RELISE

DISPOSAL AND RECYCLING OF LEADED PEROVSKITES: AN ENVIRONMENTAL LOOK AT PHOTOVOLTAIC SUSTAINABILITY

DESCARTE E RECICLAGEM DE PEROVSKITAS COM CHUMBO: UM OLHAR AMBIENTAL SOBRE A SUSTENTABILIDADE FOTOVOLTAICA[1]

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ABSTRACT

This study analyzes the significance of lead-based perovskite solar cells as emerging photovoltaic materials and their associated challenges, with a particular focus on lead disposal. The research highlights that while these materials are promising for photovoltaic sustainability, their use raises significant concerns regarding heavy metal pollution. The methodology, based on a literature review and data analysis, underscores the importance of recycling photovoltaic materials as a strategic solution. Life cycle analyses demonstrate that recycling can drastically reduce resource depletion and human toxicity. It is concluded that effective end-of-life management for these devices, supported by regulations and efficient recycling technologies, is crucial for mitigating environmental risks and aligning technological innovation with environmental responsibility in the sector.

Keywords: lead-based perovskite, emerging photovoltaic materials, lead disposal, heavy metal pollution, recycling photovoltaic materials.

RESUMO

O presente estudo analisa a relevância das células solares de perovskita com chumbo como materiais fotovoltaicos emergentes e os desafios associados, com foco especial no descarte de chumbo. A pesquisa destaca que, embora promissoras para a sustentabilidade fotovoltaica, a utilização desses materiais levanta preocupações significativas sobre a poluição por metais pesados. A

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metodologia, baseada em revisão de literatura e análise de dados, aponta a importância da reciclagem de materiais fotovoltaicos como solução estratégica. Análises de ciclo de vida demonstram que a reciclagem pode reduzir drasticamente o esgotamento de recursos e a toxicidade humana. Conclui-se que a gestão eficaz do fim da vida útil desses dispositivos, apoiada por regulamentações e tecnologias de reciclagem eficientes, é crucial para mitigar os riscos ambientais e alinhar a inovação tecnológica com a responsabilidade ambiental no setor.

Palavras-chave: perovskita com chumbo, descarte de chumbo, materiais fotovoltaicos emergentes, reciclagem de materiais fotovoltaicos, poluição por metais pesados.

INTRODUCTION

The advancement of lead-based perovskite solar cells has positioned them as promising candidates for next-generation photovoltaic technologies due to their high efficiency and low production costs. However, the presence of toxic lead in these devices raises significant environmental and health concerns, particularly regarding their disposal at the end of their service life. Improper handling may result in lead leaching into the environment, posing risks to ecosystems and human health, as lead from perovskites can enter the food chain more efficiently than other sources of lead contamination (Torrence et al., 2022; Li et al., 2020).

To address these challenges, recent research has focused on developing sustainable recycling and disposal methods that enable the recovery and reuse of lead and other valuable materials, thereby minimizing environmental impacts and complying with electronic waste regulations (Binek et al., 2016; Chen et al., 2021; Chhillar et al., 2019; Khac et al., 2024; Schmidt et al., 2023; Yazawa et al., 2024). These efforts include innovative layer-by-layer removal techniques, ion-exchange resin recovery, and solvent-free extraction processes, all aimed at reducing lead waste and supporting the safe commercialization of perovskite solar cell technology.

Throughout this research, alternatives for safe encapsulation, emerging

recycling methods, and public policies aimed at the proper treatment of such waste will be examined, as discussed by Ustulin (2024) in the analysis of the national and international legislative landscape. Furthermore, a critical reflection will be undertaken on the role of electrical engineers in developing sustainable energy solutions by integrating technological innovation and environmental responsibility.

The main objective of this research is to analyze the challenges and opportunities associated with the disposal and recycling of lead-containing perovskites in light of environmental requirements and the principles of photovoltaic sustainability.

To this end, the study examines the role of these perovskites in advancing solar energy, highlighting their structural, optical, and electronic properties, and reflecting on how these characteristics affect their commercial viability and potential environmental risks.

Finally, this study seeks to contribute to a critical analysis of the following question: “How can the electrical sector contribute to the development of safe disposal and recycling processes for lead-containing perovskites?” with the aim of supporting the development of feasible, responsible solutions aligned with the ethical principles of contemporary electrical engineering.

THEORETICAL FRAMEWORK

In order to understand the main environmental challenges associated with perovskite solar cells, especially with regard to the disposal of lead-containing compounds, this section presents a review of the scientific literature focused on the technological solutions proposed for the recovery and recycling of these materials. Starting from an understanding of the role of perovskites in the development of solar energy, it discusses how their structural and functional properties contribute both to their efficiency and to their environmental risks.

Furthermore, the factors influencing the feasibility of implementing these solutions are analyzed, including government incentives, raw material availability, and impacts on the already established photovoltaic market, thereby consolidating the state of the art on the subject.

Perovskite solar cells: operation, advantages, and challenges

In recent years, perovskite-based solar cells using organic-inorganic lead halides have attracted worldwide attention due to their impressive power conversion efficiency (PCE) and low-temperature solution-processable fabrication (Zhang, 2023). With such impactful characteristics, it becomes evident that predictions made in the previous decade (regarding the assurance of a future large-scale use of photovoltaic energy) have great potential to become reality if implemented. Recent data demonstrate that there is still a long way to go, considering that photovoltaic energy currently accounts for approximately 4 to 5% of total electricity generation worldwide, which, although representing a significant increase compared to previous years, still constitutes only a small share of the global energy matrix (Green, 2014; Haegel, 2023).

