Publishing Excellence
Inspiring Progress
ARISTON PUBLICATIONS
ChemSci Advances
ISSN: 2997-9587 https://aristonpubs.com/journal/chemsci-advances https://doi.org/10.69626/csa.2026.0133

REVIEW ARTICLE

Environmental Impacts of Potentially Hazardous Materials and Chemicals in Emerging Solar Cells: A Life–Cycle Perspective

Raghul Ramachandran[1], Jeyaprakash Jenson Samraj [1,2], Bernaurdshaw Neppolian [1,*]

ABSTRACT: Emerging solar cell technologies are attracting increasing attention because of their potential for lightweight, flexible, and low-cost solar energy conversion. However, their environmental performance depends not only on how efficiently they are run, but also on the materials, chemicals, and manufacturing processes used in their life cycle. Technologies such as perovskite solar cells (PSCs), dye-sensitized solar cells (DSSCs), organic photovoltaics (OPVs), and quantum dot solar cells (QDSCs) have many advantages, but their development is accompanied by concerns surrounding the use of hazardous materials such as lead, cadmium, and selenium-containing compounds, metal-based materials, and organic solvents. In addition, the fabrication of substrates, electrodes, charge transport layers, and other device elements can be a major contributor to resource consumption and environmental impacts. This review focuses on the materials and chemicals used in emerging solar cells and their potential impact on human health and the environment. It discusses the role of life cycle assessment (LCA) and energy payback time for assessing their environmental performance and possible contamination pathways during production, use, and end-of-life management. Considered approaches include green chemistry, safer selection of materials, waste minimization, solvent recovery, improved encapsulation, and reuse and recycling. The review points to the need for more comparable LCA studies, reliable toxicity and leaching assessments, and effective end-of-life management strategies. To summarize, the development of sustainable solar cell technologies is a balancing act between device performance, material safety, manufacturing requirements, and environmental responsibility over the entire life cycle.

Keywords: Emerging solar cells, life-cycle assessment, environmental impact, hazardous materials, perovskite solar cells, dye-sensitized solar cells, organic photovoltaics, quantum-dot solar cells, recycling

Received: 07 May 2026; Revised: 02 July 2026; Accepted: 19 July 2026; Published Online: 08 August 2026

1. INTRODUCTION

Traditional power systems face increased strain owing to the rising demand for electricity, industrial output, transportation, telecommunications networks, and quality-of-life issues [1]. The burning of fossil fuels leads to greenhouse gas emissions and is linked to air pollution, resource exhaustion, and health impacts due to climate change [2]. Solar, wind, hydroelectric, geothermal, and properly managed bioenergy are renewable sources of energy that are integral to diversifying energy sources and reducing carbon emissions [3]. These sources have different environmental impacts, such as land use, mineral needs, manufacturing impacts, water use, and ecological impact, depending on the source and location [4]. Such a comparison requires consideration of the entire energy system rather than just operational emissions [5].

The appeal of solar energy lies in its abundance, direct conversion to electricity through solar panels, and the use of this type of energy for various applications ranging from portable to utility-scale power plants [6]. Solar panels do not involve the burning of fuels and emit minimal greenhouse

[1] Energy and Environmental Remediation Laboratory, Department of Chemistry, Faculty of Engineering and Technology, SRM Institute of Science and Technology, Kattankulathur, Chengalpattu - 603 203, Tamil Nadu, India. E-mail: neppolib@srmist.edu.in
[2] Department of Applied Chemistry, Osaka Metropolitan University, 1-1 Gakuen-cho, Sakai, Osaka 599-8531, Japan

* Author to whom correspondence should be addressed: neppolib@srmist.edu.in (Bernaurdshaw Neppolian)

© Ariston Publications 2026. All rights reserved.

gases throughout their lifetime [7]. The benefits of solar panels include their modularity, silent operation, compatibility with buildings, and mobility [8]. However, the production and utilization of electricity generated by solar panels has certain environmental effects [9]. The extraction of materials and processing of glass and metals, chemicals, assembling modules, transporting, maintaining, and decommissioning of the systems affect the environment [4]. The extent of environmental impact is influenced by the composition of the electricity mix, manufacturing technology, efficiency, lifetime, and recycling rates [5].

