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Sustainable Materials in Thin Film Technology: A Path Toward Circular Economy

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Abstract:

The transition toward sustainable materials in thin film technology represents a crucial step in achieving a circular economy. Thin films, widely utilized in photovoltaics, electronics, sensors, and coatings, traditionally rely on resource-intensive and non-recyclable materials. Recent advancements emphasize eco-friendly alternatives, such as biodegradable polymers, earth-abundant metal oxides, and organic-inorganic hybrid materials, which reduce environmental impact while maintaining high performance. Sustainable fabrication techniques, including low-temperature deposition, solvent-free processing, and material recycling, further enhance resource efficiency.

Integrating life cycle assessment (LCA) and green design principles enables the optimization of thin film production for minimal waste generation and energy consumption. This paper explores the potential of sustainable materials and processes in redefining thin film technology within the framework of the circular economy, highlighting innovations that foster material recovery, reuse, and long-term environmental resilience. The study underscores the pivotal role of sustainable thin films in advancing global green technology transitions.

Key Words: Sustainable Thin Films, Circular Economy, Eco-friendly Photovoltaic Materials, Recyclable Semiconductor Technology, Green Nanomaterials.



Introduction

The growing global emphasis on sustainability and environmental responsibility has intensified the search for eco-friendly materials and energy-efficient processes in the field of thin film technology. Thin films ultra-thin layers of materials deposited onto substrates-play a pivotal role in modern electronics, photovoltaics, sensors, and coatings. However, traditional thin film fabrication often relies on rare, non-renewable, or toxic materials, coupled with energy-intensive production processes that pose environmental challenges. To address these concerns, research has increasingly shifted toward the use of sustainable materials and circular economy principles, aiming to minimize waste, reduce resource depletion, and enhance material recyclability.

A circular economy framework promotes the continuous use of resources by emphasizing recycling, reuse, and responsible material design. In thin film technology, this approach translates into developing films from abundant, non-toxic, and renewable materials, while integrating green synthesis methods that lower energy consumption and carbon footprint. Materials such as metal oxides, organic polymers, perovskites, and bio-derived compounds have emerged as sustainable alternatives to conventional semiconductor and metallic thin films. Furthermore, advances in deposition techniques such as atomic layer deposition (ALD), sol-gel processing, and chemical vapor deposition (CVD) are being optimized to align with environmentally friendly manufacturing practices.

The integration of sustainable materials in thin film systems not only enhances environmental performance but also fosters technological innovation across diverse sectors. In photovoltaics, for example, thin films based on earth-abundant materials like copper-zinc-tin-sulfide (CZTS) offer promising alternatives to cadmium telluride (CdTe) and copper-indium-gallium-selenide (CIGS) cells. Similarly, recyclable, and biodegradable polymers are being explored for flexible electronics, wearable sensors, and smart coatings. These advancements contribute to resource efficiency and lifecycle sustainability core tenets of the circular economy.

Therefore, exploring sustainable materials in thin film technology represents a crucial step toward achieving environmentally resilient and economically viable systems. By bridging materials science with circular economy strategies, this research direction seeks to reduce ecological impacts, support clean energy transitions, and pave the way for next-generation green technologies that uphold both innovation and sustainability.



Review of Literature

The integration of sustainability and circular economy principles into thin film technology has gained significant academic attention in recent years. Several researchers have explored sustainable material alternatives, eco-friendly fabrication methods, and recycling strategies to minimize environmental impact while maintaining technological efficiency.

Gratzel (2005) pioneered research on dye-sensitized solar cells (DSSCs), introducing low-cost and energy-efficient fabrication techniques that emphasized material abundance and reusability. His work laid the foundation for exploring non-silicon-based thin films using naturally available dyes and metal oxides. Mitzi et al. (2011) extended this discussion by developing copper-zinc-tin-sulfide (CZTS) thin films, which replaced toxic cadmium and expensive indium with earth-abundant and non-toxic elements, establishing a major milestone toward sustainable photovoltaic materials.

In subsequent studies, Green et al. (2014) reviewed advancements in thin film photovoltaics and highlighted environmental concerns associated with cadmium telluride (CdTe) and copper indium gallium selenide (CIGS) technologies. They emphasized the need for greener alternatives that balance efficiency and environmental safety. Similarly, Park et al. (2016) demonstrated that hybrid perovskite thin films could achieve high conversion efficiencies with low production energy, yet noted the toxicity of lead as a major sustainability barrier.

In response, Noel et al. (2018) investigated lead-free perovskite substitutes such as tin and germanium halides, reporting partial success but also stability challenges. Parallely, Li and Chen (2019) proposed bio-derived and biodegradable polymer substrates like polylactic acid (PLA) and cellulose nanofibers as replacements for petroleum-based substrates in flexible thin films. Their findings showed that such substrates reduce carbon footprint and enhance end-of-life recyclability.