Although not yet extensively implemented, the rapid growth of perovskite solar cells (hereinafter PSCs) is closely related to their unique physicochemical properties. According to the research developed by Casarin (2024), this is due not only to their original composition, but also to the ability of this composition to be synthetically replicated with different combinations of elements, allowing numerous technological applications, including photovoltaics.

From a structural perspective, the perovskite materials used in PSCs follow the general formula ABX_3, where A is a small organic cation such as formamidinium (FA^+) or a large inorganic cation such as cesium (Cs^+), B is a divalent cation, generally lead (Pb^{2+}) or tin (Sn^{2+}), and X represents a halide (I^-, Br^-, or Cl^-) (Zhang, 2023; Jena, 2019; Zhao, Tan, 2020). This structure provides the material with excellent optoelectronic properties (the study of devices that generate or detect light), such as a high absorption coefficient, long carrier diffusion lengths, and low defect density (Green, 2014; Jena, 2019). According to Teixeira (2023), the mere presence of lead in this structure provides high power conversion efficiencies, currently exceeding 25% in laboratories, placing them among the highest-performing emerging photovoltaic technologies.

From the perspective of device engineering, PSCs can be arranged in various architectures, the most common being the n-i-p (conventional) and p-i-n (inverted) structures. Both basically consist of three parts working together: (i) an electron transport layer (ETL), (ii) the active perovskite layer, responsible for absorbing light and generating electron-hole pairs, and (iii) a hole transport layer (HTL) (Zhao, Tan, 2020; Jena, 2019), illustrating how perovskites are incorporated into solar cells.

Furthermore, the charge transport processes within these devices are closely related to the crystalline quality of the perovskite and the properties of the interfaces. Recombination mechanisms, whether radiative, non-radiative, or interfacial, directly limit the quantum efficiency of the devices (Correa-Baena, 2017; Tress, 2017).

However, despite the existence of significant advances in laboratory efficiencies — which, as will be discussed later in subsequent sections, already exceed 27.8% in single-junction perovskite cells (which use a single semiconductor layer to absorb light and generate electricity) and 34.9% in tandem (perovskite-silicon) devices (NREL, 2025) — challenges related to thermal stability, photodegradation, moisture sensitivity, and the presence of toxic metals such as lead still represent significant barriers to the consolidation of this technology on a commercial scale (Jena, 2019; Tress, 2017; Zhao, Tan, 2020).

In principle, perovskite is a revolutionary material that combines high performance, low production cost, and application flexibility, but it requires

caution regarding its durability and environmental impact, mainly due to the use of heavy metals such as lead. These factors make it essential to develop encapsulation, recycling, and lead substitution strategies using elements that are less harmful to human health and the environment (Silva, 2016).

Formation of the perovskite film

The formation of the perovskite film is a fundamental step in the fabrication of solar cells based on this material, directly influencing the performance, stability, and efficiency of the photovoltaic device. It consists of a process involving the controlled deposition of a thin layer of the perovskite compound onto a conductive substrate, forming a uniform and crystalline film capable of absorbing sunlight and generating electric current (Cruz; Isidoro; Fernandes, 2020).

According to Ustulin (2024), the successful formation of the perovskite film depends on several physicochemical factors, such as the choice of precursor, the deposition method, the solvent evaporation rate, the crystallization temperature, and humidity control. The precursors generally used are lead iodide (PbI_2) combined with organic cations in solvents such as dimethylformamide (DMF), dimethyl sulfoxide (DMSO), or a combination of both.

According to Yin (2023), the precursor solution presented above is then deposited onto the substrate, and the film forms as the solvents evaporate and the crystals organize into a perovskite structure.

The perovskite film formation process is a complex balance between materials chemistry, process engineering, and environmental control, being decisive not only for the performance of solar cells but also for their durability and environmental impact. Investments in research and development aimed at improving this process are indispensable to making this technology not only efficient but also sustainable and safe for large-scale application (Machado;

Miranda, 2015).

Technological aspects of perovskites in the photovoltaic context

In the study developed by Casarin (2024), perovskite technology in solar cells has been established as one of the most promising innovations in the field of renewable energy, especially in the photovoltaic sector, which is based on the use of compounds with a perovskite-type crystalline structure that, as also discussed in Green's study (cf. p. 4), possess exceptional optoelectronic properties, thereby driving a new paradigm in the way solar energy is captured and converted.

However, it is important to emphasize that the technology still faces considerable challenges. The first concerns the stability of perovskite solar cells. The material is sensitive to moisture, prolonged exposure to UV light, and high temperatures, factors that contribute to its degradation over time (Casarin, 2024). In this regard, solutions such as efficient encapsulation, modification of the chemical composition, and the use of stabilizing additives have been adopted with partial success, but they still do not fully meet the durability requirements for long-term commercial applications (Teixeira, 2023).

Another critical issue is the use of lead, a toxic metal, as the main component of most perovskite formulations. Although the amount used per cell is small, the possibility of leakage during use, transportation, or disposal represents an environmental risk. Therefore, research is actively seeking less toxic alternatives, such as the use of tin, bismuth, or antimony. However, to date, these alternatives have not demonstrated the same efficiency or stability as lead-based cells (Pinto, 2022), since these substitutions generally reduce the device's lifespan and present difficulties in the synthesis and quality control of the perovskite film (Hao et al., 2014).

Impacts of improper disposal

According to data obtained from the NREL laboratory graph (cf. p. 5), PSCs represent an emerging and promising technology for renewable energy production due to their high efficiency and potential for low manufacturing costs, especially through solution-processing methods (Schmidt et al., 2023). Significant improvements in power conversion efficiency have paved the way for the commercialization of this technology (Torrence et al., 2023). However, most of the most efficient PSCs critically depend on the use of lead (Pb) (Schmidt et al., 2023).