Attempts have been made to categorize different solar cell technologies into generations; however, this classification is not universal throughout the literature [10]. First-generation solar cells mainly consist of crystalline silicon cells, either monocrystalline or multi-crystalline [9]. Second-generation solar cells are mostly thin-film solar cells, such as amorphous silicon, cadmium telluride (CdTe), and copper indium gallium selenide (CIGS) [10]. Third-generation or emerging solar cells include PSCs, DSSCs, OPVs, polymer-based solar cells, QDSCs, tandem, and other advanced solar cell architectures [11]. This is a good way to categorize the technologies; however, it does not mean that all emerging technologies have the same development stage or impact on the environment [12].

Environmental impact assessments of traditional silicon and thin-film photovoltaic cells have revealed environmental effects related to energy-intensive purification, mining, and the possible toxicity of the materials used [9]. Novel types of solar cells use new sets of materials and production methods [11]. The potential benefits of novel solar cells, such as low-temperature processing, lower material consumption, and flexibility of form factors, should be considered in light of the risks associated with solvents, critical metals, toxic absorbers, short lifetimes, and recycling difficulties [12]. New comparative studies on the environmental aspects of emerging photovoltaic systems have identified material-specific hotspots, such as fullerenes in organic solar cells, glass and electrodes in dye-sensitized and perovskite solar cells (PSCs), and heavy metal absorbers in quantum dot cells [10]. In particular, for PSCs, prospective life cycle assessments (LCA) indicate that upscaling, material choices, and recycling pathways strongly determine their environmental performance [13].

This review aims to assess the environmental and human health impacts of materials and chemicals used in new solar cell technologies, focusing on life cycle aspects. First, LCA and energy payback are introduced. Subsequently, the environmental impact and hazards inherent to each new technology are assessed. This is followed by a description of the cross-cutting health and environmental impacts and mitigation options. Gaps in the current knowledge include the need for comparable inventories, leaching test protocols, and end-of-life scenarios for new devices.

1.1. Life cycle assessment

LCA is a systematic tool for evaluating the environmental impacts of a product or process at different stages of its life cycle [14]. For solar cells, cradle-to-grave LCA may include steps such as raw material mining, precursor production, substrate and electrode production, cell manufacturing, module assembly, packaging, transportation, installation, operation, maintenance, decommissioning, recycling, and the final disposal of solar cells [11]. The cradle-to-gate LCA ends at the factory gate, whereas the cradle-to-grave assessment covers the use and end-of-life phases [15]. The functional unit must be well defined (e.g., one square meter of module, one installed kilowatt-peak, or one kilowatt-hour of electricity produced in the lifetime) because the results cannot be compared without identical functional units and system boundaries [4, 14].

The popular impact classes include climate change, cumulative energy demand, human toxicity, freshwater and marine ecotoxicity, particle formation, acidification, eutrophication, water consumption, land use, scarcity of minerals and fossil fuels, and waste production [16]. The approach and assumptions behind the selected impact assessment must be stated [11]. It is important to note that lab-scale equipment does not necessarily reflect industry-scale manufacturing, as lab-scale manufacturing processes involve excessive solvent usage, purification on small scales, material losses, and energy-demanding machines [13]. Predictive LCA allows the estimation of possible future impacts but is dependent on certain assumptions about scale-up, manufacturing yield, electricity supply, efficiency, and lifetime [12, 16].

LCA is especially important for new solar cell technologies because high efficiency does not necessarily translate to an environmentally friendly device [10]. Solar cells with toxic absorbers, dangerous solvent systems, low manufacturing yields, or short lifetimes can have a greater environmental impact per kWh than less efficient but more durable solar cells [9]. Thus, any comparative study must include efficiency, along with lifetime, degradation rate, manufacturing yield, recycling possibilities, and assumptions regarding electricity production [11, 12].

1.2. Energy payback time

The energy payback time (EPBT) refers to the time period during which a solar energy system must work to create the same amount of energy used to manufacture the system and is based on the study boundary during the installation and at the end-of-life phase [7]. The EPBT is an energy-related index and should not be viewed as an alternative to LCA because it does not directly measure toxicity, water use, land use, or resource depletion [14]. The calculation procedure must clearly indicate whether the energy is calculated in terms of electricity or equivalent electricity [4, 17]. This can be calculated using the following formula:

$$EPBT = E_{input}/(E_{PV}/\alpha) \quad (1)$$

© Ariston Publications 2026. All rights reserved.