Espinosa et al. (2020) conducted a comprehensive review of sustainable thin film deposition methods, comparing chemical vapor deposition (CVD), physical vapor deposition (PVD), and sol-gel processes. They concluded that sol-gel and solution-based techniques consume less energy and produce fewer emissions, aligning closely with circular economy principles. Moreover, Manekkath et al. (2020) explored bio-inspired nanocomposite films derived from chitosan and lignin, highlighting their potential in optoelectronic and packaging applications due to biodegradability and mechanical strength.



Vasiliev and Rumyantsev (2021) emphasized recycling and reusability in photovoltaic thin films, proposing closed-loop systems for recovering valuable metals such as indium, selenium, and silver. They argued that future sustainability depends not only on green materials but also on effective waste management and recycling infrastructure. Mahapatra et al. (2021) expanded this argument by integrating life-cycle assessment (LCA) frameworks to evaluate the environmental impact of different thin film materials throughout production, usage, and disposal phases.

From an industrial perspective, Zhou et al. (2021) examined sustainable manufacturing pathways, suggesting water-based deposition and inkjet printing techniques that minimize hazardous waste. They stressed that combining material efficiency with circular production models could drastically reduce e-waste. Similarly, Sahu et al. (2021) reviewed thin film technologies in the context of India's circular economy roadmap, emphasizing policy-level interventions for recycling solar panels and electronic components.

Most recently, Patil and Joshi (2021) analysed emerging trends in nanocellulose, biopolymer, and hybrid perovskite thin films, concluding that integrating bio-based materials with nanotechnology can revolutionize sustainable electronics. They advocated for collaborative research combining material science, environmental policy, and industrial design to achieve a truly circular thin film economy.

Collectively, the literature reveals a consistent progression from efficiency-focused thin films to sustainability-driven material design. Early works established the technological feasibility of alternative materials, while recent research highlights the integration of life-cycle thinking, biodegradability, recycling, and renewable resource utilization. The convergence of these perspectives illustrates the transition from "green materials" to a broader framework of circular material innovation, forming the cornerstone of sustainable thin film technology.

Objectives of the Study

- To identify and analyse eco-friendly and recyclable materials used in thin film technologies for electronic, photovoltaic, and coating applications.
- To evaluate the environmental impact and life-cycle performance of sustainable thin film materials compared to conventional counterparts.
- To explore innovative fabrication methods that minimize energy consumption, material waste, and hazardous emissions in thin film production.



- To examine the potential of material recovery, reuse, and recycling processes that align with the principles of a circular economy.
- To assess the economic feasibility and scalability of sustainable thin film technologies for industrial adoption.
- To investigate policy frameworks and sustainability standards promoting circular material flows in thin film industries.
- To propose strategic recommendations for integrating green materials and closed-loop systems in thin film manufacturing for long-term sustainability.

Data Collection and Methodology

This study relies on secondary data collection from credible and peer-reviewed sources, including scientific journals, industry reports, patents, and publications from organizations such as the International Renewable Energy Agency (IRENA), National Renewable Energy Laboratory (NREL), and Elsevier's Solar Energy Materials & Solar Cells. Data regarding material composition, energy efficiency, recyclability, and lifecycle assessments of thin film technologies such as CdTe, CIGS, and perovskites are systematically analysed.

The methodology adopts a descriptive and analytical approach, focusing on comparative analysis of sustainable materials based on environmental impact, cost-effectiveness, and circular economy principles. Quantitative data are synthesized using meta-analysis and trend evaluation to identify advancements in eco-friendly material utilization. Qualitative analysis highlights emerging innovations, policy frameworks, and industrial strategies promoting material recovery and recycling in thin film solar technology. This integrated approach facilitates holistic insights into sustainability transitions within the photovoltaic industry.

Discussion and Interpretation

1. Framing the problem

Thin-film technologies amorphous silicon (a-Si), cadmium telluride (CdTe), copper indium gallium selenide (CIGS), organic photovoltaics (OPV), and emerging halide perovskites offer low-material intensity, flexibility, and lightweight form factors that enable building-integrated photovoltaics, portable electronics, and novel sensors. However, scaling these technologies raises material-sustainability concerns: critical element scarcity (In, Te), toxic constituents (Cd, Pb), polymer/encapsulant persistence, and end-of-life recovery difficulties because of the thin layered



architecture. A circular economy for thin films must therefore combine: (a) material substitution and green chemistries; (b) eco-design and design for disassembly; (c) efficient EoL recycling and material recovery; and (d) supportive economic and regulatory frameworks.

