Environmental impacts of photovoltaic module recycling: technologies, carbon footprint and sustainability aspects

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Abstract. This review examines the environmental impacts associated with the recycling of photovoltaic (PV) modules based solely on published scientific literature. The analysis summarizes the results of life cycle assessment (LCA) studies for c-Si, CdTe, CIGS, and recently developed perovskite technologies. Key indicators such as carbon footprint, emissions, energy consumption, material recovery rates, and avoided impacts are evaluated. The results from the literature demonstrate significant variations due to differences in recycling routes, technological conditions, and system boundaries. High-purity recovery processes are typically associated with lower environmental impacts, while some thermal or chemical treatments may generate additional impacts, particularly when energy-intensive or involving heavy use of reagents. The review evaluates the role of the EU WEEE Directive in guiding recycling practices and reporting requirements. In general, available data indicates that the recycling of PV modules provides environmental benefits, but more consistent and widespread information is needed to support reliable and comparable conclusions.

1 Introduction

The rapid global expansion of photovoltaic (PV) installations over the past two decades is expected to generate a substantial volume of end-of-life (EoL) modules beginning in the early 2030s, with global PV waste projected to exceed 70–80 million tons by 2050, dominated by crystalline silicon (c-Si) technologies [1]. This growing waste stream poses a dual challenge: on the one hand, EoL modules contain complex composite materials such as glass, aluminum, polymers, and, in some cases, hazardous metals (e.g., Cd, Pb-based solder or back-sheet fluorides), raising concerns about landfill pressure and local contamination if not adequately managed [2]; on the other hand, the same waste stream represents a significant resource opportunity for recovering high-value materials such as silicon, silver, indium, and aluminum, which can be fed back into PV manufacturing and other sectors, supporting a circular economy [1, 3].

From an environmental perspective, poorly designed collection and treatment systems risk undermining the overall sustainability of PV technologies by locking in long-term

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disposal of mixed hazardous and non-hazardous materials, increasing secondary emissions and soil–water impacts [2 ,4]. Conversely, well-designed recycling routes can reduce primary resource extraction, lower associated energy demand and carbon emissions, and improve the net environmental performance of PV systems over their full life cycle [3, 5]. However, the extent and magnitude of these benefits are highly sensitive to the choice of recycling technology, system boundaries, and local infrastructure conditions, making comparative assessment essential for evidence-based policy and investment decisions [4, 6].

Regulatory frameworks, especially the EU Waste Electrical and Electronic Equipment (WEEE) Directive, are acting as a key driver shaping the design, scale, and reporting of PV recycling systems by establishing minimum collection, recovery, and recycling targets and mandating extended producer responsibility (EPR) along the value chain [7, 8]. Despite these developments, the existing literature on environmental impacts of PV recycling remains fragmented: most comparative LCA studies focus narrowly on c-Si modules and particular technological routes, without systematically addressing CdTe, CIGS, and emerging perovskite-based technologies under consistent methodological and boundary conditions [3, 5, 9]. Moreover, there is limited integration of recycling performance with operational strategies that extend PV lifetime—such as maintenance and cleaning practices—meaning that current analyses often isolate end-of-life recovery from in-use resource efficiency [6]. This research gap emphasizes the need for a literature-based, cross-technology, comparative LCA–oriented review that explicitly links recycling pathways, environmental indicators (carbon footprint, energy demand, hazardous emissions, material recovery), and policy-driven EPR mechanisms to support more robust and generalizable conclusions on the sustainability of PV recycling.

2 Photovoltaic technologies and recycling approaches: overview

2.1 PV technology types and end-of-life recycling workflow

Crystalline silicon (c-Si) technologies dominate the global PV market, accounting for approximately 90–95% of installed capacity due to their high efficiency, mature manufacturing base, and well-established supply chains [1, 10]. These modules, mainly mono- and multi-crystalline silicon variants, are built from glass superstrates, EVA encapsulants, silicon cells, metal interconnects, and polymer back sheets, which makes them the primary target of current recycling efforts [6, 9]. As a result, c-Si modules are expected to generate the largest share of end-of-life (EoL) waste, with projections exceeding 70 million tonnes by 2050 [1, 2].

Thin-film technologies, particularly cadmium telluride (CdTe) and copper indium gallium selenide (CIGS), represent around 5–10% of the market and are valued for building-integrated PV applications [6, 10], low-light performance, and lightweight systems. At the same time, CdTe modules contain hazardous cadmium and tellurium, while CIGS relies on scarce indium and gallium, which makes specialized recovery routes important for both environmental protection and critical material supply [5]. Emerging perovskite and tandem perovskite-silicon technologies remain at an early stage of commercialization, with market shares below 1%, but they are developing rapidly and already show efficiency above 25%; however, their long-term stability and recyclability remain uncertain because of organic halides and complex multilayer structures [9].