Although alternatives using metals such as Sn and lead-free compositions (for example, double perovskites such as $Cs_2AgBiBr_6$) are being considered, they generally do not achieve the same performance in terms of efficiency or stability compared to their Pb-based counterparts (Torrence et al., 2023). The large-scale use of lead represents an environmental and social acceptance concern that may limit the commercialization of the technology (Schmidt et al., 2023).

Lead is a well-known pollutant metal and is highly regulated. Brazilian environmental legislation requires manufacturers and importers to ensure the reverse logistics of lead-acid batteries, guaranteeing their proper disposal (CONAMA, 2008). The improper disposal of PSCs containing lead raises serious environmental and health concerns. Events such as accidents during manufacturing or transportation, damage caused by severe weather conditions (hail, tornadoes, hurricanes), accidents (collisions, thrown objects), and end-of-life disposal may result in the release of lead into the environment (Torrence et al., 2023).

The main toxicological concern is the mobility of lead in the environment, which may occur through leaching, contaminating soil and groundwater (Schmidt et al., 2023). Leaching studies, such as the Toxicity Characteristic Leaching

Procedure (TCLP) in the United States or similar tests in other countries, simulate the behavior of waste in landfills. Compiled data show that, on average, lead leaching from a broken PSC module (electronic component) may exceed safe limits unless a lead-sequestration layer is incorporated into the module (Torrence et al., 2023).

In some TCLP tests using broken encapsulated and non-encapsulated modules, leached lead concentrations varied significantly, with some values greatly exceeding the regulatory limit of 5 mg/L for classification as hazardous waste in the United States (Dias, 2015). For example, modules on polymer substrates, in some tests performed by Li et al. (2022), Li et al. (2021), and Moody et al. (2020), released much higher amounts of lead (up to 127 mg/L or 713 mg/L) compared with glass substrates (up to 16 mg/L or 14.2 mg/L). The presence of leached lead above regulatory limits classifies PSC waste as hazardous waste (Class I under the Brazilian standard NBR 10004/2004).

Lead is a highly toxic substance. Once inside the body, it is stored in soft tissues and, after continuous exposure, is eventually absorbed into bones and teeth, where it has an elimination half-life of 20 to 30 years (BRASIL, 2023).

Bioaccumulation in plants and biomagnification throughout the food chain are also risks associated with soil contamination by lead (Torrence et al., 2023). In addition to lead, other elements present in PSCs, such as tin (Sn), chromium (Cr), cadmium (Cd), and cesium (Cs), as well as toxic solvents used during manufacturing (such as DMF, DMSO, NMP, and chloroform), also pose risks to human health and the environment. Cadmium, in particular, is classified as a probable or known human carcinogen (Goes, 2023).

Classification as hazardous waste implies significantly higher disposal costs in specialized landfills (Goes, 2023). It is estimated that hazardous waste disposal may cost approximately US$3,300/t compared with US$40/t for municipal waste. This cost difference makes end-of-life management an important factor to be considered for the economic and environmental sustainability of PSCs (Schmidt et al., 2023).

Waste management through recycling

The sustainable management of lead in PSCs, especially at the end of their service life, is crucial for the large-scale acceptance and commercialization of this technology. The development of a robust recycling program would reduce environmental impacts by preventing disposal in landfills (Torrence et al., 2023). Recycling aims to recover valuable and/or toxic materials, minimizing the need for primary mining and mitigating pollution risks. Accordingly, several recycling approaches for PSCs have been investigated, including:

Selective Dissolution in Organic Solvents: Early methods focused on selective dissolution in different organic solvents to recover components of the device stack. For example, some approaches used DMF to extract PbI_2 (Schmidt et al., 2023). However, the use of solvents such as DMF is highly regulated because of their toxicity (for example, reproductive toxicity) (Torrence et al., 2023). Efficient solvent recovery is required, increasing costs. Studies show that methods based on organic solvents may have greater environmental and toxicological impacts than the original materials due to the quantity of solvents used (Schmidt et al., 2023).

Molten Salt Electrolysis: Another approach employed was molten salt electrolysis for subsequent electrochemical recovery. These methods can be energy-intensive and, therefore, are not widely used (Schmidt et al., 2023).

Leaching and Adsorbent Materials: Leaching followed by the use of ion-exchange resins or composite materials to concentrate Pb has been explored (Torrence et al., 2023). These methods may be costly due to the demand for materials and effluent treatment (Schmidt et al., 2023). More recent approaches demonstrate the use of ion-exchange resins, such as weakly acidic cation exchange (WAC) resin with carboxylic acid functional groups, to adsorb Pb^{2+} ions from solutions in organic solvents (such as DMF) and subsequently release them into aqueous solution. This method demonstrated Pb recovery efficiencies exceeding 99%. The resin can be regenerated and reused (Chen, 2021; Schmidt et al., 2023; Yazawa, 2024).

Hot Water Extraction: A novel and environmentally benign recycling route exploits the strong temperature dependence of the solubility of PbI_2 in water. The process involves mechanical pre-treatment (cutting or breaking), extraction of the perovskite layer with hot water, separation of the solid residues (glass, plastic) from the water containing dissolved Pb, and crystallization of high-purity PbI_2 (>95.9%) through cooling. This method demonstrated high Pb extraction efficiencies (92.6–100%) and quantitative Pb recovery from glass-based PSCs after two extraction/precipitation cycles. The solid residues remaining after extraction contain sufficiently low metal concentrations so that they are no longer classified as hazardous materials. The use of water as the only extracting agent is considered environmentally benign (Schmidt et al., 2023).

Thermal Decomposition: In some studies, perovskite films were thermally decomposed into PbI_2, which was subsequently recycled and converted back into perovskite. The feasibility of this approach depends on the original fabrication route of the perovskite film (Chhillar, 2019).