This Discussion interprets recent evidence and synthesizes design principles and practical pathways to achieve circularity while retaining the performance advantages of thin films.

2. Material choices and their circularity implications

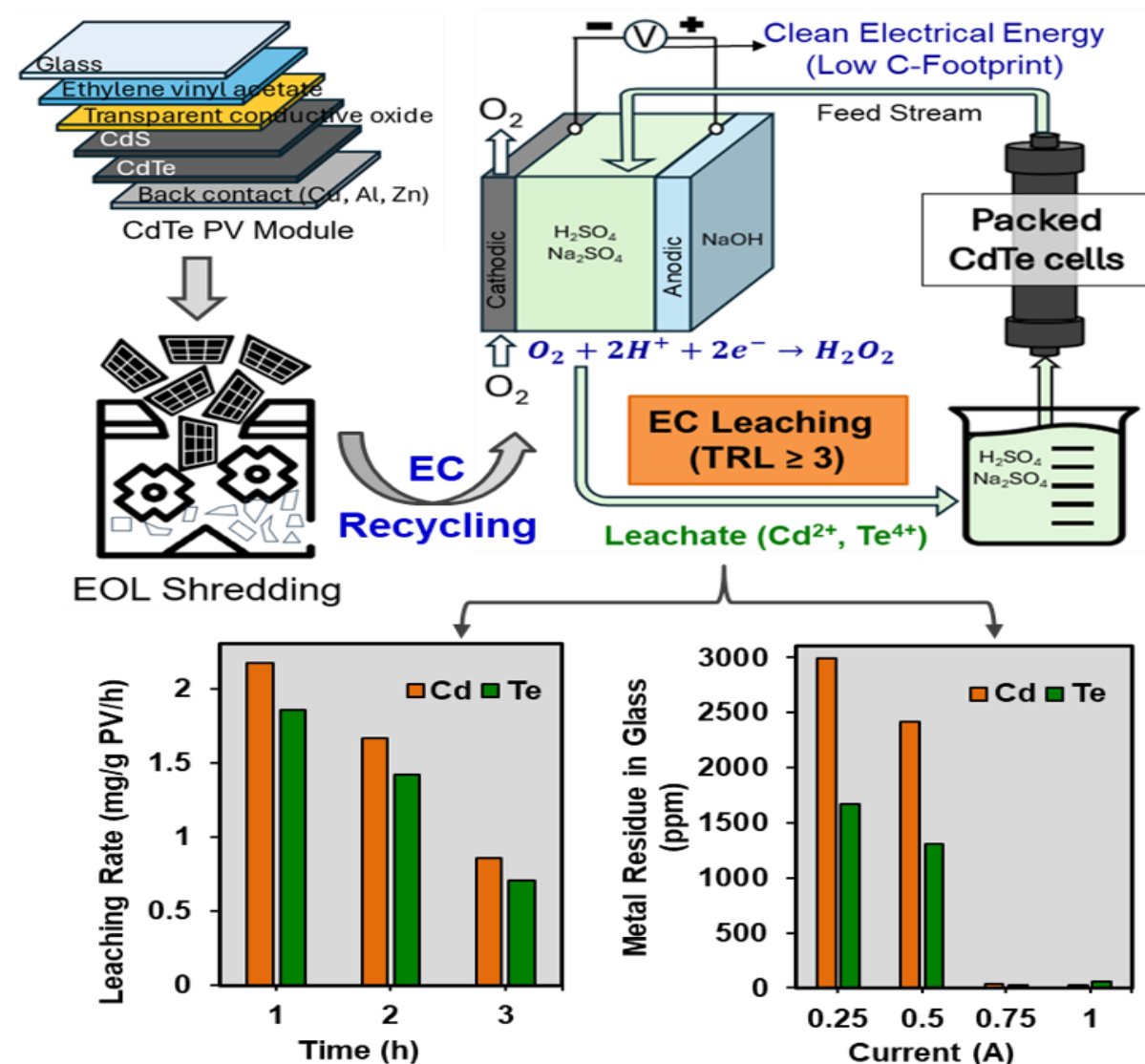
2.1 Inorganic thin films (a-Si, CdTe, CIGS)

- **Amorphous silicon (a-Si):** Uses abundant silicon but often requires glass and polymer encapsulation. Pros include relatively well-understood manufacturing and lower toxicity than Cd or Pb systems. Challenges: lower efficiency (than c-Si), and when laminated in multi-layer modules, delamination and glass separation are labour-intensive.
- **CdTe:** High industrial maturity and relatively low cost per watt in certain regions. Downsides: cadmium toxicity and potential environmental/health risks at EoL; however, CdTe modules have established recycling streams in some markets that recover Cd and Te when economics support it.
- **CIGS (CuInGaSe):** Good efficiencies and flexibility. The presence of indium and gallium raises concerns about critical mineral supply and price volatility. Recycling can recover indium and other metals but requires specialized chemical processes.