The standard recycling workflow begins with collection and dismantling, during which modules are manually or robotically disassembled to remove aluminium frames, junction boxes, cables, and bypass diodes, producing cleaner laminate feedstock [1, 6, 11]. This stage aligns with WEEE preparatory treatment requirements and reduces the complexity of mixed-waste processing [7, 8]. The next key step is delamination, where the glass-EVA-cell-backsheet laminate is separated through mechanical shredding, thermal pyrolysis, chemical solvents, or advanced electrothermal impulses [11, 12]. Mechanical routes rely on size reduction and physical separation, thermal routes remove polymers by volatilization, and chemical routes focus on EVA dissolution and selective component release [6, 9].

Material recovery then yields glass, aluminium, silicon, silver, and polymers, while additional refining enables potential closed-loop reuse [1, 3]. Reported recovery rates are generally high for glass and aluminium, while silicon and precious metals require more advanced processing to achieve higher purity (Table 1). Hybrid routes, which combine several treatment stages, can exceed 95% mass recovery and are especially relevant for more complex module designs, including thin-film technologies where Cd and Te extraction is a priority [5].

Table 1. Comparative evaluation of recycling routes (literature-based ranges).

Method	Recovery efficiency (%)	Cost per panel (USD)	Material purity	Key advantages	Limitations
Mechanical	70–90 (glass/Al)	10–20	Low (Si/Ag)	Low cost, simple [1]	Downcycling, EVA contamination [6]
Thermal	85–98	20–40	Medium	Polymer removal, scalable [12]	Emissions (HF), energy use [11]
Chemical	>96 (Si/Ag)	40–80	High	Virgin-grade outputs [3]	Wastewaters, slow [13]
Hybrid	~99	30–60	Very high	Optimal yield/purity [4]	Complex integration [9]

Recycling methods can be grouped into four main categories. Mechanical methods use shredding, sieving, magnetic and electrostatic separation, and optical sorting; they are low-cost and effective for glass and aluminium recovery, but they usually produce low-purity silicon and metal fractions that are difficult to reuse directly [1, 2, 6]. Thermal methods, including pyrolysis, incineration, and flash Joule heating, provide efficient polymer removal and clean glass-silicon separation, but they are energy-intensive and may generate harmful emissions such as HF from fluoropolymer-containing backsheets [11, 12]. Energy intensity ($20–40/panel) is offset by scalability [9]. Chemical methods use solvents, acids, alkalis, or deep eutectic solvents to dissolve encapsulants and leach metals, achieving very high purity but at higher cost ($40–80/panel) and with greater liquid waste generation [3]. Hybrid methods integrate mechanical pre-treatment with thermal or chemical refinement, and they currently offer the best compromise between yield, purity, and scalability for industrial implementation [4, 9, 11].

Overall, mechanical routes are best suited for high-volume recovery of glass and aluminium, thermal methods excel in delamination speed, chemical methods maximize material value but are environmentally more intensive, and hybrid systems provide the strongest balance between efficiency and circularity [1, 6, 9]. The most suitable route depends on module type, local regulatory conditions, and the chosen LCA boundaries [2], which strongly affect the interpretation of environmental performance.

2.2 Classification of recycling methods by separation mechanism and selectivity

To supplement the conventional taxonomy of mechanical, thermal, chemical and hybrid recycling routes, we propose an alternative classification that organises recycling technologies according to their dominant separation mechanism and the resulting level of material selectivity. This classification highlights the technical logic that governs process choice, clarifies trade-offs between throughput, purity and environmental burden, and facilitates comparison of methods by their suitability for specific module architectures (c-Si, CdTe, CIGS, tandem/perovskite). The five classes are described below and summarised in Table 2.

Table 2. Classification of PV recycling methods by dominant separation mechanism and selectivity (advantages and disadvantages).

Class	Dominant mechanism/ criterion	Representative examples	Advantages	Disadvantages
Direct physical separation routes	Physical fractionation by size/density/ magnetism/optics	Shredding, sieving, gravity/air separators, magnetic/electrostatic, optical sorting	Low cost; high throughput; simple operations; effective bulk recovery of glass and Al	Low Si/Ag purity; EVA contamination; down-cycling risk; limited closed-loop reuse
Thermally assisted debonding routes	Heat or rapid thermal impulse to decompose/soften encapsulant	Pyrolysis, incineration, flash Joule heating, electrothermal impulses	Fast delamination; effective polymer removal; improves access to cells/metals	High energy demand; hazardous emissions (HF) from fluoropolymers; gas-cleaning required; possible material damage
Selective dissolution routes	Chemical solubilisation of encapsulant or targeted leaching	Organic solvents, acids/alkalis, deep eutectic solvents (DES)	High selectivity and product purity; potential for direct remanufacture of Si/Ag	Higher operational cost; liquid waste generation and treatment; slower throughput
Integrated multi stage routes	Sequenced combination of separation principles	Mechanical pre-treatment + thermal/chemical refinement; FRELP	Maximises recovery and purity; adaptable; enables closed-loop recycling	Complex integration; high CAPEX/OPEX; LCA outcomes sensitive to configuration and energy mix
Design specific recovery routes	Tailored flows based on module type and materials	CdTe-specific Te recovery; CIGS-specific In/Ga recovery; perovskite-tailored delamination	Improved selectivity for critical/ hazardous materials; better economic fit per feedstock	Requires segregation and feedstock characterisation; low standardisation; potential scaling challenges