In addition to PbI_2 recovery, other materials can also be recycled. Gold (Au) from the upper electrodes can be removed mechanically (for example, using adhesive tape) or by dissolving the hole transport layer followed by filtration (Yazawa, 2024). Substrates such as glass/FTO/TiO_2 can be recycled and reused for manufacturing new devices (Chhillar, 2019). Methods such as thermal delamination can separate encapsulated modules, recovering the front glass (with transparent conductor such as ITO) and the rear glass (Chen et al., 2021). The recovery of other metals such as indium (In) and silver (Ag) is also possible

from the remaining solid residues after Pb extraction (Schmidt et al., 2023).

The reusability of recovered materials is important for sustainability and economic viability. PbI_2 recovered through the hot water extraction process has been successfully incorporated into new perovskite layers with optoelectronic properties similar to those of commercial PbI_2 (Schmidt et al., 2023). PSCs manufactured using PbI_2 recycled through ion-exchange resin also demonstrated performance comparable to devices produced with high-purity commercial PbI_2 (Chen et al., 2021).

The main economic driver for PSC recycling is the avoidance of the high costs associated with hazardous waste disposal (Schmidt et al., 2023). The recovery of valuable materials such as FTO/glass (which may be the most expensive component of the module) and gold (Au) also contributes to economic feasibility. The value of recovered PbI_2 itself may not be the primary economic incentive (Schmidt et al., 2023; Chhillar, 2019; Binek, 2023).

Regulations such as the European WEEE (Waste Electrical and Electronic Equipment) Directive and state-level actions in the United States (for example, Washington and California) requiring end-of-life management for photovoltaic modules also encourage the development of recycling programs (Schmidt et al., 2023; Torrence et al., 2023).

In addition to post-use recycling, incorporating lead-sequestration layers into modules is a promising solution for mitigating lead release in the event of damage during operation, thereby improving safety (Torrence et al., 2023). These layers can capture and immobilize lead. However, the durability of these layers and their long-term impact on PSC performance still require validation (Torrence et al., 2023).

Although lead-free perovskites represent the ideal route to eliminate the problem at its source, current challenges regarding efficiency and stability suggest that Pb-based PSCs will likely reach the market first on a large scale.

Therefore, the development of effective lead sequestration and recycling technologies is essential (Torrence et al., 2023).

Analysis of the feasibility of implementing sustainable disposal solutions in the photovoltaic energy market

The rapid growth in the use of photovoltaic systems as a renewable energy source has raised concerns regarding the disposal of their components, especially solar panels at the end of their service life (approximately 25 to 30 years). Although solar energy is clean, improper disposal may represent a significant environmental risk, as is the case of perovskites containing lead in their composition. According to IRENA and IEA-PVPS (2016), it is estimated that by 2050 approximately 60 to 78 million tonnes of end-of-life photovoltaic panels will have been generated worldwide, and between 300,000 and 750,000 tonnes in Brazil, requiring sustainable and economically viable solutions.

One solution with the potential to meet this need is the implementation of the circular economy. The circular economy is conceived as a regenerative system that seeks to replace the traditional concepts of disposal and obsolescence with strategies focused on the restoration and reuse of resources, promoting practices such as industrial symbiosis, efficient product design, sustainable business models, and reverse logistics (LILLIESKOLD et al., 2019).

The proposal is to manage finite resources by recovering their value, promoting regeneration, and reducing the use of new materials. The analysis of corporate sustainability reports suggests that companies operating in Brazil are directing significant efforts toward a sustainable circular economy. Despite the progress of some corporate initiatives, the absence of specific public policies and regulations still represents an obstacle to the transition toward a circular economy in Brazil, revealing an institutional gap at the macro level (SANCHES et al., 2022).

To implement the circular economy in the photovoltaic energy market, it is necessary to evaluate points along the value chain where circular strategies can be introduced, thereby promoting the transition of the photovoltaic industry toward circularity (Franco & Groesser, 2021). The circular economy can be applied to the design of photovoltaic panels since current designs do not allow easy disassembly and separation of materials.

Analysis of sustainability policies and the benefits offered by governments

The demand for renewable energy has been increasing on a large scale worldwide. According to the Global Energy Review of the International Energy Agency (IEA), in 2024 the addition of renewable energy capacity increased by 25%, reaching the milestone of 700 GW installed, marking the 22nd consecutive year in which renewable energy achieved a new expansion record, with solar photovoltaic energy accounting for more than three-quarters of the increase in renewable energy capacity. “However, the proliferation of photovoltaic installations has led to concern regarding the growing number of photovoltaic modules produced and their end-of-life (EoL) phase.” (YU et al., 2022, p. 1).

Given this scenario of accelerated growth, it is essential to understand how different countries are preparing to deal with the proper disposal of this equipment at the end of its service life. It is therefore necessary to analyze the measures adopted by leaders in the sector:

United States: The Resource Conservation and Recovery Act (RCRA) aims to reduce waste generation, promote recycling and reuse, ensure the safe treatment and disposal of waste, and regulate hazardous waste from "cradle to grave." The RCRA adopts specific measures for each classification of solid waste and its management:

Hazardous solid waste: Identification and classification of waste according to its potential risk; registration and labeling of generators with the EPA; traceable transportation control from the point of origin to the final destination;

storage and treatment by licensed facilities; continuous responsibility of the generator even after disposal; promotion of waste minimization and encouragement of recycling and reuse; enforcement and penalties, including inspections, fines, and criminal actions in cases of non-compliance.

Non-hazardous solid waste: States and municipalities are responsible for managing this waste with support and general guidelines from the EPA; local planning for proper waste management; encouragement of practices that prevent waste generation from the production stage onward; promotion of recycling, reuse, and composting; requirements for sanitary landfills aimed at protecting the environment and public health; public education and awareness programs to encourage public participation in waste separation and reduction.