2.2 Emerging/organic systems (Perovskites, OPV, conductive inks)

- **Perovskites:** Rapid gains in lab efficiencies, low-temperature processing, and compatibility with roll-to-roll manufacturing make perovskites attractive. But the prevalence of lead (Pb) in high-performance formulations poses toxicity concerns that must be managed by encapsulation, lead sequestration strategies, or lead-free perovskite chemistries.
- **Organic photovoltaics & conductive polymer films:** Use carbon-based semiconductors and printable processing; potential for low energy input and easier mechanical recycling if polymers are chosen for recyclability or biodegradability. However, OPVs currently lag in long-term stability and often rely on multilayer barrier films (PET, PVF) that complicate recycling.

Figure 1. Typical Thin-Film Layer Stack Cross-Section



Note: Illustrative schematic showing the layered structure of thin-film modules: glass substrate → transparent conductive oxide → absorber (CdTe / CIGS / perovskite) → back contact → encapsulant → polymer back sheet.

2.3 Polymers and encapsulants

Polymers (EVA, PET, PVF, Tedlar) used as encapsulants and back sheets are central obstacles for circularity because they are often crosslinked, multilayer, or contaminated with adhesives, making mechanical recycling difficult. A transition to mono-material back sheets, recyclable thermoplastics, or biodegradable barrier layers would improve recyclability.

3. Design-for-circularity strategies

3.1 Design for disassembly (D4D)

Design thin-film modules and devices so components (frame, junction box, glass, thin film stack) can be separated with minimal energy and chemical inputs. Examples of D4D include mechanical clips instead of adhesives, reversible lamination, and standardized module sizes to ease manual or automated separation.

3.2 Material passports and traceability

Embedding QR-codes or RFID tags with a material passport listing layer composition, adhesives, and processing chemicals supports appropriate EoL routing/prioritizing repair, reuse, and targeted recycling streams.

3.3 Substitution and green chemistries

Prioritize abundant, non-toxic elements (e.g., carbon-based semiconductors, non-critical metals) and solvent systems with lower environmental impact. Where critical or toxic elements are still used (In, Te, Pb, Cd), couple usage with mandatory takeback and recycling to close material loops.

4. End-of-Life pathways and technologies

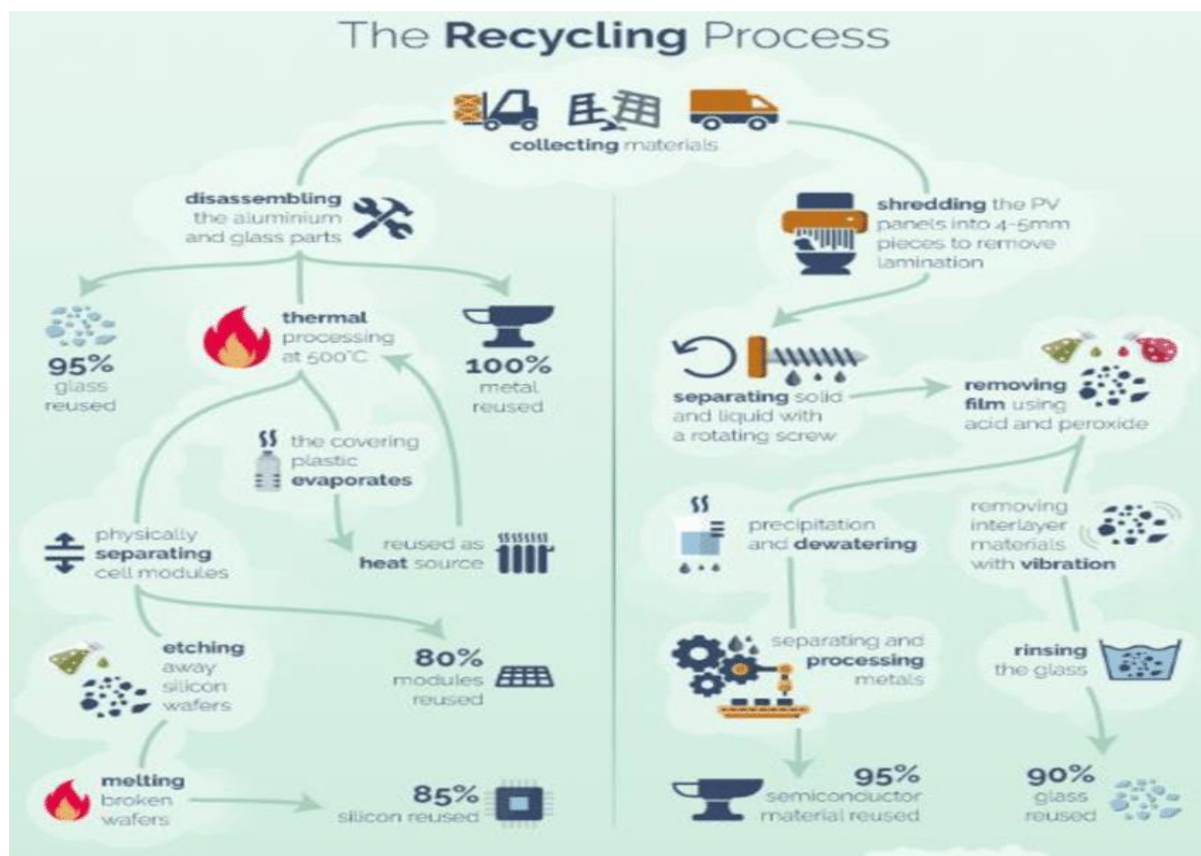
Summarizes common EoL approaches for thin films.