Direct physical separation routes – These methods rely on mechanical size reduction and physicochemical sorting (shredding, sieving, density/gravity separation, magnetic and electrostatic separation, optical sorting) to fractionate laminate components without substantive chemical or thermal transformation of the polymeric encapsulant. Advantages include low capital and operating cost, high throughput and straightforward process control, which make them well suited to bulk recovery of glass and aluminium. Limitations are the generally low purity of silicon and precious-metal fractions, contamination by EVA residues, and consequent propensity for down-cycling rather than closed-loop reuse.

Thermally assisted debonding routes – Delamination is achieved by heat-induced decomposition or rapid thermal impulses that weaken or volatilise encapsulants and backsheets (e.g. pyrolysis, flash Joule heating, electro-thermal impulses). These approaches enable rapid separation of glass, cells and metallisation and improve accessibility of internal components, supporting higher recovery yields for certain fractions. Their drawbacks include substantial energy demand, potential formation of hazardous gaseous species (notably HF from fluorinated backsheets) and the need for gas-cleaning systems to mitigate emissions; moreover, poorly controlled thermal treatment can damage sensitive materials, reducing their recovery value.

Selective dissolution routes – Processes in this class apply targeted solvents, reagent systems or novel green solvents (including deep eutectic solvents and advanced organic solvents) to selectively dissolve EVA or to leach specific metals, enabling high-purity recovery of silicon, silver and other valuable elements. Selective dissolution attains product qualities that are compatible with direct re-use or re-introduction into manufacturing streams, delivering high environmental and economic value per unit of material recovered. However, selective dissolution is typically more resource- and labour-intensive, produces aqueous or solvent wastes that require neutralisation and treatment, and entails higher operating costs and longer processing times.

Integrated multi-stage routes – This class groups process flows that intentionally combine two or more separation principles in a sequenced, optimised chain (e.g. mechanical pre-treatment followed by thermal delamination and chemical refining, or FRELP-style integrated plants). Integrated systems are designed to maximise overall mass recovery and product purity while minimising emissions and energy use through internal synergies. They represent the current state of the art for high-quality recycling, achieving mass recovery rates >95% in reported implementations and enabling closed-loop material flows for several fractions. The principal limitations are increased process complexity, higher capital expenditure, and the need for careful integration and control; life-cycle impacts depend strongly on plant configuration, energy sources and system boundaries.

Design-specific recovery routes – Rather than treating recycling as a universal sequence, this class advocates adaptation of the recycling pathway to the module architecture and material composition (for example, tailored flows for c-Si, CdTe, CIGS, or tandem/perovskite modules). Design-specific routes enable process optimisation for critical materials (e.g. Te recovery from CdTe, In/Ga recovery from CIGS, or selective removal of perovskite organic halides) and can improve selectivity and economic viability for targeted waste streams. The main constraints are the reduced standardisation of processes, the requirement for accurate feedstock characterisation, and potential logistical challenges linked to segregating diverse module types at scale.

Implementation of this classification in comparative assessments clarifies which technical levers control environmental performance (e.g. energy intensity of thermal steps, reagent consumption in selective dissolution, or transport/logistics for feedstock segregation) and supports stronger linkage between recycling technology, module design, and policy measures (such as EPR and WEEE reporting). Applying separation-mechanism classification in LCA studies improves interpretability by making explicit which physical or chemical transformations dominate environmental burdens and where process optimisation can yield the largest sustainability gains.

3 Environmental and carbon footprint assessment of PV recycling

3.1 Assessment framework and environmental indicators

Environmental assessment of PV module recycling is performed using a literature-based LCA framework, including energy and exergy analyses. To ensure consistency across the studies, a functional unit of 1 kg of end-of-life PV module was used. The framework makes a distinction between foreground processes (recycling operations) and background processes (electricity generation, chemical supply, and transportation), as these significantly influence environmental outcomes. In particular, the electricity mix and regional conditions are treated as key parameters, as they influence energy demand and carbon emissions.

To evaluate the environmental performance of PV module recycling, a set of key indicators commonly used in LCA studies is applied. Energy consumption is a key indicator, typically expressed in MJ/kg of processed PV modules, and reflects the intensity of recycling processes as well as their contribution to the overall environmental impact. In parallel, the environmental impacts associated with emissions are assessed using established LCIA methodologies such as ReCiPe and CML, as well as region-specific frameworks including TRACI and the ILCD, which include potential impacts on human health and ecosystems, including effects of toxicity, acidification, and eutrophication [14].

