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Feasible Strategies for Lead Recovery and Recycling from End-of-Life Perovskite Solar Cells Towards Environmentally Sustainable Technologies

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Abstract

Perovskite solar cells (PSCs) have emerged as one of the most promising next-generation photovoltaic (PV) technologies, offering high power conversion efficiencies (PCEs) and low fabrication costs. Despite these advantages, their short operational lifetime and the use of toxic lead (Pb) compounds remain major obstacles to industrial deployment. The limited stability of PSCs compared to conventional silicon solar cells reduces their economic viability, while the risk of lead leakage raises serious environmental concerns. Recycling PSCs not only addresses the risk of lead pollution but also enables the recovery and reuse of valuable materials, thereby lowering raw material costs and minimizing production waste. This paper reviews recycling strategies reported in recent studies and evaluates their effectiveness, cost benefits, and feasibility for large-scale industrial applications.

1. Introduction

In 2009, perovskite solar cells (PSCs) emerged as a promising solution for efficient and low-cost solar energy conversion technology with an initial power conversion efficiency (PCE) of 3.8% [1]. Hybrid organic-inorganic metal halide perovskite materials exhibit exceptional properties, including tunable band gap [2], large absorption coefficient [3], long carrier diffusion length [4], low exciton binding energy [5], high defect tolerance [6], and solution processability [7]. These attributes make them highly suitable for use in photovoltaic (PV) technologies as photoabsorber materials. According to the latest report from the National Renewable Energy Laboratory, the efficiency of single-junction PSCs has reached 27% [8]. This ranks PSCs alongside costly single-crystalline silicon solar cells, while outperforming multi-crystalline silicon solar cells and thin-film solar technologies such as cadmium telluride and copper indium gallium selenide based solar cells [8]. Solution process ability makes PSC manufacturing technology more cost-effective and provides the opportunity to print PSCs on flexible substrates, further extending its PV applications [9-11].

However, PSCs have not yet entered commercial markets. The critical challenges include poor material stability, short device lifetime [12], and the toxicity of Pb-based components in PSCs [13]. Intensive studies have been conducted focusing on improving the performance of PSCs [14-16]. It should be noted that Pb is essential for achieving high PCE in metal halide PSCs, yet it is also a highly hazardous material [17], whereas lead free alternatives still lag in both performance and stability [9, 10, 18, 19]. In addition, although PSCs are considered more cost-effective than conventional silicon solar cells, their fabrication still relies on expensive materials such as gold (Au), silver (Ag), and transparent conductive oxides (TCOs), including indium-doped tin oxide (ITO) and fluorine-doped tin oxide (FTO), which are used as front and back electrodes. With successful commercialization, usage of these valuable materials will be

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significantly increased. For end-of-life devices, development of effective recycling methods is urgently required [9, 10, 20]. The most common recycling strategy is layer-by-layer disassembly of the device, involving delamination of the encapsulating material, mechanical removal of electrodes (e.g., using tape), and selective dissolution of active, carrier transport and interfacial layers, until only the glass or TCO-coated glass remains. However, this process is manual, non-scalable, and economically unviable.

Recent developments have focused on introducing scalable methods and enabling solvent or material reuse. In this paper, existing recycling approaches and their effectiveness, feasibility, ecological footprint, and scalability are reviewed and evaluated. Then, the efficiency of lead extraction is assessed and the corresponding PCEs of recycled devices are compared with original devices. The analysis confirms that recycling offers ecological benefits by reducing toxic waste, supports commercialization by complying with international lead regulations, and provides economic advantages by recovering valuable components and reducing payback time.