where E_{input} is the required energy for the solar cell production

E_{PV} - Electricity generation from solar cells/year

α - Electricity-producing energy conversion factor

2. OVERVIEW OF EMERGING SOLAR CELLS

2.1. Development and operating principles

New photovoltaic technologies are being developed to supplement traditional silicon solar cells in situations where qualities such as light weight, flexibility, semitransparency, low-temperature processability, and coating over large areas are important [18]. The working principles of these new technologies differ owing to the different materials used and charge-separation processes [10]. PSCs use metal halide perovskites for absorption, dye-sensitized solar cells (DSSCs) use light-absorbing dyes fixed on a porous semiconductor, organic photovoltaics (OPVs) use organic donor-acceptor semiconductors, polymer solar cells use conjugated polymers as active or charge transport layers, and quantum dot solar cells (QDSCs) use semiconductor nanocrystals of different sizes [18]. Each new technology requires individual analysis because it has different sets of materials and hotspots [11].

"Polymer solar cells" is a term used for an organic photovoltaic device that uses at least one component in its active layer, which consists of a conjugated polymer [19]. This implies that it is not always appropriate to refer to organic and polymer solar cells as two distinct technologies [20]. In this review, OPVs are described broadly, whereas polymer solar cells are considered to be material-based cells [21].

2.2. Classification and key material components of emerging solar cells

New solar cells can be classified according to the structure of the photoactive materials and the processes involved in the conversion of light radiation into electric power [18]. These include inorganic metal halide perovskites, dye-sensitized semiconductor systems, organic molecules/polymer semiconductors, and semiconductor quantum dots [18]. Apart from the photoactive part of the cell, there are other components, such as substrates, transparent conductive electrodes, charge-transporting layers, counter electrodes, interface layers, and encapsulation layers [10]. Different technologies differ significantly in terms of the makeup of these layers and methods of their fabrication, and thus, their impact on resource use and the environment [11].

The selection of materials plays an important role in the evaluation of new solar cells because the performance and environmental properties depend on the total design of the cell and not only on the photoactive layer [10]. For example, absorbers with metals, organic solvents, redox electrolytes, metallic contacts, and nanostructured semiconductors play different roles in determining the environmental profile of a solar cell [13]. Thus, an assessment of environmental impact should include the entire set of materials used in the manufacturing process [11].

2.3. Life cycle stages of emerging solar cell technologies

The environmental impacts of new solar cell technologies must be considered throughout the full lifecycle of the technology, from the mining and processing of materials to the manufacturing process, transport, installation, operation, maintenance, and disposal of the solar cells [11]. Different stages can have varying impacts on energy consumption, greenhouse gas emissions, resource depletion, chemical exposure, and waste production [10]. Although some new solar cell technologies have positive aspects, such as low-temperature manufacturing and material savings, these must be weighed against the environmental impacts of material production and disposal [13].

LCA provides a structured approach for comparing environmental impacts by considering material and energy inputs, emissions, and waste generated over the specific boundaries of the system [16]. The environmental performance of new types of solar cells is influenced by factors such as material choice, manufacturing efficiency, type of electricity used, working lifetime, energy production, and recyclability at the end of the product life cycle [12]. Thus, considering only one process or component may lead to a lack of comprehensive sustainability assessment [11].

3. ENVIRONMENTAL IMPACT OF INDIVIDUAL EMERGING SOLAR-CELL TECHNOLOGIES

3.1. Perovskite solar cells

Metal halide perovskites have been widely studied in the scientific literature owing to their high optical absorption, tunable band gap, long carrier diffusion lengths, and suitability for both solution processing and vapor deposition techniques [32]. In general, the absorber material consists of an organic/inorganic cation, a metal cation, and a halide anion [33]. Although the study of lead-containing materials is still widespread, tin-containing and other materials with reduced lead content or without lead are also being researched [32]. The structure of such solar cells can contain transparent conducting oxides, electron/hole transport layers, metal contacts, glass substrates, and other elements [11]. Lead is the main toxin in most high-performance PSCs [34].

Lead exposure poses risks to the nervous system, kidneys, and hematopoietic system, and to development, with children being more sensitive to lead [34]. Environmental issues extend beyond the small amount of lead present in one laboratory cell because accidents such as breakage, fire, weathering, waste from manufacturing processes, or disposal can create a pathway for lead-

© Ariston Publications 2026. All rights reserved.

containing particles or dissolved compounds to enter the soil and water [35]. The real risk depends on the device design, encapsulation, rate of release, route of exposure, and environmental conditions; hence, the presence of lead must be considered a hazard, rather than an indication of lead exposure [13]. In addition to the inherent toxicity of lead, there is another danger in the way that it can be released through the manufacturing, utilization, and disposal processes of PSCs (Figure 1) [35].