Indicators related to energy, emissions, and resource efficiency are assessed using metrics such as material recovery rates, purity, and potential for reuse. High recovery of valuable materials (e.g., aluminium, silicon, rare metals) improves environmental performance [2, 11]. The concept of avoided environmental impacts is also included by taking into account the substitution of primary raw materials with recycled secondary resources. This approach allows for the quantification of the environmental benefits associated with recycling by reducing the need for energy-intensive primary production processes [14]. Together, these indicators provide a comprehensive and consistent basis for comparing different recycling pathways for photovoltaic systems.

3.2 Carbon footprint assessment and interpretation

The carbon footprint of PV module recycling is primarily determined by the energy requirements of the process and the carbon intensity of the primary energy supply. Mechanical recycling methods exhibit the lowest CO_2 emissions due to their relatively low energy requirements, typically in the range of 0.1–1.0 kWh/kg, corresponding to 0.04–0.40 kg CO_2/kg PV under average electricity mixes. However, these processes are associated with limited recovery of high-value materials. In contrast, thermal recycling processes require significantly higher energy input, typically in the range of 1.5–5.0 kWh/kg, leading to CO_2 emissions of up to 2.0 kg CO_2/kg PV, particularly when fossil-based energy sources are used. [11, 12]. These values are derived from the ranges reported in the literature and are normalized to a unit mass of PV modules to ensure a consistent comparison across different studies.

Chemical recycling methods enable the recovery of high-purity materials, but their environmental performance remains highly dependent on process conditions. Reported energy requirements typically range between 2.0 and 8.0 kWh/kg, resulting in CO_2 emissions between 0.8–3.2 kg CO_2/kgPV, depending on reagent consumption and process efficiency

[6]. Hybrid recycling technologies, combining mechanical pretreatment with selective thermal or chemical steps, demonstrate improved overall performance. Recent studies report energy consumption in the range of 0.5–2.0 kWh/kg for hybrid recycling systems, reflecting improved efficiency compared to conventional processes [11]. Consequently, hybrid approaches often exhibit the lowest overall carbon footprint while maintaining high recovery efficiency. A comparative summary of the energy demand, carbon footprint, and overall performance of the main recycling technologies is presented in Table 1. The net energy balance represents the difference between the energy recovered through avoided primary material production and the energy consumed during recycling, expressed in kWh/kg.

Hybrid recycling approaches are often associated with improved recovery efficiency and a reduced overall environmental impact. However, reported energy consumption and carbon footprint values for hybrid recycling systems vary significantly across the literature. Values range widely from less than 0.1 kWh/kg in studies focused on individual process stages to over 2.0 kWh/kg when considering the full system boundaries, including pretreatment, separation, and post-treatment. The main reason for this wide range stems primarily from differences in system boundaries, as well as variations in process integration, operational scale, and the inclusion of auxiliary processing steps. As a result, direct comparison remains limited within the sequential LCA framework, therefore hybrid recycling is not included in Table 3.

Table 3. Comparative energy and carbon performance of PV recycling technologies (literature-based ranges and calculations).

Recycling process	**Energy demand (kWh/kg)**	**CO_2 emissions (kg CO_2/kg PV)**	**Material recovery**	**Net energy balance (kWh/kg)**
Mechanical	0.1–1.0	0.1–0.4	Low–moderate	+5 to +8
Thermal	1.5–5.0	0.6–2.0	Moderate	+3 to +10
Chemical	2.0–8.0	0.8–3.2	High (high purity)	+3 to +13

The values are literature-reported normalized per kg of PV modules.

A quantitative overview of the carbon footprint results was performed using literature-based LCA data. The analysis is normalized to the defined functional unit, allowing for a consistent comparison between recycling pathways and process configurations. The analysis at stage-level shows that the early steps of recycling, including disassembly and material separation, contribute to less than 45% of total emissions, while advanced recovery processes—particularly for silicon and silver—account for 56.16% of total emissions, even though they process only 4.4% of the module's mass [4]. This indicates that high-purity material recovery is the dominant factor in the overall carbon footprint of recycling systems.

Advanced recycling technologies further improve carbon performance. Comparative LCA results show that emissions decrease from 0.059 kg CO_2/kWh in landfill scenarios to 0.054 kg CO_2/kWh for laminated glass recycling (LGRF) and 0.046 kg CO_2/kWh for full recovery processes (FRELP) [4]. This corresponds to an overall reduction in environmental impact of 8–22%, depending on the recovery efficiency applied and the system configuration. System-level parameters also play an important role. The electricity mix, transport distance, and process efficiency strongly influence total emissions. Transportation can account for up to 80% of the selected impact categories, while the thermal treatment and post-treatment stages represent 20–30% of the potential global warming impacts.

These findings indicate that the carbon footprint of photovoltaic system recycling is highly sensitive to regional conditions and operational assumptions. From a technological standpoint, crystalline silicon (c-Si) modules offer the greatest potential for reducing emissions due to their dominant market share and higher material content. In contrast, thin-film technologies such as CdTe and CIGS exhibit lower emissions per module but provide a smaller overall contribution to emissions reduction at the system level.

