP): The release of substances is examined under acidified conditions resembling acid rain exposure. (U.S. EPA, 1994; Nain & Kumar, 2022).

Accelerated Weathering Tests: Natural environmental degradation process is replicated by subjecting the samples to UV radiation and repeated temperature changes (Jordan et al., 2017).

These tests are used to examine the rate of release and concentrations of hazardous substances under controlled conditions.

2.3 Chemical Analysis

Inductively Coupled Plasma Mass Spectrometry (ICP-MS): Trace metals at low concentrations are detected and quantified.

Atomic Absorption Spectroscopy (AAS): Selected metal concentrations in water and sediment extracts are assessed.

Chromatographic Techniques: Organic degradation products are identified (Nain & Kumar, 2022).

2.4 Ecotoxicity Assessment

Biological impacts are evaluated through bioassays using model freshwater organisms:

***Daphnia magna* (Water Flea):** Acute and chronic toxicity are assessed using endpoints such as immobilisation and reproductive effects (OECD, 2004).

Fish Embryos (e.g., Zebrafish): Developmental effects, hatching success, and mortality are assessed as key indicators of toxicity (Brun et al., 2016).

Algae (e.g., *Pseudokirchneriella subcapitata*): Growth inhibition assays are used to assess disruptions in photosynthetic activity (OECD, 2011; Newman, 2019).

Dose–response relationships are determined by exposing organisms to different concentrations of leachates (Newman, 2019).

2.5 Data Analysis:

Correlation Analysis: To determine the relationship between contaminant levels and their biological effects.

Multivariate Analysis: The cumulative effects of multiple contaminants is measured.

Risk Assessment Models: The exposure levels and toxicity data of contaminants are considered to estimate the ecological risks. (Newman, 2019; U.S. EPA, 1998).

3. Key Findings

3.1 Leaching Profiles

The most common metals detected in solar panel leachates are lead, cadmium, and chromium (Nain & Kumar, 2022). Research shows that thin-film panels, CdTe-based modules in particular, release these metals at higher rates than crystalline silicon panels (Brun et al., 2016). Acidic conditions and UV exposure increases the release of contaminants (Jordan et al., 2017).

3.2 Freshwater Contamination Levels

The water and sediments downstream of disposal and recycling sites show enhanced levels of heavy metals (Chapman et al., 1998). Such sites act as long-term sources of contamination due to continued accumulation of pollutants in sediments (Luoma & Rainbow, 2008; Chapman et al., 1998).

3.3 Biological Impacts

Bioassays show that contaminants cause dose-dependent toxic effects, including increase in mortality and impaired reproduction in *Daphnia magna* and zebrafish embryos (Brun et al., 2016). Reports show a reduction in algal growth, leading to decrease in primary productivity (OECD, 2011; Newman, 2019). Metals move through different trophic levels through bioaccumulation, and impact the structure and functioning of aquatic food webs (Luoma & Rainbow, 2008). Prolonged exposure

alters the structure of aquatic communities leading to decline in biodiversity (Newman, 2019).

3.4 Ecosystem Implications

Contamination changes the species composition by favouring more tolerant species (Newman, 2019). This shift results in the declination of species richness and abundance in freshwater systems (Clements & Newman, 2002). Ecosystem functions and services, like nutrient cycling, water purification, and the availability of habitats for aquatic organisms are adversely affected by these alternations (Newman, 2019).

4. Conclusion

Development of less toxic or non-toxic photovoltaic materials can reduce the environmental hazards (Weckend et al., 2016; Nain & Kumar, 2022). The containment and recovery of hazardous substances should be done with advances in recycling and disposal technologies. Integration of chemical, biological, and ecological information can improve the environmental risk assessment, and management (Weckend et al., 2016).

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