Table 1. Classification and principal components of emerging solar-cell technologies

Technology	Photoactive material	Other major device components	Ref.
PSCs	Metal halide perovskites, typically based on lead or tin halides	Electron- and hole-transport layers, transparent conducting substrate/electrode, counter electrode and encapsulant	[22, 23]
DSSCs	Photosensitizing dyes, including ruthenium-based complexes and metal-free organic dyes	Mesoporous TiO_2 or ZnO photoanode, redox electrolyte, transparent conducting substrate and counter electrode	[24, 25]
OSCs/OPVs	Organic donor-acceptor semiconductors, including conjugated polymers, small-molecule donors and fullerene or non-fullerene acceptors	Transparent and back electrodes, electron- and hole-transport interlayers, and flexible or rigid substrates	[26, 27]
OPVs	Conjugated polymer donors combined with polymeric or small-molecule electron acceptors.	Electrodes, electron- and hole-transport layers, substrates and encapsulation layers	[28, 29]
QDSCs	Semiconductor quantum-dot nanocrystals, including PbS, CdS, CdSe and other emerging compositions	Surface ligands, electron- and hole-transport layers, electrodes, substrates and encapsulation materials	[30, 31]

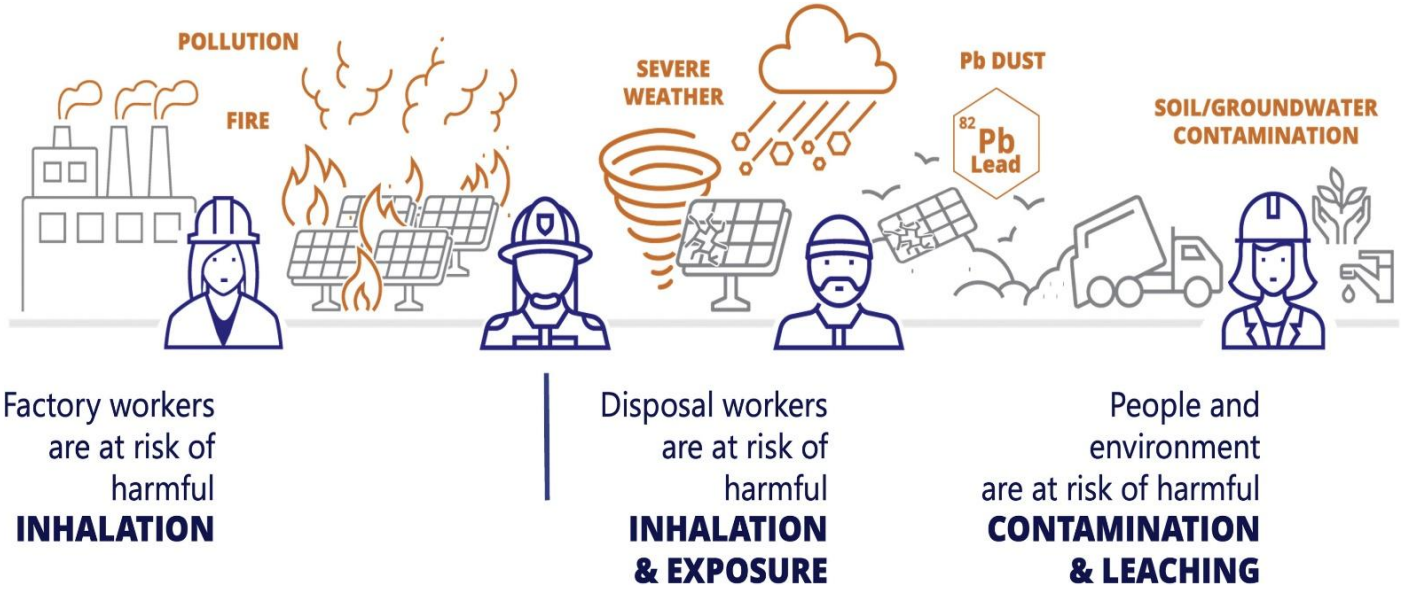


Fig. 1. Potential occupational and environmental exposure routes related to lead-containing PSCs during production, destruction, and disposal, which can include the inhalation of lead-containing dust, direct exposure, and soil and groundwater contamination through leaching. Reproduced with permission from Ref. [35]. Torrence, C.E., Libby, C.S., Nie, W. and Stein, J.S., **2023**. Environmental and health risks of perovskite solar modules: Case for better test standards and risk mitigation solutions. *Iscience*, *26*(1). https://doi.org/10.1016/j.isci.2022.105807. Copyright © 2023 Elsevier.