The data from PV CYCLE ITALIA demonstrate the environmental benefits of recycling PV modules, with significant greenhouse gas emissions avoided. For crystalline silicon (c-Si) modules, total avoided emissions reach 8,052,516 kg CO_2eq, while for thin-film modules, avoided emissions are 31,202 kg CO_2eq.

The results presented in this study reveal significant variation in the reported environmental indicators for PV module recycling in the literature. Differences in approaches to the allocation of by-products and recycled materials further contribute to variations in reported results. These limitations reduce the comparability of results and introduce uncertainty in the quantitative assessment of the benefits of recycling. Therefore, the development of harmonized LCA methodologies – defining consistent system boundaries, data quality requirements, and impact assessment approaches – is essential for improving the reliability and comparability of future studies.

3.3 Exergy analysis in PV recycling

In addition to environmental and energy-based assessments, exergy analysis is applied as a thermodynamic tool for evaluating the quality of energy consumption and identifying irreversibilities in the recycling processes of PV systems. Exergy efficiency η_{ex} is defined as the ratio of useful exergy to total input exergy, while irreversibility represents the exergy destroyed due to thermodynamic losses in the system. These indicators allow for a more detailed comparison of recycling pathways beyond energy balances. Chemical recycling processes exhibit exergy efficiency in the range of 1–6%, reflecting significant irreversibilities associated with multi-step reactions, reagent consumption, and separation processes. In contrast, mechanical and direct recycling processes - particularly for aluminium and glass - demonstrate significantly higher exergy efficiency due to lower processing temperatures and fewer transformation steps [2, 6].

The presented results reveal a clear trade-off between thermodynamic efficiency and material recovery yield. Processes that achieve high-purity recovery of critical materials (e.g., silicon and silver) tend to exhibit lower exergy efficiency and higher energy consumption, leading to increased CO_2 emissions [12]. Conversely, mechanically dominated processes, although more thermodynamically efficient, yield lower recovery rates of high-value materials and thus smaller environmental benefits [2, 6]. This trade-off highlights the importance of process optimization and hybrid approaches. By combining pretreatment with low exergy losses with targeted, highly efficient recovery steps, hybrid recycling systems can reduce overall irreversibility while maintaining high levels of material recovery [11].

4 Role of maintenance and cleaning in extending PV lifetime

4.1 Soiling impacts and maintenance as a sustainability strategy

Soiling – the accumulation of dust, sand, bird droppings, and other particulate matter on the surface of photovoltaic (PV) modules – is a critical factor in accelerated PV degradation. The presence of such deposits acts first as a physical barrier that progressively reduces photon absorption by blocking incident light from reaching the photoactive semiconductor layer, thereby lowering current and overall energy yield over time [6, 9, 10, 11]. In regions with frequent dust events or limited rainfall, optical losses from soiling alone can reach double-digit percentages, significantly shortening the effectively useful lifetime unless counteracted by maintenance.

On a micro-system level, uneven soiling patterns can lead to partial shading of individual cells within a module, causing some cells to operate in reverse bias and dissipate power as heat. This phenomenon generates "hotspots," localized temperature increases that induce mechanical stress, microcracks, and delamination at cell-encapsulant-glass interfaces, all of which are recognized as pathways for premature module failure. By promoting thermal overstress and localized aging, hotspots not only degrade the electrical performance but also compromise the structural integrity of the laminate, ultimately increasing the likelihood that a module reaches end-of-life earlier than its nominal 25–30-year design horizon.

Beyond purely optical and thermal effects, soiling combined with moisture and temperature cycling can drive chemical degradation processes. Dust and associated contaminants, especially in humid or coastal environments, can facilitate moisture ingress into the module package, accelerating corrosion of metal interconnects and gridlines, as well as hydrolytic degradation of the ethylene-vinyl acetate (EVA) encapsulant [6]. Over time, this contributes to bubble formation, loss of adhesion, delamination, and discoloration, all of which further reduce transmittance and mechanical robustness. When considered together, these mechanisms – photon-blocking, hotspot formation, corrosion, and accelerated aging – directly increase the frequency of premature module retirement, raising the volume of PV waste over the system lifetime and amplifying the overall carbon footprint of the PV value chain [3, 4, 6].

From a sustainability perspective, regular maintenance and cleaning of PV panels can be viewed as a key lever for extending system lifetime and reducing lifecycle environmental impacts. The literature indicates that repair and maintenance activities, including routine inspection, soiling removal, and corrective measures around electrical components, can significantly prolong the service life of PV modules toward or beyond their 25–30-year design life, especially in harsh environmental conditions. By suppressing the progression of hotspot-driven degradation, EVA aging, and corrosion-related failures, proper O&M practice helps prevent "early losses" and defers the need for replacement modules, which in turn slows the generation of end-of-life waste.