2. Critical Materials in PSCs

Life Cycle Assessment (LCA), a common tool for evaluating environmental impacts [21, 22], conducted by Celik et al. [23] has shown that the environmental impacts from manufacturing of PSCs are lower than that of monocrystalline Si PVs. Billen et al. [24] found that if PSCs were to meet the electricity demand of the United States, their total Pb usage would remain significantly lower than the annual emissions from automotive and aviation sources. Furthermore, over a 20-year operational period, the toxicity potential of PSCs is estimated to be nearly 20 times lower than that of conventional grid electricity [24]. Compared with other Pb-containing products, the toxicity risk of PSCs during their operational lifetime is considered relatively minimal [25]. Nevertheless, Pb remains a highly hazardous substance. It is carcinogenic and can enter the human body through ingestion, inhalation, or skin contact, disrupting enzymatic and receptor functions and leading to heavy metal poisoning, particularly in breastfed infants [17]. The short operational lifetime of PSCs introduces an additional concern, as frequent large-scale disposal at end-of-life increases the risk of environmental contamination, underscoring the urgent need for effective recycling and recovery technologies. Although Sn-based PSCs have been developed as an alternative to Pb-based devices, they continue to suffer from reduced PCE and stability [26]. Beyond the toxicity concerns of Pb in the perovskite absorber, the sustainability of other critical materials used in PSC architectures must also be considered. Indium (In) and tin (Sn) are key elements in the production of TCOs, and both are classified as critical materials due to their limited availability [27]. ITO is the most widely used TCO, while FTO serves as an alternative that provides comparable performance without significant loss of stability. However, Sn also faces supply constraints and limited substitution potential [28, 29] which may pose challenges for the large-scale deployment of PSC technologies. Furthermore, the metals commonly used in the back electrode of PSCs, including gold (Au), silver (Ag), aluminum (Al), and nickel (Ni) are not only costly but also heavily utilized across various industries [30]. As PSC commercialization is accelerated, ensuring a stable supply chain of raw materials becomes more important.

3. Recycling and recovery

Recycling plays an important role in reducing environmental and health hazards while enabling the reuse of valuable materials used in PSC production. Transparent conductive oxides (TCO) substrates, owing to their stability and reusability, are particularly well-suited for recycling. In contrast, perovskite and its lead-containing derivatives require careful recycling due to associated environmental and biological risks. The recovery of metals employed as top electrodes, especially Au and Ag, is also a key priority within the circular economy framework. This section discusses methods for dissolving active layers, extracting lead, and recycling or recovering TCO substrates and metallic electrodes.

3.1. Dissolution of the active layers

Different solvents are used to dissolve perovskite active layers and separate the components during PSC recycling. Table 1 summarizes the key properties of commonly employed solvents. N,N-dimethylformamide (DMF) is a widely used solvent for dissolving the perovskite active layer during recycling. In general, the selection of solvents for chemical lead separation is guided by their intrinsic physicochemical properties, such as dielectric constant, Mayer bond order, and Gutmann donor number. These properties exhibit a significant correlation with the ability of solvents to coordinate with lead halide salt, thereby forming lead-solvent complexes. In a conventional solution preparation procedure, the perovskite pre-

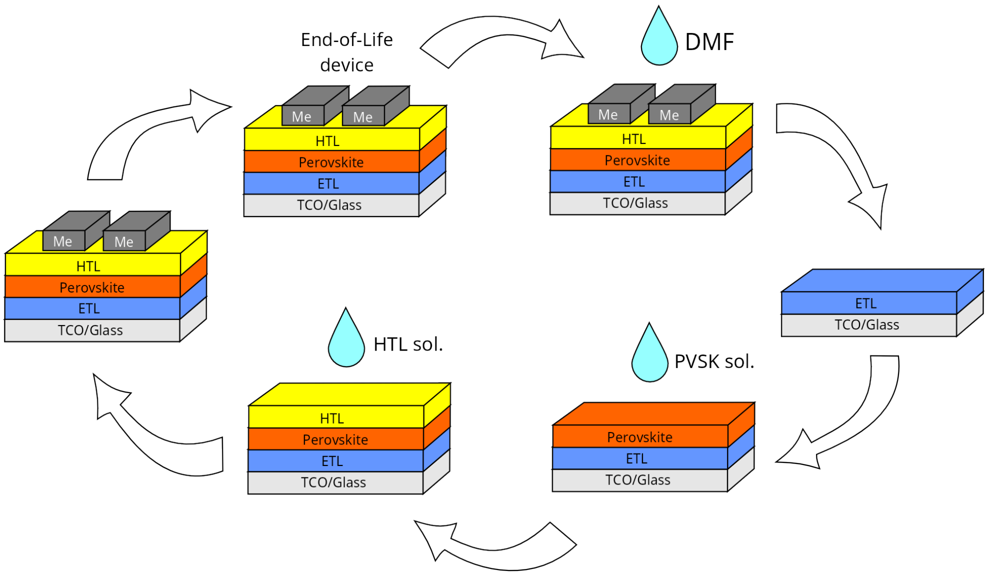

Fig. 1. Schematic illustration of PSC recycling via dissolution of active layers.