 © Ariston Publications 2026. All rights reserved.

Table 2. Potentially hazardous materials and chemicals used in perovskite solar-cell fabrication, their functions, safety concerns, and water solubility

Material/chemical	Function in PSC fabrication	Principal safety concerns	Water solubility	Ref.
Lead iodide (PbI_2)	Lead and iodide precursor for the perovskite absorber	Toxic, reproductive and developmental health hazards associated with lead exposure; environmental hazard	Poorly soluble	[38]
Lead bromide ($PbBr_2$)	Lead and bromide precursor for mixed-halide perovskites	Toxic lead-containing compound; environmental hazard	Poorly soluble	[38]
Methylammonium iodide (MAI)	Organic cation and iodide precursor	Irritation and potential harmful effects; handle according to supplier SDS	Soluble in water	[39]
Formamidinium iodide (FAI)	Organic cation and iodide precursor	Compound-specific hazard classification; avoid inhalation and direct contact	Miscible with water	[40]
Cesium iodide (CsI)	Inorganic cation precursor in mixed-cation perovskites	May irritate; avoid dust exposure	Soluble in water	[40]
Dimethylformamide (DMF)	Solvent for dissolving perovskite precursors	Reproductive toxicant; harmful by inhalation and skin exposure	Miscible with water	[41]
Dimethyl sulfoxide (DMSO)	Solvent and coordinating agent in precursor solutions	Relatively lower toxicity than DMF; can enhance dermal absorption of dissolved substances	Miscible with water	[42]
γ-Butyrolactone (GBL)	Solvent for perovskite precursor preparation	Eye damage and other exposure-related hazards; requires controlled handling	Miscible with water	[41]
Isopropanol (IPA)	Antisolvent, washing and cleaning solvent	Highly flammable; may cause eye irritation and dizziness	Miscible with water	[42]
Chlorobenzene	Antisolvent and solvent for organic charge-transport materials	Harmful; volatile; potential environmental hazard	Poorly soluble in water	[42]
Acetone	Substrate cleaning and washing solvent	Highly flammable; causes eye irritation	Miscible with water	[38]
Ethanol	Cleaning, washing, and selected solution-processing solvent	Highly flammable; may cause eye irritation	Miscible with water	[38]
Tin dioxide (SnO_2)	Electron-transport layer	Dust inhalation may cause respiratory irritation	Insoluble in water	[43]
Zinc oxide (ZnO)	Electron-transport layer	Fine-particle inhalation and aquatic toxicity concerns	Insoluble in water	[43]

© Ariston Publications 2026. All rights reserved.

PCBM ([6,6]-phenyl-C_{61}-butyric acid methyl ester)	Fullerene-based electron-transport material	Potential concerns associated with fullerene exposure; limited toxicological evidence	Insoluble in water; soluble in selected organic solvents	[44]
Nickel oxide (NiO_x)	Inorganic hole-transport layer	Inhalation hazard; nickel-containing materials may pose occupational and environmental concerns	Insoluble in water	[45]
Copper thiocyanate (CuSCN)	Inorganic hole-transport material	Avoid inhalation and uncontrolled environmental release. Consult compound-specific safety data sheets (SDS).	Poorly soluble in water	[45]
Gold (Au)	Back electrode	Bulk gold has relatively low chemical reactivity, and occupational concerns depend on the form and processing method.	Insoluble in water	[40]
Silver (Ag)	Back electrode	Silver ions and some silver compounds can be toxic to aquatic organisms	Insoluble in water	[40]
Aluminium (Al)	Back electrode in selected device architectures	Fine aluminium powder is flammable; bulk aluminium is comparatively stable	Insoluble in water	[40]
Titanium isopropoxide	Precursor for preparing TiO_2 electron-transport layers	Flammable; moisture-reactive; may cause serious eye and skin irritation or burns	Reacts with water rather than simply dissolving	[43]

Tin-based perovskites are being studied as replacements for lead-based perovskites; however, replacement does not necessarily imply environmental benefits [32]. Tin (II) ions are prone to oxidation into tin (IV) ions, which can adversely affect the properties of the devices. The toxicological profile and life cycle impact depend on many factors, including the synthesis of precursors, additional materials, solvents, transport layers, and manufacturing efficiency [36]. A comprehensive comparison of the entire composition, rather than just the absorber metal, should be conducted [11].