On the recycling and circular-economy side, maintenance and cleaning also play a preparatory role. Before PV modules can be certified for reuse or repurposing, thorough cleaning is typically required to remove accumulated soiling and ensure that performance metrics are representative of the module's underlying condition [5, 6]. In this sense, cleaning is not only a means of maintaining yield but also a prerequisite for maximizing reuse and minimizing the number of modules that enter recycling streams prematurely. Life cycle assessment studies that incorporate extended service life due to effective maintenance show reductions in energy demand, primary material extraction, and associated emissions, indicating that O&M choices are integral to the overall LCA performance of PV systems [6].

Consequently, panel cleaning should be framed not merely as an operational expenditure, but as a sustainability-oriented strategy that simultaneously improves energy yield, reduces replacement rates, lowers lifecycle GHG emissions, and supports the circular-economy goals embodied in the EU WEEE framework. By integrating soiling-oriented maintenance into PV-system planning, developers and operators can better align technical performance with environmental compliance and lifecycle-cost objectives [7, 8].

4.2 Evaluation of cleaning approaches in support of long-term PV efficiency and circularity

Dry cleaning (textile-based) using specially engineered textile materials represents a resource-efficient and environmentally friendly strategy for mitigating soiling on photovoltaic modules. As demonstrated in prior studies by our research group, the use of soft, low-abrasive fabrics - such as microfiber weaves, structured knit textiles, or controlled-friction technical cloths - enables effective removal of loose particulate contaminants while preserving the integrity of anti-reflective coatings and glass surfaces. This makes textile-based methods particularly suitable for frequent cleaning cycles in arid or water-limited regions, where conventional wet cleaning introduces substantial logistical burdens related to water transport, energy use, and wastewater handling.

The performance of dry textile cleaning is strongly influenced by the composition and morphology of the deposited soiling. Fine dust and sand are efficiently removed through controlled mechanical contact, whereas more adherent contaminants (e.g., biological residues, sticky organic films) may require complementary or hybrid cleaning interventions. Nevertheless, our empirical findings indicate that properly selected textile structures can minimise surface stress, reducing the risk of micro-scratching and mechanically induced degradation over prolonged operation **-** a crucial factor for maintaining optical transmission and long-term module reliability.

In the context of this review, textile-based dry cleaning emerges as a low-impact, operationally flexible technology that aligns with broader sustainability objectives. By enabling frequent, non-intrusive maintenance with minimal resource inputs, it contributes to stabilising energy yield, delaying degradation-driven replacement cycles, and ultimately reducing the lifecycle-specific carbon footprint of photovoltaic installations.

Wet cleaning, typically involving purified or deionized water and sometimes mild detergents, is generally more effective at removing stubborn, sticky, or crusty deposits than dry methods alone. The addition of water enables dissolution and mechanical flushing of adhered particles, which can restore a larger share of the original transmittance and, by extension, electrical output. Professional wet-cleaning services are commonly used in large-scale PV plants and industrial rooftops where high energy-yield targets justify higher operational inputs.

From an environmental standpoint, wet cleaning is more resource-intensive, as it consumes water and energy for pumping, heating, and transportation, and may generate runoff that must be controlled or treated to prevent local contamination. Nevertheless, when implemented within well-managed systems (e.g., using filtration, recirculation, or low-chemical formulations), the net effect is often a substantial extension of module service life and a net reduction in lifetime-specific emissions due to avoided replacement modules [4, 6]. Therefore, wet cleaning can be viewed as a higher-intensity but high-return maintenance strategy, most appropriate for locations where dust and organic deposits are persistent and where water is available at acceptable cost.

Hybrid cleaning approaches and self-cleaning coatings, particularly super hydrophobic or anti-soiling nanocoatings, are increasingly promoted as ways to reduce the frequency and intensity of manual or mechanized cleaning interventions. These coatings repel water and particulates, enhance the “self-wetting” effect of rainfall, and limit the adhesion strength of dust to the glass surface, thereby keeping modules cleaner over time and reducing the need for scheduled O&M visits. In practice, this translates into lower operational costs, fewer mechanical contacts, and reduced risk of surface damage during cleaning cycles.

From a lifecycle-sustainability perspective, self-cleaning coatings can be seen as a form of upstream design-for-maintenance that complements downstream cleaning strategies. While the coatings themselves require additional manufacturing steps and material inputs, their long-term effect is to maintain higher transmittance, suppress hotspot formation, and delay corrosion-related degradation, all of which contribute to longer service life and lower waste generation. In this context, hybrid systems that combine periodic dry cleaning with anti-soiling coatings offer a balanced approach, minimizing both recurring resource use and long-term degradation risks.