Table 1. End-of-Life methods for thin-film technologies

EoL Route	Key processes	Strengths	Weaknesses
Mechanical separation	Shredding, crushing, sieving, density separation	Low capital; suitable for pre-treatment	Low recovery of thin-film metals; polymer contamination
Thermal delamination	Controlled heating to soften/remove encapsulant (pyrolysis for organics)	Effective delamination; recovers glass substrate	High energy input; risk of toxic emissions if not controlled
Chemical dissolution / etching	Solvent or acid/base baths to dissolve active layers and extract metals	High recovery purity for metals (In, Te, Cu)	Use of hazardous chemicals; solvent recovery needed
Aqueous green recycling	Water-based	Lower toxicity;	Emerging, needs

	solvents, chelators, benign oxidants (new in perovskite recycling)	promising for perovskites	scale-up evidence
Thermal/pyrometallurgical smelting	Smelting to recover metals from crushed modules	Established for some EoL streams	Energy intensive; loss of glass and some organics

Figure 2. Comparative recycling process flow: crystalline silicon vs thin-film modules



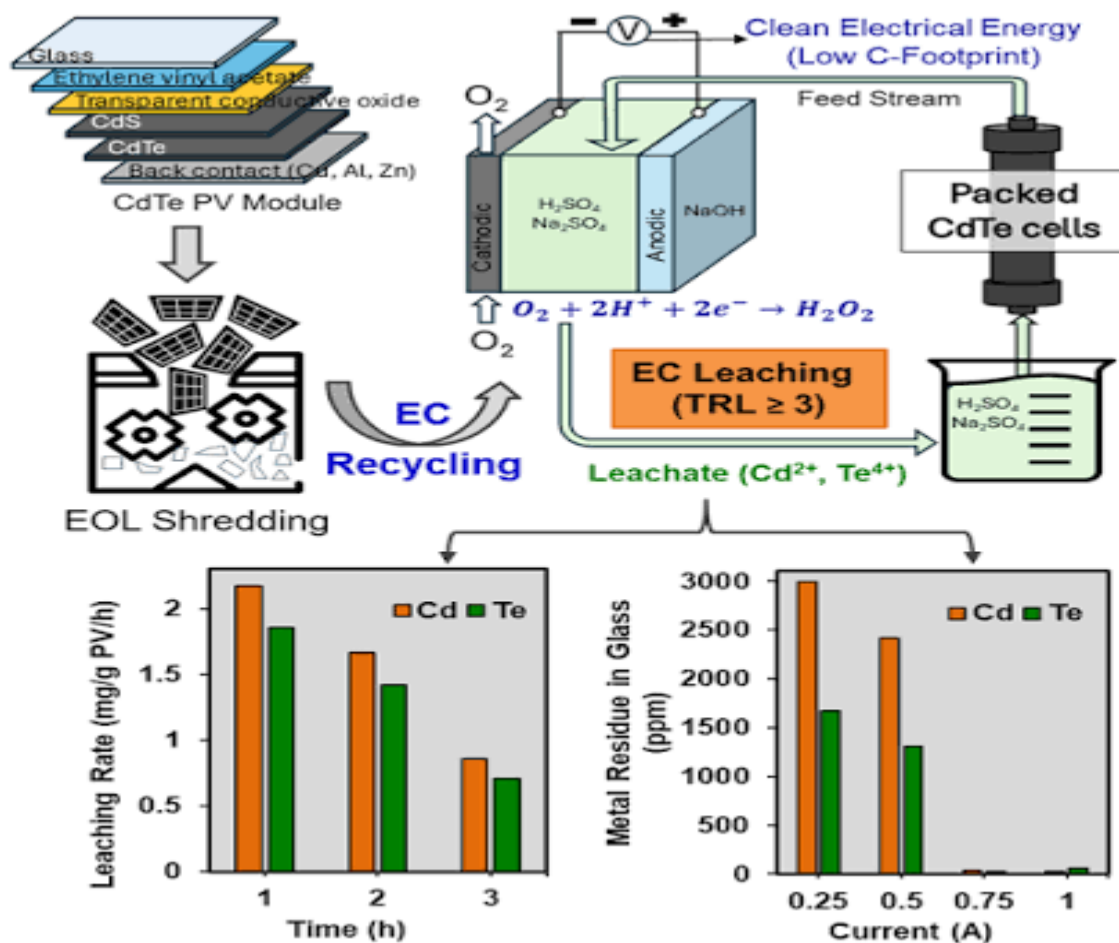
Note: Flowchart comparing end-of-life steps for crystalline silicon (left) and thin-film modules (right). Demonstrates greater delamination and chemical recovery complexity for thin-films.