cursor solution is prepared using a primary solvent like DMF and a secondary solvent such as dimethyl sulfoxide (DMSO), in a predetermined molar ratio [31]. Figure 1 schematically represents typical end-of-life PSC recycling via dissolution of active layers and reusing of expensive TCO and electron transport layers (ETLs). Polar aprotic solvents are commonly used in PSC fabrication due to their ability to form strong interactions with metal halides. In particular, PbI_2 interacts with DMF through a Pb–O bond, leading to the formation of a PbI_2–DMF complex. The resonance structure of DMF enhances its Lewis basicity at the carbonyl oxygen, enabling coordination with cations such as Pb^{2+} and thereby increasing the solubility of PbI_2 in DMF [32]. DMF also demonstrates high lead-absorption efficiency and high Pb-release ratio, a crucial factor for sufficient lead extraction [33]. After Pb-containing compounds are dissolved, degraded solar cells can be rendered safe for disposal or prepared for recycling. However, the resulting Pb-contaminated DMF requires additional lead separation to minimize environmental impact and enable potential solvent reuse.

A study by Kim et al. [34] demonstrated solvent reuse after lead dissolution in a two-step process using chlorobenzene for spiro-OMeTAD and DMF to recover PbI_2. Hematite nanoparticles were employed to filter lead from DMF. The recycled DMF was reused to fabricate PSCs, achieving a PCE of 25.02%, which was comparable to the 25.12% efficiency of the control PSCs. Chen et al. [33] demonstrated an efficient recycling approach in which Pb-containing DMF from decommissioned PSC modules was purified using a weakly acidic cation-exchange resin. Lead was recovered as soluble $Pb(NO_3)_2$ and subsequently precipitated as reusable PbI_2, achieving a recycling efficiency of 99.2%. In parallel, thermal delamination allowed disassembly of encapsulated modules while preserving transparent conductors and cover glasses. Poll et al. [35] investigated deep eutectic solvents, a rapidly emerging class of ionic solvents with strong capabilities for dissolving metal oxides and salts, and with established use in metal electrodeposition [36]. Perovskite films were dissolved in a choline chloride/ethylene glycol solution, after which Pb was recovered through electrochemical extraction. The retrieved material exhibited high purity and was suitable for reuse in industrial applications. Reported extraction efficiencies reached 99.7% for $MAPbI_3$, 98.7% for $FAPbI_3$, and 99.8% for $MAPbI_{3-x}Cl_x$. This method offers straightforward scalability, as the authors estimated that one liter of deep eutectic solvents (DES) could process approximately 1 m^2 of hybrid organic–inorganic perovskite film. Ren et al. [37] introduced a low-toxicity route in which ethyl acetate is used to remove the HTL, followed by a quick water dip that decomposes the perovskite and water immersion that removes PbI_2. Zeolite is then applied to recover iodide and lead with strong Pb stabilization, achieving 96.5% iodide recovery. Recycled devices reached a champion efficiency of 21.58%. While promising, the method is presently demonstrated at lab scale and would benefit from process automation for industrial applications. Schmidt et al. [38] introduced water as a solvent, exploiting the temperature-dependent solubility of PbI_2. In this approach, PbI_2 dissolves in hot water and, upon cooling to room temperature, precipitates as a solid with 95.9% purity.