In summary, dry cleaning with textile materials, wet cleaning, and hybrid/ self-cleaning technologies each have distinct trade-offs in terms of resource consumption, technical performance, and environmental impact. For the purposes of the present review, dry cleaning based on textile materials stands out as a particular low-impact, operationally feasible option that aligns well with efforts to extend PV module lifetime and reduce lifecycle-specific carbon emissions. By integrating appropriate cleaning strategies into PV-system planning and O&M routines, operators can simultaneously improve energy yield, postpone recycling needs, and support broader sustainability and circular-economy goals.

5 Regulatory framework and policy analysis

The EU Waste Electrical and Electronic Equipment (WEEE) Directive (2012/19/EU) constitutes a central regulatory instrument shaping the development and standardization of PV module recycling across Member States by embedding photovoltaic panels within the broader EEE-waste regime [7, 8]. The Directive sets binding targets for collection, preparation for re-use, recycling, and recovery, commonly interpreted as an 85% collection rate and 80% recovery target for PV equipment, and obliges producers placing PV modules on the EU market to finance the collection, take-back, treatment, and environmentally sound recovery of EoL modules. By assigning these obligations to producers, the WEEE framework aims to internalize end-of-life costs into product design and market decisions, thereby stimulating investment in dedicated recycling infrastructure, standardized collection networks, and high-efficiency recovery technologies tailored to PV waste streams.

Extended Producer Responsibility (EPR), as implemented through national WEEE schemes and Producer Responsibility Organizations (PROs), further strengthens circularity by requiring manufacturers to report material flows, design products for easier disassembly and recyclability, and participate in harmonized monitoring and compliance mechanisms [8]. In practice, however, implementation remains uneven across EU countries due to differing national transpositions, administrative capacities, and levels of industry participation, leading to variations in collection rates, treatment standards, and the sophistication of recycling technologies deployed [1, 8]. These divergences can create competitive distortions and complicate cross-border assessment of technological performance, yet they also reflect learning-by-doing that is feeding back into the design of newer, more integrated recycling routes, including thermal, electro-thermal, and hybrid processes for EoL modules [4 ,12]. As a result, the WEEE Directive and its EPR logic not only define the minimum regulatory “floor” for PV recycling but also act as a catalyst for innovation in more environmentally and economically efficient recycling technologies that can be benchmarked across PV technology families.

6 Innovations, trends, and future directions in sustainable PV recycling

6.1 Recent innovations and trends (2022–2025)

Recent developments in PV recycling have increasingly focused on improving process sustainability, material selectivity, and overall environmental performance. A notable innovation is the use of green solvents, including dimethyl isosorbide (DMI) and deep eutectic solvents (DES), which enable selective delamination of PV modules while reducing the environmental burden associated with conventional chemical treatments. These approaches have demonstrated high selectivity and reduced chemical consumption, with reported reductions in process-related environmental impacts compared to conventional solvent-based methods [6].

At the process level, high-recovery recycling technologies have emerged as a key trend. Advanced systems such as Full Recovery End-of-Life Photovoltaics (FRELP) and related integrated recycling flows achieve recovery efficiencies exceeding 90–95% for glass and aluminium and enable high-purity recovery of silicon and silver. Compared to conventional mechanical processes, these technologies can reduce overall environmental impacts by up to 20%, while maintaining high material quality and circularity [11].

In parallel, recent comparative LCA studies, including system-level evaluations conducted in different regional contexts such as South Korea, provide deeper insights into the performance of mechanical, thermal, and chemical recycling pathways. These studies show that optimized hybrid systems can reduce emissions by 10–30% compared to single-process approaches, depending on electricity mix and process configuration. In addition, mechanical pre-treatment combined with targeted recovery stages has been shown to significantly reduce energy demand while preserving recovery efficiency [15].

Recent developments show a consistent trend toward improved material recovery, lower environmental impact, and wider adoption of advanced recycling solutions. Figure 1 summarizes the indicative trends identified in the reviewed literature and presents developments in the field of PV system recycling and sustainability from 2022 to 2025.

