Hazardous Chemical Constituents of Photovoltaic Waste: Challenges and Sustainable Management in Bangladesh

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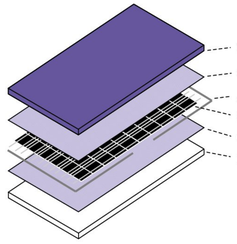
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Objective

This study investigates the chemical composition of end-of-life photovoltaic (PV) panels. It focuses on hazardous substances such as Pb, Cd, Sb and halogenated polymers. The study evaluates the physical and chemical behavior, leaching potential, exposure pathways, and toxicological risk of these substances under typical disposal and dismantling scenarios. The research also looks at green and sustainable chemical management strategies, such as bioleaching, chelation, solid-state stabilization, and low-emission thermal delamination, to detoxify or selectively recover individual toxicants. Additionally, it examines the feasibility of using circular chemistry principles and material substitution, like lead-free solders and non-toxic encapsulants, in PV design. The main goal is to create a chemistry-based framework for assessing exposure risks and managing PV waste safely and efficiently in Bangladesh.

Solar Cell Components



(a)

Chemical Species	PV Source	Leaching Concentration	Toxicological Risk	Reference
Pb^{2+} (Lead)	Solder, interconnects (c-Si, a-Si)	Up to **23.37 mg/L**; (acidic leachate)	Neurotoxicity, developmental delays, kidney damage	[1]
Cd^{2+} (Cadmium)	CdTe thin-film	Up to **1.86 mg/L**; nearly **100% release** at pH 3 (long-term)	Carcinogenic (Group 1), nephrotoxic, affects bone density	[2][3]
Sb^{3+} (Antimony)	Backsheet flame retardants (PET + Sb_2O_3)	**~0.2–0.5 mg/L** (estimated)	Endocrine disruption, genotoxicity	[4]
Cu^{2+} (Copper)	Interconnects, contacts	Up to **43.9 mg/L**	Gastrointestinal irritation, aquatic toxicity	[5]
Al^{3+} (Aluminum)	Frame, junction box	Up to **36.4 mg/L**	Neurotoxicity (long-term), soil pH alteration	[5]
Se (Selenium)	CdSe, CIGS layers	**~0.14 mg/L**	Liver/kidney toxicity, ecological bioaccumulation	[6]
Te (Tellurium)	CdTe layers	**~0.25 mg/L** (acidic conditions)	Toxic to aquatic organisms, bioaccumulative	[7]
Halogenated Polymers (PVF, PVDF)	Encapsulants, backsheets	Release **HF, dioxins, furans** upon burning or degradation	Persistent, toxic gases, endocrine disruption	[8]
Ag⁺ (Silver)	Front contact (metal paste)	Minor leaching (~0.1 mg/L) under standard test	Antimicrobial, may disrupt microbiota in soil/water	[9]

(b)

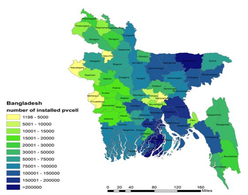
Fig 1. **(a)** Structural Components of a PV Panel **(b)** Associated Toxic Elements

Modern photovoltaic (PV) modules, particularly crystalline silicon-based cells, are multi-layered composite devices comprising both inert and potentially hazardous materials. The main structural components include tempered glass (~70–75% wt), aluminum alloy frame (~6–10% wt), polymeric encapsulants such as ethylene-vinyl acetate (EVA) (~10% wt), and a polymeric backsheet (e.g., PET, PVDF). The active layer typically consists of doped monocrystalline or polycrystalline silicon (~3–5% wt) with surface coatings like SiNx and TiO_2 as anti-reflective layers. Conductive elements include silver (~0.1–0.3% wt) in front contacts and aluminum (~1% wt) in back contacts. Trace dopants such as boron (B) and phosphorus (P) are introduced at ppm or μg/cm² levels to create p–n junctions.

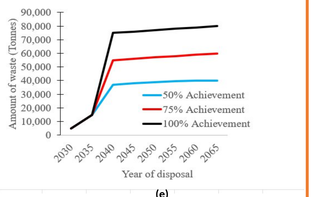
Prospective Analysis of PV Waste in Bangladesh



(c)



(d)

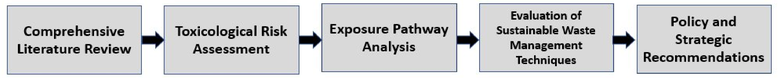


(e)

Fig 2. **(d)** Installed solar panels in Bangladesh; **(e)** Future projection of solar waste in tonnes.

Bangladesh's increasing use of photovoltaic (PV) systems is expected to reach 41 MT by 2041. This situation raises serious concerns because discarded panels release toxic ions like **Pb^{2+}**, **Cd^{2+}**, **Sb^{3} and halogenated polymers** due to improper disposal. Without adequate policy or public awareness, these substances leach into the environment, exceeding WHO safety limits (e.g., Pb^{2+} at 10 μg/L), posing long-term ecological and health risks. There is an urgent need for sustainable chemical management and targeted recycling strategies.