European Union: Directive 2012/19/EU concerns the management of Waste Electrical and Electronic Equipment (WEEE), assigning producers responsibility for WEEE management, including mandatory registration and labeling of equipment; Member States must ensure effective free selective collection systems; treatment and recovery requirements establishing that WEEE must be processed with the removal of hazardous fluids and critical components; recovery, recycling, and preparation for reuse targets must be achieved; annual reporting on electrical and electronic equipment (EEE) placed on the market and WEEE processed; Member States must ensure inspections and apply effective penalties in cases of non-compliance.

Brazil: The National Solid Waste Policy (PNRS) establishes the shared responsibility of all parties involved throughout the product life cycle (from manufacturer to consumer); all stakeholders must contribute to proper waste management; reverse logistics enables post-consumer products to return to the business sector for reuse, recycling, or proper disposal; integrated waste management includes collection, transportation, treatment, and environmentally sound final disposal of waste; non-generation, reduction, reuse, recycling, and treatment constitute the hierarchy of priorities in waste management (known as the 3Rs plus treatment and final disposal); solid waste management plans must be prepared by municipalities, companies, and specific sectors; open dumps are prohibited, requiring their elimination and replacement by licensed sanitary landfills.

China: According to the IEA PVPS report, China currently does not have specific regulations for end-of-life photovoltaic modules. However, related technological research has been initiated through the country's Five-Year Plans, which discuss goals and strategies for national development. The importance of photovoltaic panel recycling has begun to be addressed, although there are still no specific regulations governing this issue. This indicates that China remains in the early stages of planning waste management for the solar energy industry.

METHODOLOGY

This is an exploratory study employing a mixed-methods approach, developed through the integration of quantitative and qualitative methods. This choice is based on the understanding that, in complex research contexts, combining different analytical strategies allows for a broader and deeper understanding of the object of study. According to Creswell et al. (2018), the mixed-methods approach is particularly appropriate when no single approach is sufficient to fully understand the problem, making it ideal for research involving interdependent technical, social, and environmental variables.

This perspective is supported by Galvão et al. (2016), who emphasize that mixed-methods research does not merely combine techniques but integrates distinct research logics into a complementary approach, an essential characteristic when analyzing emerging technologies from multiple perspectives, as is the case with lead-containing perovskite solar cells. Similarly, Fetters (2019) emphasizes that mixed-methods research is effective in identifying contradictions, deepening understanding, and generating more robust inferences, which is crucial for fields characterized by technical and regulatory uncertainties.

In the present study, the quantitative component involves the collection and analysis of data on leaching levels, material recovery efficiency, and disposal and recycling costs, enabling an objective comparison among different technological pathways. This strategy is consistent with what Creswell et al. (2018) classify as a convergent mixed-methods design, in which quantitative and qualitative data are collected separately but integrated during the interpretation phase.

The qualitative component examines environmental and public health risks, current regulatory challenges, and the strategic role of electrical engineering in proposing sustainable solutions. This stage follows the approach proposed by Galvão et al. (2016), who advocate the critical analysis of the literature as a means of enriching the interpretation of empirical data within regulatory, social, and institutional contexts.

Thus, the mixed-methods approach adopted in this study is justified not only by the complexity of the topic but also by the objective of producing a critical interpretation of the challenges and opportunities associated with the sustainability of lead-containing perovskites in the photovoltaic sector. The proposed methodology makes it possible not only to evaluate the technical feasibility of the proposed solutions but also to understand the limitations imposed by regulatory and socio-environmental contexts, as recommended by the aforementioned authors.

Methodological framework

The literature review followed an organized and systematic structure composed of the following stages:

Problem definition: The central research problem was the identification of the environmental and health impacts resulting from lead in Perovskite Solar Cells (PSCs), considering technical, regulatory, environmental, and economic aspects.

Data collection: Relevant sources were selected based on thematic and temporal criteria, focusing on experimental studies, risk analyses, and regulatory assessments.

Data analysis: Content, quantitative, and comparative analyses were applied to the data extracted from the selected sources.

Synthesis and discussion: The results were integrated to discuss the solutions proposed in the literature, as well as the technical, economic, and regulatory challenges that still remain.

The methodological framework adopted enabled the compilation, critical analysis, and synthesis of the literature, providing a solid foundation for discussing the challenges and opportunities in the sustainable management of lead-containing Perovskite Solar Cells.

Data collection method

The data and information supporting this research were obtained from three main sources:

Scientific literature review: Articles and documents from institutions such as NREL, CONAMA, IEA, IRENA, EPA, and IEA-PVPS were analyzed, providing an overview of the challenges, alternatives, and environmental impacts associated with sustainable photovoltaic energy.

Secondary data from experimental studies: Quantitative data on environmental, economic, and policy-related aspects were extracted from academic articles and journals, supporting the analysis with a solid numerical

basis.

Institutional sources and reports: Data from regulatory agencies (EPA, CONAMA, CDC, among others), international organizations (IRENA, WHO), and guidelines such as the EU WEEE Directive, RoHS, REACH, and NBR 10004 were used to contextualize risks, waste management practices, and the photovoltaic energy market.

Sampling and selection criteria

The selection of sources and data for this review followed thematic and temporal criteria to ensure the relevance and currency of the information.

Thematic criterion: Priority was given to studies focused on the recycling and disposal of perovskite solar cells, especially those detailing experimental methods, leaching tests, and cost analyses.

Temporal criterion: Preference was given to publications from the last 10 years, with particular emphasis on those published within the last 5 years, in order to reflect the most recent advances in recycling technologies and risk assessment.