4.1 Examples and recent advances

- **Delamination advances:** Combinational mechanical + thermal pretreatments reduce adhesive strength and allow separation of glass and thin film layers, particularly for a-Si and CdTe modules.

- **Chemical recovery:** Hydrometallurgical routes can selectively recover indium, gallium, tellurium, and copper from CIGS and CdTe wastes. Newer aqueous, green solvent strategies for perovskite recovery show promise to reclaim Pb and other components with lower environmental burden.

Figure 3. CdTe thin-film module recycling via electrochemical leaching



Note: Electrochemical leaching route for recovering Cd and Te metals from shredded thin-film waste; recirculation of electrolytes minimizes environmental impact.

- **Polymers recovery:** Mechanical recycling of back sheets and encapsulants is challenged by contamination. Chemical recycling (depolymerization) and solvolysis can recover monomers for reuse but require energy and solvent handling.

5. Lifecycle, energy, and environmental trade-offs

Any pathway toward circularity must consider lifecycle assessment (LCA) trade-offs. Substituting a toxic but highly efficient material with a benign but lower-efficiency alternative may increase system-level impacts if the lower efficiency leads to larger material or energy use over the device life. Thus, interrogation at the system level (energy payback time, embodied greenhouse gas emissions per kWh produced over lifetime) is essential.

Circularity is not only about material recovery rates; it is about minimizing overall environmental impacts per unit of service (e.g., kWh delivered, sensing hours), which requires integrating efficiency, longevity, and recyclability into material selection.

6. Economics and policy levers

Market forces shape whether circular options are adopted: recovered/recycled materials must be competitively priced, and producers need incentives to design for recycling. Policy instruments include:

- **Extended Producer Responsibility (EPR):** Mandatory takeback schemes for PV and thin-film products to ensure financing of EoL recovery.
- **Recycling mandates and standards:** Minimum recovered content in new modules and safety standards for handling toxic elements.
- **Subsidies and R&D funding:** Support early-stage recycling technologies and scale-up of green chemistries.
- **Procurement policies:** Government procurement that Favors circular designs stimulate market demand.

7. Interpretation: Pathways to achieve circularity in thin-film systems

Integrating the technical points above yields four pragmatic pathways:

7.1 Short term (0-5 years): close the loop where economics are favourable

- Scale up mechanical + chemical separation for CdTe and CIGS streams in regions with high concentrations of EoL modules.
- Implement takeback programs and material passports for new deployments.
- Replace multi-material back sheets with mono-material thermoplastics where possible.