Table 1. Solvents used in PSC recycling: Safety classification, Impact and Cost (Sigma Aldrich)

Reagents	Toxicity		Cost (Euro per L)	Ref.
	Classification	Impact		
DMF	Acute toxicity (Cat. 4), Eye irritation (Cat. 2), Reproductive toxicity (Cat. 1B).	Harmful if inhaled. Harmful in contact with skin. Causes serious eye irritation. May damage the unborn child.	586	[32], [33], [38], [41], [42], [43]
Ethyl acetate	Eye irritation (Cat. 2), Specific target organ toxicity single exposure (Cat. 3).	Causes serious eye irritation. Central nervous system.	98.5	[37]
Nitric acid (HNO_3)	Acute toxicity, Inhalation (Cat. 3), Skin corrosion (Sub-Cat. 1A), Serious eye damage (Cat. 1).	Causes severe skin burns and eye damage. Toxic if inhaled.	66.30	[37]
Ethylene glycol	Acute toxicity, Oral (Cat. 4).	Harmful if swallowed. May cause damage to organs (Kidney) through prolonged or repeated exposure if swallowed.	94.60	[36]
Choline chloride	Not a hazardous substance or mixture according to Regulation (EC) No. 1272/2008.	N/A	190.39	[36]
DMSO	Not a hazardous substance or mixture according to Regulation (EC) No. 1272/2008.	N/A	271	[43]
Chloro-benzene	Flammable liquids (Cat. 3), Acute toxicity, Inhalation (Cat. 4) Skin irritation (Cat. 2), Hazardous to the aquatic environment (chronic) (Cat. 2).	Flammable liquid and vapour Harmful if in-haled. Causes skin irritation. Toxic to aquatic life with long lasting effects.	35.80	[38]

3.2 Lead Extraction

Lead recycling from PSCs typically proceeds in two stages: (i) dissolving the active layer separated from the device via solvents or thermal delamination, and (ii) extracting the Pb compounds [32]. Following extraction, the remaining device components are Pb free and can be reclassified as non-hazardous waste, while the recovered lead can be handled with minimal environmental impact. Reported recycling trials generally show a drop in device PCE. The extraction route influences the purity of the recovered lead, and additional processing (e.g., recrystallization [38]) could improve PbI_2 purity. Table 2 compares the PCEs of devices fabricated using recycled and commercial lead, showing a consistent performance loss that can be reduced by improving lead purity during recovery. Lead separation has been achieved via ion exchange [33, 36, 39-43], evaporation [43], particle adsorption [32, 37, 41-43], thermal precipitation [38], magnetic separation [42], centrifugation [41], and filtration [37].

Kim et al. [41] dissolved the perovskite layer in a polar aprotic solvent (e.g., DMF), which simultaneously facilitated the separation of Au electrodes. Lead removal then followed a two-step route: the DMF solution was poured into diethyl ether to precipitate Pb compounds and isolated by centrifugation, followed by hydroxyapatite (HAP) ion exchange to capture residual Pb^{2+} and a final centrifugation. This approach can extract 99.99% of PbI_2 from the solution. The authors additionally recovered the FTO glass and Au electrodes; after ten recycling cycles, the FTO substrates showed no measurable degradation, with conductivity remaining stable. Park et al. [42] developed a method to absorb trace amounts of lead dissolved in DMF. They employed Fe-decorated hydroxyapatite (Fe-HAP) solid particles to separate lead ions, purifying the toxic solvent to a lead concentration below the safe parts-per-billion (ppb) level. The Fe-HAP particles, bonded with lead, were magnetically removed, and 99.97% of the absorbed lead was recovered in the form of lead iodide. Devices made from recycled

Table 2. The comparison of device performance before and after lead recycling.

Perovskite Composition	Reference PCE (%)	Recycled PCE (%)	Lead Extraction Approach	Ref.
$Cs_{0.1}FA_{0.9}PbI_3$	21	20.4	Cation exchange with WAC-exchange resin. Mixing with $Pb(NO_3)_2$ to release PbI_2. Mixing with NaI to precipitate. Washing, collecting by centrifugation and drying under vacuum precipitate.	[33]
$FA_{0.90}Cs_{0.05}MA_{0.05}PbI_{2.85}Br_{0.15}$	25.12	25.02	Ion exchange with hematite nanoparticles	[34]
$FAPbI_3$	21.5	21.0	Ion exchange with Zeolite, filtration, mixing with $Pb(NO_3)_2$ to release PbI_2. Washing and drying the precipitate.	[37]
$MAPbI_3$	14.6	13.5	DMF removed under vacuum PbI_2 is recrystallized	[39]
$(FALI)_{0.85}(MAL\ Br)_{0.15}$	15.98	15.91	Centrifugation with diethyl ether and HAP powder ion exchange	[41]
Multiple cations mixed halides perovskite	16.65	16.04	Ion exchange with Fe-HAP nanoparticles, magnetic separation	[42]
$MAPbI_3$	16.63	15.30	Evaporation of lead-containing DMF:DMSO	[43]