Indirect participants: The analysis considered the findings of research groups and institutions with expertise in photovoltaic materials, environmental chemistry, and waste management, as identified through the literature review.

Analytical tools and techniques

The analysis of the collected information and data was carried out in multiple stages, combining qualitative and quantitative techniques.

Content analysis: The main recycling methods, toxic materials involved, environmental and health risks, applicable regulations, technical and economic challenges, mitigation strategies, and financial feasibility were identified.

Quantitative analysis: Data on process yields, leachate concentrations, purity of recovered materials, and associated costs were synthesized. The concentrations were compared with legal limits in order to classify PSC waste.

Comparative studies: Recycling approaches were compared in terms of their efficiency in recovering lead and other materials, the purity achieved, their feasibility for different types of PSCs, and their environmental and economic impacts in both national and international contexts.

DATA ANALYSIS

The rapid growth of global photovoltaic capacity in recent years has raised increasing concern regarding the volume of waste generated by solar panels at the end of their service life. It is estimated that, by 2050, the annual generation of photovoltaic panel waste may reach significant levels, ranging from 60 to 78 million tonnes (IRENA et al., 2016).

Although perovskite solar cells (PSCs) represent an emerging and promising technology due to their high efficiency and low-cost potential, their reliance on lead in the most efficient formulations introduces significant environmental and public health concerns (Torrence et al., 2022; Li et al., 2020). In this context, it is necessary to justify why lead is used instead of solutions that are less harmful to the environment and society.

Lead is still used in perovskite solar cells primarily because, to date, it offers a unique combination of properties that no other material has been able to match in terms of efficiency and stability, making it essential for the high performance of these devices (Torrence et al., 2023). This is demonstrated by power conversion efficiencies that currently exceed 25% in laboratory settings, as reported in the studies by Teixeira (cf. p. 5).

This becomes evident when considering that, despite the well-recognized toxicity of lead, the alternatives tested, such as tin (Sn), bismuth (Bi), and antimony (Sb), have not yet achieved the same level of performance. Tin, for example, undergoes rapid oxidation, which compromises the stability and efficiency of the cell. Furthermore, these substitutions generally reduce the device's lifetime and present difficulties in the synthesis and quality control of the perovskite film (Jena et al., 2019).

Nevertheless, even considering these factors, compiled data show that lead leaching from damaged or broken PSC modules may exceed the regulatory limits for classification as hazardous waste—for example, 1 mg/L in Brazil (ABNT, 2004)—making a careful analysis of the disposal of this type of material essential.

Table – Concentracion of metals in photovoltaic solar panel waste

Parameter	Unit	Result A	Result B	Detection Limit (DL)	Maximum Limit (NBR 10004)
Cadmium	mg/L	ND[1]	ND	0.017	0.5
Lead	mg/L	5.50	21.6	0.054	1.0
Chromium	mg/L	0.016	0.025	0.012	5.0
Silver	mg/L	ND	ND	0.015	5.0

Table 1. Comparison of leaching test results for different PSCs and regulatory standards.
Source: Adapted from Dias (2015).

Some countries, such as the United States, have higher permissible concentration limits for toxic substances such as lead. According to the U.S. Environmental Protection Agency (EPA) Resource Conservation and Recovery Act (RCRA) regulations, published in 1990, the maximum allowable concentration of lead in non-hazardous waste is 5 mg/L, which is five times higher than the limit established in Brazil. Despite this more permissive threshold, several Pb sequestration techniques are employed to reduce lead concentrations.

Classification as hazardous waste entails significantly higher disposal costs in specialized landfills (estimated at US$3,300/t for hazardous waste versus US$40/t for municipal waste) (Schmidt et al., 2023). Consequently, end-of-life waste management has become an important factor in the economic sustainability of PSCs (Góes, 2023).

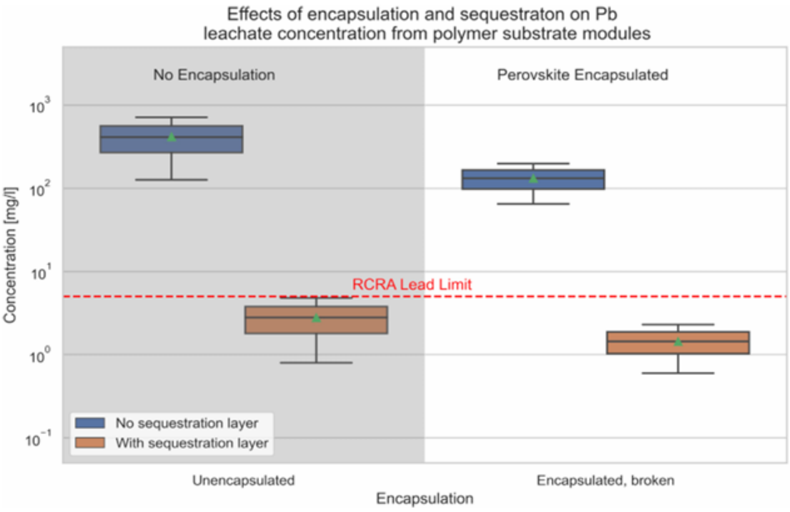

Figure 1. Leaching data for polymer-substrate cells/modules, showing variability and the influence of factors such as encapsulation and Pb-sequestration layers. Source: Torrence et al. (2023).

To mitigate these risks and costs, the development of a robust recycling program is essential. Recycling aims to recover valuable and/or toxic materials, minimizing the need for mining while reducing the risks of environmental contamination. Several recycling approaches for PSCs have been investigated, including Selective Solvent Dissolution, Hot Water Extraction, Ion-Exchange Resins and Adsorbents, and Thermal Decomposition.

Figure 2. Schematic illustration of lead (PbI_2) recycling using hot water. Source: Schmidt et al. (2023).