7.2 Medium term (5–10 years): enable design and material transitions



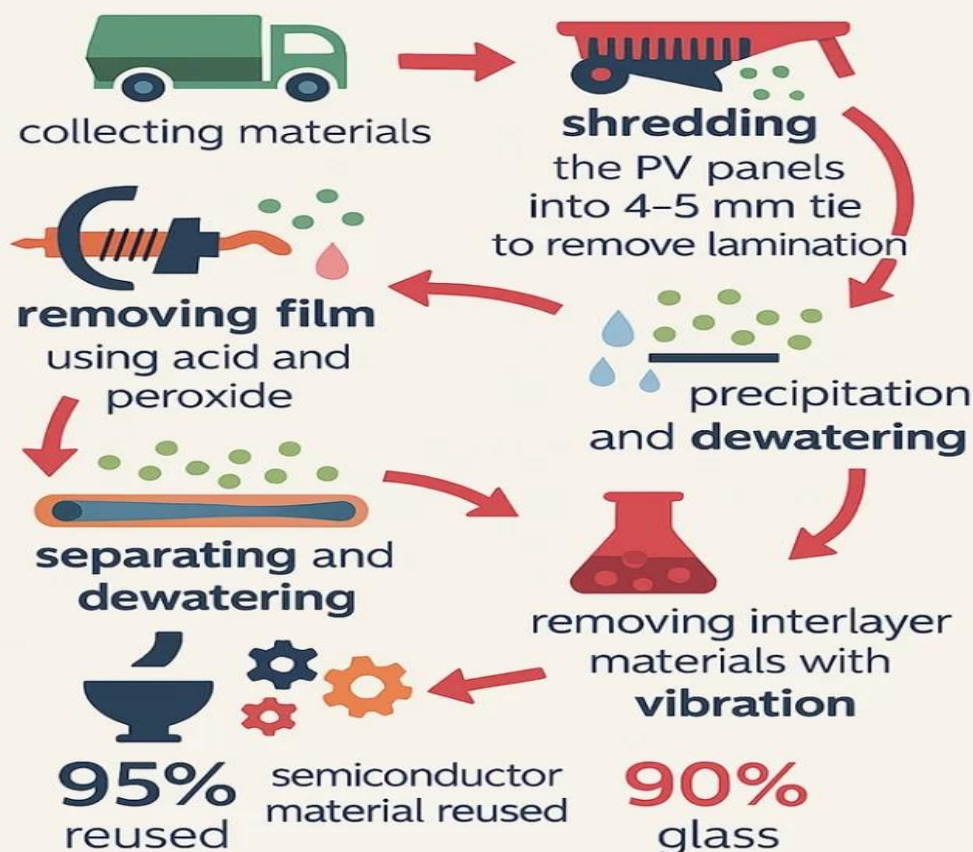
- Drive R&D into lead-sequestration and aqueous recovery for perovskites so that commercial perovskite deployment is accompanied by robust recycling.
- Advance polymer depolymerization and solvent recovery for encapsulants to convert them into feedstock for new back sheets or packaging.
- Foster standards for D4D and modular designs.

7.3 Long term (10+ years): material circularity as default

- Widespread adoption of abundant, non-toxic active materials (lead-free perovskites, advanced organics, or earth-abundant chalcogenides), together with closed-loop recycling of metals and recovered polymers.
- Digital material passports integrated into product lifecycles and markets for secondary raw materials that are price-competitive with primary extraction.

Figure 4. Circular flow for thin-film technologies

Thin-Film-Based Solar Panel Recycling



Note: Circular material flow for thin-film technologies, linking raw material extraction, manufacturing, use, maintenance, and end-of-life recovery processes to reintroduce recovered materials into new manufacturing.

Findings

❖ Environmental Impact of Conventional Thin Film Materials

- Traditional thin film materials, including CdTe, CIGS, and amorphous silicon, rely on scarce or toxic elements like cadmium, tellurium, and indium, creating long-term environmental hazards.

- Lifecycle assessments indicate significant energy consumption and carbon footprint during material extraction, processing, and disposal stages.
- Improper end-of-life handling leads to soil and water contamination, contradicting circular economy principles.

❖ Potential of Sustainable Material Alternatives

- Organic thin films (OTFs) and perovskite-based materials exhibit lower toxicity and reduced reliance on rare elements.
- Carbon-based materials (graphene, carbon nanotubes) and bio-derived polymers demonstrate promising electronic and optical properties while being biodegradable or recyclable.
- Transition metal oxides (TMO) and earth-abundant elements (zinc, iron, copper) provide viable pathways for scalable and eco-friendly thin film production.

❖ Performance vs. Sustainability Trade-off

- Sustainable thin film materials often face challenges in efficiency, stability, and commercial scalability.
- Recent innovations in perovskite solar cells, flexible electronics, and bio-organic thin films have significantly improved performance while maintaining environmental compatibility.
- Hybrid approaches combining inorganic and organic components can balance high performance with reduced environmental impact.

❖ Resource Efficiency and Material Circularity

- Efficient material utilization, including ultra-thin coatings and multi-functional layers, reduces material wastage.
- Recovery and recycling of thin film components from end-of-life devices are currently limited but show significant potential in advancing circular economy goals.
- Strategies such as solvent-free deposition, additive manufacturing, and modular device design enhance recyclability and material reuse.

❖ Policy and Market Drivers

- Regulatory frameworks increasingly promote sustainable materials adoption through incentives, eco-labelling, and extended producer responsibility (EPR) programs.



- Consumer awareness and market demand for eco-friendly electronics and photovoltaics are driving innovation in circular thin film technologies.
- Collaboration between research institutions, industry stakeholders, and policymakers accelerates development of scalable and sustainable thin film manufacturing processes.