Methodology



Toxicological Risk Profiling

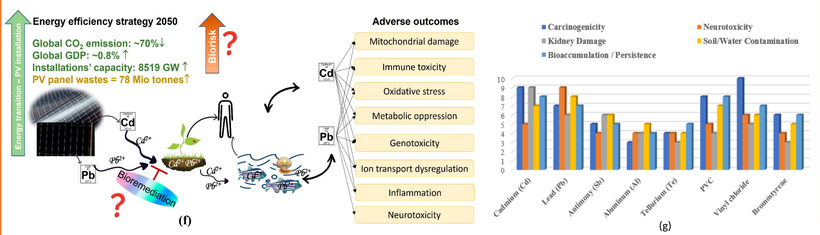


Fig 3. (f) *Cd and Pb release pathways from solar panels.* **(g)** *Toxicity comparison of PV waste chemicals (scale 1–10).*

Cd^{2+}, Pb^{2+}, and Sb^{3+}, along with halogen ions like Br^- and Cl^- from PVC, pose serious health and environmental threats. These ions can damage DNA, disrupt enzymes, and trigger neurotoxicity, organ damage, or respiratory issues. On heating, halogens may form toxic dioxins, raising long-term pollution risks. Safer ionic alternatives and better PV waste strategies are urgently needed.

Sustainable Material Recovery Technique

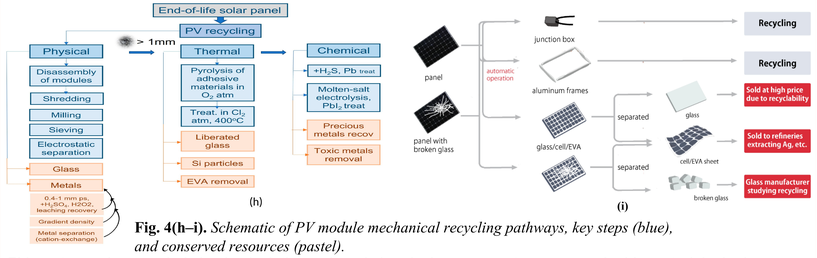


Fig. 4(h–i). *Schematic of PV module mechanical recycling pathways, key steps (blue), and conserved resources (pastel).*

PV waste can be recycled via physical, thermal, and chemical processes to recover valuable materials. Ionic species such as Ag^+, Pb^{2+}, Cd^{2+}, and Sb^{3+} are extracted through leaching and oxidative treatments. Si, glass, and metals are efficiently separated, while EVA removal and detoxification of hazardous ions ensure environmental safety and promote material reuse.

Table.1

Process	Mechanism	Target Metals	Use Stage	Notes / Reference
Bioleaching	Microbial oxidation & solubilization	Cd, Te, Pb, Sb	Detoxification	Eco-friendly, slow [1]
Chelation	Metal complexation by ligands (e.g., EDTA)	Pb, Cd, Sb	Extraction or stabilization	Selective, waste risk [2]
Solid Stabilization	Immobilization in solid matrices	Pb, Cd, Sb	Final containment	No recovery, stable [3]
Thermal Delamination	Heat-based layer separation	Si, Ag, Al, CdTe	Material recovery	Efficient, needs control [4,5]

Table.2

Toxic Component (Formula)	Sustainable Alternative (Formula)	Global Warming Potential (kg CO_2-eq/kg)
Lead Halide Perovskite ($CH_3NH_3PbI_3$)	Tin Halide Perovskite ($CH_3NH_3SnI_3$)[1]	4.5–6.0 (Pb) [2] 3.5–4.0 (Sn) [3]
Cadmium Telluride (CdTe)	Kesterite (Cu_2ZnSnS_4)[4]	6.0–10.0 (CdTe) [5] 2.5–3.5 (CZTS) [6]
Lead–Tin Solder (Pb–Sn)	Bismuth-based Solder / Conductive Adhesives[7]	5.5–6.5 (Pb–Sn) [7] 3.5–4.5 (Bi solder) [7]
Ethylene–Vinyl Acetate ($(C_4H_6O_2)_n$)	Polyolefin Elastomers ($(C_2H_4)_n$–$(C_4H_8)_n$)[8]	2.5–3.0 (EVA) [8] 1.8–2.2 (POE) [8]
Antimony Sulfide (Sb_2S_3)	Bismuth Sulfide (Bi_2S_3) [9]	4.0–4.5 (Sb_2S_3) [9] 2.5–3.5 (Bi_2S_3) [9]

Table 1–2. Sustainable PV recovery and redesign (Table 1) and alternatives to toxic components with GWP values (Table 2).

Toxic metals in PV waste (Cd^{2+}, Pb^{2+}, Sb^{3+}, Te^{2-}) are treated via bioleaching, chelation, solid stabilization, or thermal delamination to enable detoxification or recovery. Sustainable alternatives like Sn-based perovskites, kesterite, and bismuth compounds reduce environmental impact with lower GWP (1.8–6.5 kg CO_2-eq/kg).

Conclusion

- Identify hazardous ions like Cd^{2+}, Pb^{2+}, Sb^{3+}, and harmful halogenated compounds in PV waste.
- Understand their toxic effects on human health and the environment.
- Raise awareness among policymakers and stakeholders about these chemical risks.
- Develop and enforce regulations to control the handling, disposal, and recycling of PV waste.
- Ensure policies promote safer materials and sustainable waste management practices.

Recommendations

- Develop non-toxic, earth-abundant alternatives such as kesterite (Cu_2ZnSnS_4), perovskites free of Pb, and organic-inorganic hybrids with enhanced stability.
- Design halogen-free flame retardants and polymers to replace brominated/chlorinated compounds.
- Explore novel polymer matrices with superior thermal stability and minimal toxic degradation products.
- Investigate catalytic processes and bio-based methods for sustainable PV waste recycling.
- Conduct life cycle assessments (LCA) integrating chemical toxicity, resource depletion, and environmental impact for new materials.

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