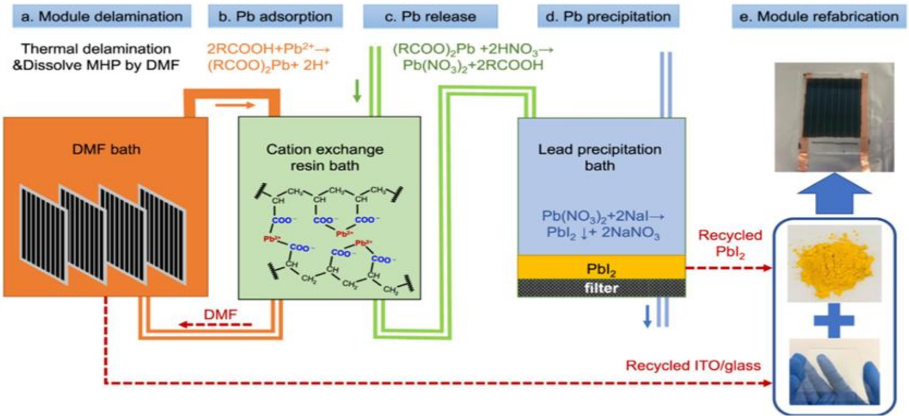

Figure 3. Recycling process for encapsulated perovskite solar modules using ion-exchange resins and adsorbents. Source: Adapted from Suo et al. (2024).

The reusability of recovered materials is crucial for both sustainability and economic viability, considering that, in addition to PbI_2, other materials such as substrates, electrodes, and other valuable layers can also be recovered. Recovered PbI_2, for example, obtained through hot water extraction or ion-exchange resin processes, has demonstrated optoelectronic properties and purity comparable to those of commercial-grade material and has been successfully reincorporated into new perovskite layers with similar performance (Suo, 2024; Schmidt, 2023), thereby contributing to the deposition of high-quality perovskite films in solar cells (Ustulin, 2024).

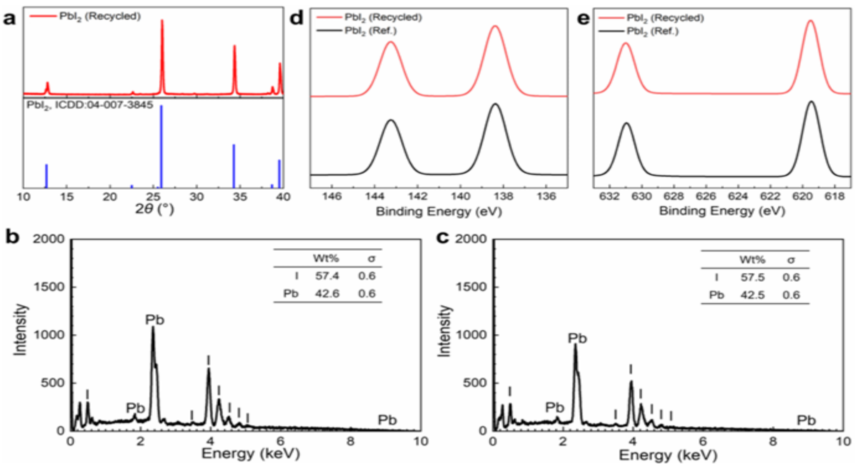

Figure 4. X-ray diffraction (XRD) patterns comparing the crystalline structure of recycled PbI_2 with the XRD patterns of virgin lead iodide (reference material). Source: Adapted from Suo et al. (2024).

The environmental benefits of recycling are evident. Life cycle assessment (LCA) studies have demonstrated that recycling PSCs can significantly reduce resource depletion (by 96.6% compared with landfilling), human toxicity (68.8% for carcinogenic effects and 57.6% for non-carcinogenic effects), and other environmental impacts (Xiao, 2024).

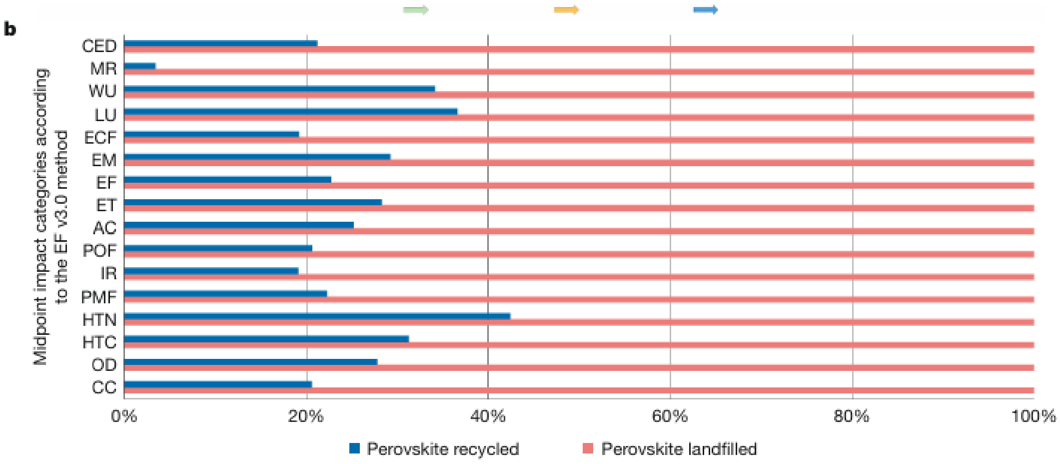

Figure 5. Comparison of environmental impacts between recycling and landfill scenarios. CED, cumulative energy demand; MR, material resources (metals/minerals); WU, water use; LU, land use; ECF, freshwater ecotoxicity; EM, marine eutrophication; EF, freshwater eutrophication; ET, terrestrial eutrophication; AC, acidification; POF, photochemical oxidant formation (human health); IR, ionizing radiation (human health); PMF, particulate matter formation; HTN, human toxicity (non-carcinogenic effects); HTC, human toxicity (carcinogenic effects); OD, ozone depletion; CC, climate change. Source: Adapted from Xiao et al. (2024).