lead were shown to have performance comparable to those using fresh materials. However, these encouraging results are not universal across studies. Binek et al. [39] did not achieve comparable results with recycled PbI_2. The devices made from recycled PbI_2 and FTO exhibited a lower PCE compared to the control devices. The study attributed the decrease in PCE to potential impurities in the recycled PbI_2 solution. The impurities can be mitigated via the recrystallization of PbI_2. Deng et al. [43] recovered PbI_2 from $MAPbI_3$ and $CsPbI_2Br$ by first mechanically removing the carbon electrode and then dissolving the active layers in a DMF/DMSO mixture. The dissolved PbI_2 was retrieved by solvent evaporation, while the evaporated solvent was captured in an activated-carbon unit. Chhilar et al. [44] created a method for directly recycling solar cells, skipping steps of dissolution and extraction of lead. Unlike methods focusing on PbI_2 disposal or re-purpose, they applied methylammonium iodide (MAI) solutions directly onto degraded perovskite films containing lead to regenerate the $MAPbI_3$ structure. The reapplication of MAI resulted in recycled films with similar X-ray diffraction and photoluminescence characteristics. The authors suggest that recycling with full conversion of PbI_2 into $MAPbI_3$ will enhance the device, potentially surpassing the performance of the original material.

3.3 Transparent conductive oxides

Since TCOs are one of the most expensive components of PSCs, developing effective strategies for recycling and reusing TCOs from decommissioned PSCs is crucial for improving economic viability. A groundbreaking study in 2016 first demonstrated that glass/FTO substrates from degraded PSCs could be successfully recycled and reused to fabricate efficient ETL-free PSCs [45]. In this process, DMF was used to selectively dissolve the perovskite and HTL from the device in a configuration of glass/FTO/$CH_3NH_3PbI_{3-x}Cl_x$/spiro-MeOTAD/Ag structures while preserving the glass/FTO substrate. The recovered substrates were then utilized to fabricate new PSC devices, which achieved PCEs of approximately 10%, comparable to the original devices. Building on this concept, a subsequent study expanded the approach to recover not only FTO but also the TiO_2 ETL from PSCs with a glass/FTO/compact- or mesoporous-TiO_2 (c-TiO_2 or m-TiO_2)/spiro-MeOTAD/Ag architecture. The recovered FTO/$_2$ substrates were then used to fabricate new planar and mesoporous PSCs: devices on substrates recycled twice achieved PCEs of 11.87% and 11.03%, which represent a noticeable reduction compared with fresh-substrate devices (14.08% and 14.79%), yet remain functional for further development [46]. Recycling efforts have been also extended to glass/ITO substrates from inverted planar PSCs (glass/ITO/PEDOT:PSS/$MAPbI_3$/$PC_{60}BM$/Ca/Al). Using a potassium hydroxide (KOH) solution treatment, researchers successfully recovered ITO substrates with transmittance and electrical uniformity comparable to the original. In addition, the treatment enhanced the wettability of the ITO surface, improving layer adhesion and increasing device PCE [47]. Furthermore, DMF has been employed to recycle FTO/TiO_2 substrates from carbon-based, all-inorganic PSCs with an architecture of glass/FTO/TiO_2/$CsPbIBr_2$/carbon. The recycled FTO/TiO_2 substrates retained their optical and electrical characteristics, while residual $CsPbIBr_2$-derived species on the surface helped suppress halide phase separation and minimize defects in the upper $CsPbIBr_2$ film. As a result, the average PCE improved by approximately 25%, increasing from 6.51 ± 0.62% to 8.14 ± 0.63%, with the highest performing cell reaching a PCE of 9.12% [48].