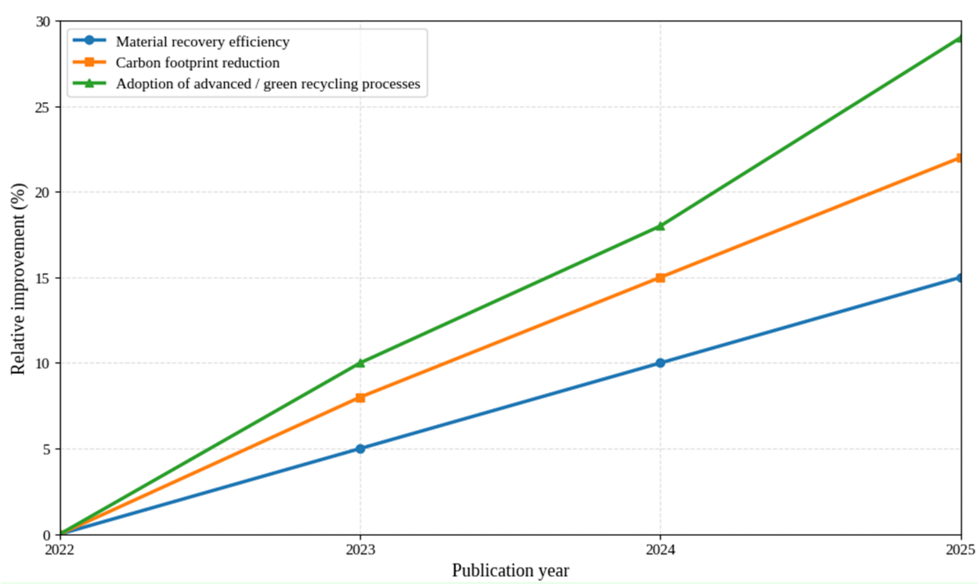

Fig. 1. Trends in sustainable PV recycling (2022–2025) illustrating relative improvements synthesized from the reviewed literature in terms of material recovery efficiency, carbon footprint reduction, and adoption of advanced recycling processes. Values are intended for comparative visualization and do not represent direct quantitative measurements.

6.2 Challenges and future directions

From a technological perspective, the development of low-energy delamination processes remains a critical challenge. Achieving high-purity silicon recovery is particularly demanding, as impurity levels must be reduced below 1–10 ppm for reuse in photovoltaic applications, requiring additional processing steps and energy input [6, 12]. On the other hand, from an economic point of view, advanced recycling technologies—especially chemical and high-purity recovery processes—are associated with operational costs typically in the range of 200–400 EUR/ton of processed PV waste. At the same time, the variability in the market value of recovered materials limits economic feasibility. Furthermore, current recycling capacities remain insufficient to address the projected PV waste volumes, expected to reach 70–80 million tons globally by 2050.

Another important limitation is the inconsistency in LCA methodologies and data. Reported carbon footprint values for similar recycling processes can vary by more than 50%, primarily due to differences in system boundaries, emission factors, and allocation methods. These discrepancies reduce the comparability and reliability of environmental assessments [15]. To address these challenges, several future directions can be identified. The development of mobile recycling systems can reduce transportation-related emissions by 30–50%, particularly in regions with decentralized PV installations. In parallel, the implementation of design-for-disassembly principles can decrease dismantling energy demand by 20–40%, facilitating more efficient material separation and recovery.

The adoption of green solvents, such as DMI and deep eutectic solvents (DES), enables reductions in chemical-related environmental impacts of 15–30%, while maintaining high selectivity and recovery efficiency [6]. In addition, integrating circular economy strategies with digital tools such as blockchain-based tracking systems can improve material traceability and enhance recycling efficiency within extended producer responsibility (EPR) frameworks. Therefore, a key future direction is the transition toward green PV recycling systems, in which recycling processes are powered by low-carbon or renewable energy sources. Replacing conventional electricity (typically 250–600 gCO_2/kWh) with renewable energy (e.g., 20–100 gCO_2/kWh) can reduce process-related emissions by more than 60–80%, particularly for energy-intensive thermal and chemical processes. Coupling recycling facilities with on-site photovoltaic generation or hybrid renewable systems further enhances sustainability by reducing operational emissions and energy dependence. These developments indicate a transition toward integrated, low-emission, and resource-efficient recycling systems, forming the basis for future sustainable PV waste management strategies.

7 Conclusion

This study provides a literature-based review of recent research on the technologies, carbon footprint, and sustainability aspects of PV modules, including end-of-life (EoL). By integrating data from life cycle assessments (LCA), techno-economic analyses, and regulatory policies, it is demonstrated that recycling offers measurable environmental benefits, particularly with high-purity material recovery and energy-efficient processes. Mechanical methods demonstrate the lowest carbon footprint (0.04–0.40 kg CO_2/kgPV at 0.1–1.0 kWh/kg), thermal methods—rapid separation of polymer layers (1.5–5.0 kWh/kg, up to 2.0 kg CO_2/kg), while chemical and hybrid methods achieve over 96% purity and efficiency up to 99%, albeit with higher energy intensity (0.5–8.0 kWh/kg).

Despite this, the results show significant variability due to differences in system boundaries, methodological assumptions, and the quality of available data, which limits comparability. A key contribution of the analysis is linking environmental evidence to policies, design, and industrial perspectives, providing a more integrated view of the circular economy in the sector. Data from PV CYCLE ITALIA confirm avoided emissions of 8 million kg CO_2eq for c-Si modules, with full recovery reducing total emissions by 8–22% compared to landfilling.

Taking into account the expected growth in PV waste by 2050, the priority guidelines include: strengthening extended producer responsibility (ERP) instruments and reporting requirements under the WEEE Directive; investing in large-scale low-emission hybrid technologies; implementing design-for-recycling principles as early as the module development phase; and a standardized LCA approach with unified system boundaries, indicators, and data requirements. These measures will improve comparability, support evidence-based policies, and promote the transition to a sustainable circular photovoltaic industry.

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