Regulations, such as the European Waste Electrical and Electronic Equipment (WEEE) Directive and national legislation (e.g., RCRA in the United States and NBR 10004 in Brazil), which require end-of-life management for photovoltaic modules, encourage the development of recycling programs.

These regulations establish guidelines regarding the responsibilities of manufacturers, importers, and end users for the proper disposal of waste generated by solar panels, thereby promoting the development of collection and treatment infrastructure. For example, according to the EUROSTAT database, approximately 47.8 tonnes of photovoltaic panel waste were collected in 2022, of which about 43.6 tonnes were recycled (EUROSTAT, 2024). The emergence of

companies and non-profit organizations specialized in collecting and processing materials from photovoltaic panels has also been driven by these regulations. One example is PV Cycle, a non-profit organization that collected approximately 14.5 tonnes of waste generated by photovoltaic energy systems in 2023 (PV Cycle, 2023).

DISCUSSION

Within the global environmental and technological context, the increasing adoption of lead-based perovskites for solar cell production has followed a path of growing prominence (Casarin, 2024), owing to the numerous advantages they offer compared with other materials (Torrence et al., 2023), as discussed throughout this article.

However, this progress, driven by the expanding photovoltaic market, presents both challenges and opportunities related to its sustainability (cf. p. 19). Although lead is a highly regulated toxic metal (CONAMA, 2008), it remains one of the principal challenges for the implementation of perovskites in solar panels, both in terms of technological issues — such as their operational lifetime, which requires encapsulation techniques and related approaches (Teixeira, 2023) — and with respect to environmental preservation and, consequently, public health (Torrence et al., 2023).

One of the most challenging environmental aspects of photovoltaic sustainability concerns the substantial generation of waste resulting from the disposal of solar panels — estimated to reach 60 to 78 million tonnes by 2050 (IRENA, 2016). In this context, the potential large-scale application of lead-based perovskites could lead to significant environmental impacts due to the toxicity of lead, despite its currently being the most effective alternative among available materials, as demonstrated by the studies of Jena et al. (2019).

Therefore, end-of-life management of these devices, particularly

recycling, becomes the key factor in maximizing both socioeconomic and environmental benefits (Schmidt et al., 2023). In this regard, the adoption of regulations such as the WEEE Directive (European Union), RCRA (United States), and NBR 10004 (Brazil) has played a fundamental role in developing disposal and recycling strategies for photovoltaic modules that have reached the end of their operational life.

The emphasis on end-of-life management has driven the development of encapsulation technologies (Teixeira, 2023), material recovery pathways, and reverse logistics initiatives (CONAMA, 2008; Lillieskȍld et al., 2019). The explicit inclusion of photovoltaic modules under the WEEE Directive established recycling and reuse targets that stimulated industrial initiatives, such as PV Cycle, and contributed to recovery rates exceeding 85%. Considering that the reusability of recovered materials is essential for both sustainability and economic viability (Suo, 2024; Schmidt et al., 2023), recovery rates of this magnitude strongly support the sustainability of photovoltaic panels based on lead-containing PSCs.

Furthermore, the analysis of available data reveals that although the disposal of lead-containing PSCs represents a significant environmental risk due to lead leaching, several recycling technologies are being developed to recover lead and other valuable materials. These approaches not only mitigate environmental and public health risks but also provide substantial economic benefits, particularly through the recovery of high-value components such as substrates and the reduction of hazardous waste disposal costs. The successful reuse of recycled materials in new solar cells with performance comparable to that of cells produced from virgin materials, together with the positive results of Life Cycle Assessment (LCA) studies, highlights the potential of recycling to make PSC technology more sustainable and competitive within the solar energy market, in alignment with sustainability goals (Wu et al., 2024).

In summary, the consolidation of lead-based PSCs as a dominant alternative in the photovoltaic sector depends on multiple factors, constituting a complex and multifaceted process whose importance extends beyond environmental considerations alone (Casarin, 2024). Effective end-of-life management of these panels, supported by stringent regulations and efficient recycling technologies, will contribute to reducing the environmental risks associated with lead toxicity. In this way, technological and environmental challenges become opportunities to innovate in recovery processes, strengthen economic viability, and ensure that the transition toward cleaner energy sources is genuinely sustainable throughout the entire life cycle of the technology (Torrence et al., 2023).

CONCLUSION

The present study achieved its proposed objectives by demonstrating that, from the perspective of electrical engineering, perovskite solar cell technology represents a transformative opportunity for the energy sector by offering innovative and highly efficient solutions for renewable energy generation.

The development and optimization of these devices require advanced technical knowledge that encompasses not only electrical performance but also the integration of these systems into modern power grids, thereby ensuring stability, reliability, and energy efficiency.

The challenges associated with lead toxicity, as well as issues related to material durability and end-of-life disposal, highlight the need for electrical engineers to work in a multidisciplinary manner, collaborating with specialists in materials science, environmental science, and sustainability to enable the development of safer and longer-lasting technologies.

It was concluded that electrical engineering, by advancing circuit design, energy storage systems, power conversion technologies, and intelligent monitoring systems, plays a crucial role in enabling perovskite solar cells to achieve their full potential within the energy matrix, thereby contributing to a sustainable and technologically advanced future. Consequently, the integration of technological innovation and environmental responsibility becomes essential for establishing lead-based perovskites as key contributors to the global energy transition, reinforcing the commitment of electrical engineering to solutions that combine efficiency with sustainability.

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