3.4 Metals

Gold is a highly conductive and chemically stable noble metal, making it a widely used material for the top electrodes of PSCs. The Au content in decommissioned PSC electrodes could be significantly higher than that found in natural ore deposits, which typically contain only a few grams of metal per ton. Compared to the extraction and refining of new metal materials, recycling Au electrodes offers substantial environmental benefits by reducing energy consumption and minimizing environmental impact.

Yang et al. [49] had demonstrated the method that makes recycling of gold electrodes feasible. They developed nanoporous Au film with high electrical conductivity and a large specific surface area. Instead of relying on the conventional energy-intensive vacuum vapor deposition process, they introduced a more energy-efficient membrane transfer method for assembling Au electrodes in PSCs. The recycling process involves immersing the used PSCs in acetone to dissolve the perovskite and HTL, allowing the nanoporous Au film to detach and float. The recovered film is then transferred onto a membrane surface, washed five times with acetone, and dried before being reused as a top electrode. While the sheet resistance slightly increases with repeated use, PCE exhibited only a minor decline after 12 cycles of reuse. This breakthrough enables continuous Au electrode recycling, significantly reducing material costs while preserving valuable metal resources.

In addition, researchers have explored special structured PSCs that allow for partial recycling, where only the degraded perovskite layer is replaced while retaining other components. For instance, Ku et al. [50] successfully recycled and reused FTO/TiO_2/Al_2O_3/Ni electrodes in printable PSCs by repeatedly cleaning and recasting the perovskite layer. Under AM1.5 standard illumination, the recycled electrode-based devices achieved an efficiency of 12.1%, slightly lower than the control sample of 13.6%. Similarly, Li et al. [51] employed DMF cleaning to recycle FTO/ TiO_2/Al_2O_3/Au:NiO_x electrodes, refilling them with fresh perovskite. Devices using once- and twice-recycled electrodes achieved efficiencies of 8.17% and 7.72%, respectively, which remained comparable to those based on new electrodes. This research highlights the feasibility of recycling all PSC materials in addition to perovskite, offering a sustainable approach to PSC manufacturing and end-of-life management.

4. Cost Effectiveness

Although Pb is the most toxic component in PSCs, its recycling is a priority for environmental reasons, whereas recycling of such expensive materials like TCOs, electron-, hole transport layers and rare metal contact has cost-saving benefits. Since 2012, PV panels have been included in waste electrical and electronic equipment (WEEE) regulation, making the disposal or recycling the responsibility of producers [52]. Recycling is a method to avoid disposal costs. Recycling of glass, gold electrodes and TCO-substrates can significantly lower both the price and environmental impact. The production of TCO/ETL substrates from raw materials involves high costs and significant environmental impacts [39], making the recycling and reuse of these substrates an important strategy for both economic and environmental sustainability. At present, reusing highly pure glass substrates from silicon-based PV waste panels is difficult due to the challenge of removing the silicon absorber layers [53]. In contrast, perovskite absorber layers can be easily removed through dissolution in DMF, offering a promising approach for industrial-scale recycling and reuse of TCO/ETL substrates from PSCs.

To date, many existing recycling methods for PSCs remain laboratory-scale, involve toxic solvents like DMF, and require intensive material and energy inputs. There are multiple requirements constituting a cost effective and environmentally friendly method that could fit industrial application. For example, Park et al. [42] developed a lead recycling method that uses a green, adsorbent Fe-doped hydroxyapatite

(HAP/Fe). Their process not only enables nearly complete lead recovery (99.97%) but also allows the retrieval of valuable glass substrates. However, a technoeconomic analysis by Oh et al. [54] revealed that the process is not economically viable in its current form. The major cost driver was the high consumption of both DMF solvent and HAP/Fe adsorbent, especially since HAP/Fe cannot be collected after it dissolves. Additionally, the method involves energy-intensive thermal delamination, further increasing operational costs. As a result, despite its high effectiveness, the method lacks cost-efficiency for industrial-scale application without further optimization.