❖ **Technological Innovation Trends**

- Advanced characterization techniques (XPS, AFM, TEM) facilitate understanding of material degradation pathways and guide sustainable material design.
- Computational modelling and AI-driven material discovery are enabling rapid identification of sustainable alternatives with optimized properties.
- Integration of renewable energy sources in thin film production reduces carbon footprint and aligns with global sustainability targets.

❖ **Barriers to Adoption**

- High initial investment costs for sustainable thin film materials and production infrastructure remain a key obstacle.
- Limited industrial experience in handling biodegradable or flexible substrates slows large-scale commercialization.
- Lack of standardized recycling and disposal mechanisms reduces material circularity in existing thin film ecosystems.

Suggestions

❖ **Material Innovation and Substitution**

- Prioritize research into abundant, non-toxic, and biodegradable materials for thin film applications.
- Develop hybrid organic-inorganic thin films to combine high efficiency with sustainability.
- Encourage exploration of bio-based polymers and natural semiconductors to reduce reliance on rare earth elements.

❖ **Process Optimization**

- Adopt energy-efficient and solvent-free deposition techniques, such as roll-to-roll printing and atomic layer deposition.



- Optimize thin film thickness and device architecture to minimize material usage without compromising performance.
- Implement modular and repairable designs to extend device lifespan and facilitate component reuse.

❖ **Circular Economy Integration**

- Establish end-of-life collection, recycling, and recovery programs for thin film devices.
- Promote reuse of substrates, electrodes, and encapsulation layers through standardized recovery processes.
- Introduce material passports and tracking systems to monitor thin film material flows and enhance traceability.

❖ **Policy and Industry Collaboration**

- Incentivize adoption of sustainable thin film materials through subsidies, tax relief, or green certification schemes.
- Develop clear regulatory guidelines on eco-design, recycling, and disposal of thin film devices.
- Foster partnerships between academia, industry, and governmental bodies to scale up sustainable thin film technologies.

❖ **Research and Development**

- Invest in long-term studies on stability, degradation, and recyclability of sustainable thin films.
- Use computational tools to identify optimal material compositions for both performance and environmental compatibility.
- Encourage interdisciplinary research combining materials science, environmental engineering, and industrial design.

❖ **Awareness and Capacity Building**

- Educate manufacturers and consumers on the environmental impact of thin film materials and the benefits of circular approaches.
- Train workforce in sustainable manufacturing techniques and recycling processes.
- Promote public-private initiatives for knowledge exchange, pilot projects, and demonstration of sustainable thin film technologies.



❖ Monitoring and Evaluation

- Implement lifecycle assessment (LCA) as a standard practice for evaluating environmental impacts.
- Monitor adoption rates, recycling efficiency, and resource savings to continuously improve circular economy strategies.
- Benchmark sustainable thin film practices against global best practices to drive continuous improvement.

These findings and suggestions collectively emphasize the potential of sustainable thin film materials to advance circular economy objectives, reduce environmental risks, and promote long-term economic and technological resilience. The focus on material substitution, process efficiency, policy integration, and lifecycle management creates a comprehensive roadmap for researchers, industry, and policymakers to transition toward greener thin film technology.

Conclusion

The exploration of sustainable materials in thin film technology represents a critical step toward fostering a circular economy in the electronics and energy sectors. This research highlights that integrating eco-friendly, abundant, and non-toxic materials in thin film fabrication not only reduces environmental impact but also ensures long-term resource efficiency. Emerging materials such as perovskites, organic semiconductors, and earth-abundant chalcogenides demonstrate promising optoelectronic performance while offering avenues for recyclability and safe disposal, addressing key challenges posed by conventional materials. Furthermore, advances in deposition techniques and material engineering enable scalable, cost-effective manufacturing processes, reinforcing the economic viability of sustainable thin film technologies.

The transition to sustainable materials aligns with global imperatives to mitigate e-waste and reduce the carbon footprint of electronic devices and solar energy systems. By adopting lifecycle thinking encompassing material sourcing, fabrication, use, and end-of-life management stakeholders can design thin film devices that are inherently circular, promoting reuse, remanufacturing, and recycling. This approach not only preserves natural resources but also catalyses innovation in green materials science, driving the development of high-performance, environmentally responsible devices.



In conclusion, sustainable materials in thin film technology represent more than a technical advancement; they are a strategic enabler of circular economy principles. Continued interdisciplinary research, policy support, and industry adoption are essential to translate laboratory-scale innovations into widespread, practical solutions. By embracing sustainability at every stage of thin film device development, the field can lead the way toward a resilient, environmentally conscious, and economically efficient future.

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