Scalability is a key factor in evaluating the viability of recycling methods. On laboratory scale, procedures like scraping off electrodes or removing them with scotch tape are not problematic and used for the proof-of-concept. In large-scale operations, methods that minimize or eliminate manual labor are far more favorable. Most recycling processes rely on solvents, the process of transporting cells from one solvent, rinsing them, and placing them in other solvents would require significant processing inputs, leading to increased expenses for the recycling companies. Therefore, potential for industrial applications is a major factor in cost assessment. The water-assisted lead recovery suggested by Schmidt et al. [38] has simple preprocessing, which is applicable to large-scale processing. However, a major drawback is the destruction of the conductive glass during the process. While the cleaned glass shards can be used for new glass production, this adds to the overall cost. Still, this solution provides a temporary cost saving measure, reducing disposal expenses by approximately 18.3 USD/m^2.

Another advantage of Schmidt et al. [38] proposed approach is usage of water over toxic DMF. Using DMF on a commercial scale requires costly safety measures and proper disposal, which also drives up the price. Therefore, methods developing on alternative solvents holds high interest. Ethyl acetate-based strategy proposed by Ren et al. [37] has low environmental impact, however, it involves manual-intensive processes. Despite this, total cost of recycling PbI_2 is 269.4 USD/kg in laboratory settings, significantly lower than 950 USD for 99% pure commercial PbI_2. If processes such as removing electrodes and scraping off PbI_2 are scaled up successfully, the cost of recycling PbI_2 will decrease even more, as chemicals are cheaper on an industrial scale. Poll et al. [35] DES method utilizes low-cost, non-toxic chemicals and maintains its efficiency even as the number of recycled cells increases, indicating strong potential for scalability. However, it does not address the recycling of TCOs, which is a major cost-saving point, and electrodeposition of lead from solvent is a long energy-exhausting process, lasting for 120 hours.

In addition to substituting toxic solvents, minimizing consumed material through solvent reuse is an important challenge. High solvent consumption drives up both price and environmental impact. This was demonstrated by comparing the unit treatment costs [54] of discarded PSCs across the methods pro-posed by Park et al. [42], Chen et. al. [33], and Schmidt et al. [38]. According to the technoeconomic assessment, Chen et. al. [33] and Schmidt et al. [38] achieved the lowest unit treatment costs of discarded PSCs at 2.54 USD/m^2 and 2.48 USD/m^2, respectively, compared to 447.07 USD/m^2 for Park et al. [42] High cost of approach proposed by Park et al. [42] is caused by high material consumption. WAC-resin-based method allows DMF reusing for up to five times, making the cost cheaper [33]. Kim et al. [34] also demonstrated that DMF can be reused in precursor preparation without compromising device efficiency, helping to control solvent costs during recycling.

5. Conclusion

The recycling of PSCs is essential for both environmental sustainability and economic feasibility. Effective Pb extraction and recovery are essential to manage environmental and health risks. Recycling other high-value components including TCO substrates, electron/hole transport layers, and rare metal contacts have demonstrated potential to significantly lower both environmental impact and manufacturing costs. However, many of these processes remain at the laboratory scale, relying on toxic solvents such as DMF and requiring significant material and energy inputs, which hinder industrial adoption. A key challenge in upscaling recycling methods is achieving cost-effectiveness while maintaining high material purity. Solvent-based recycling, such as DMF dissolution, enables effective perovskite removal but incurs high operational costs and safety concerns. Alternative approaches, including water-assisted lead recovery and ethyl acetate-based methods, offer improved environmental compatibility but often involve intensive manual processes or suffer from low scalability. Strategies incorporating DES show promise due to their low toxicity and cost but still require optimization to decrease energy consumption and fit high-throughput industrial applications. Future work should focus on optimizing recycling processes for minimal material consumption, solvent reuse, and automation will be critical for large-scale implementation. The development of alternative, non-toxic solvents and energy-efficient lead recovery techniques will enhance the sustainability of PSC recycling. In addition, integrating scalable device designs that facilitate easy material separation can further streamline recycling efforts. Collaborative efforts among researchers, policymakers, and industry players are essential to establish standardized recycling protocols and promote the commercialization of sustainable PSC recycling technologies. Future advancements in automation and solvent recovery will play a crucial role in making PSC recycling a viable component of a circular economy.

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