The choice of solvent is an additional primary consideration [33]. Solvent-based fabrication processes typically use polar aprotic solvents, such as N, N-dimethylformamide (DMF), dimethyl sulfoxide (DMSO), and N-methyl-2-pyrrolidone (NMP) [32]. This depends on the processing conditions [33]. The safety and environmental aspects of each solvent differ, and the main health hazards are DMF and NMP [32]. Other solvents that may be employed include chlorobenzene [33]. These can be applied to deposition and antisolvent processes [32]. Safe solvents, solvent recycling, closed processing, and vapor deposition systems can minimize exposure and emissions [13]. However, other resource requirements should also be considered.

The stability of PSCs is another major impediment to their widespread use [37]. Exposure of these cells to moisture, oxygen, heat, and sunlight may cause degradation of the perovskite layer and other cell parts, resulting in a loss of efficiency [37]. This process may increase the chances of lead release, especially when protective encapsulation is lost [35]. Scientists have been exploring better encapsulation systems and coatings to make PSCs more stable [37]. The increased stability of PSCs is important for improving efficiency and reducing environmental pollution [13].

Energy usage, solvent consumption, fabrication of substrates and electrodes, and the use of transport layers are important in the LCA of PSCs [13]. There are certain other environmental influences associated with perovskite/silicon tandem devices, some of which include the environmental impacts caused by the use of a silicon bottom cell and additional processes involved in the tandem design [15]. Thus, the comparisons made must consider the same electrical power output for the same service life [12, 14].

3.2 Dye-sensitized solar cells

In DSSCs, incident light is converted into electrical energy using a dye molecule adsorbed on a high-surface-area

 © Ariston Publications 2026. All rights reserved.

semiconductor, such as titanium dioxide, with a redox electrolyte and counter electrode. The manufacturing process of dye-sensitized solar cells involves the following three key steps: 1. Formation of a transparent photoanode covered with TiO_2; 2. Adsorption of dye molecules on the TiO_2 surface; and 3. The device was fabricated using a polymer counter electrode (CE), separator, and redox electrolyte (Figure 2) [46]. Ruthenium dye complexes have been widely used for their favourable optoelectronic and charge-transfer properties; however, metal-free organic dyes are also available [47]. The electrolyte is often composed of iodide/triiodide or other redox pairs and is sometimes dissolved in an organic solvent [10]. The counter electrode can be made of platinum or carbonaceous material [18]. Thus, the environmental inventory includes glass substrates, transparent conductors, TiO_2, dye precursors, electrolytes, solvents, and electrode materials [11].

Environmental issues may arise owing to the use of rare or metallic dyes, the presence of platinum in some counter electrodes, volatile or flammable electrolyte solvents, and reactive species used as redox couples [10]. Leakage is possible for liquid electrolytes when the sealing system fails [11]. Solvent evaporation and the release of volatile organics may occur during manufacturing or operation owing to incomplete sealing [13]. Toxicity is substance-specific; for cells containing either ruthenium- or iodine-based species, it is necessary to consider the actual substance, its dose, the exposure pathway, and the method of disposal, unlike general statements about DSSCs [11].

The LCA results suggest that glass substrates and electrode materials may be significant sources of environmental impact in DSSCs. This suggests that the dye component of solar cells is not always the main environmental concern. Improvements that can be made include reducing glass and metal usage, making metal-free dyes, substituting platinum when possible, choosing safer electrolytes, improving sealing, and disassembling the module [10, 13].

3.3 Organic solar cells

OPVs use organic semiconductors that serve as electron donors and acceptors [20]. The benefits of OPVs include their lightweight nature, flexibility, possible semitransparency, and suitability for printing/coating [18]. The active material can be a conjugated polymer or small molecule, a derivative of fullerenes such as PCBM, or a non-fullerene acceptor [19]. Other materials include electrodes, interlayers, substrates, encapsulants, and solvents [10]. Because of the variety of chemicals used in OPVs, there is no generic toxicity statement that will describe all OPVs [11].

Environmental issues arise in the synthesis and purification of special organic semiconductors, metal catalysis or metal reagents in some polymerization processes, fullerene synthesis, and the use of aromatic or chlorinated solvents in the synthesis of materials and the formation of films. Chlorobenzene and similar solvents may also cause occupational exposure and hazardous waste problems, despite their small role in cumulative energy demand [13].

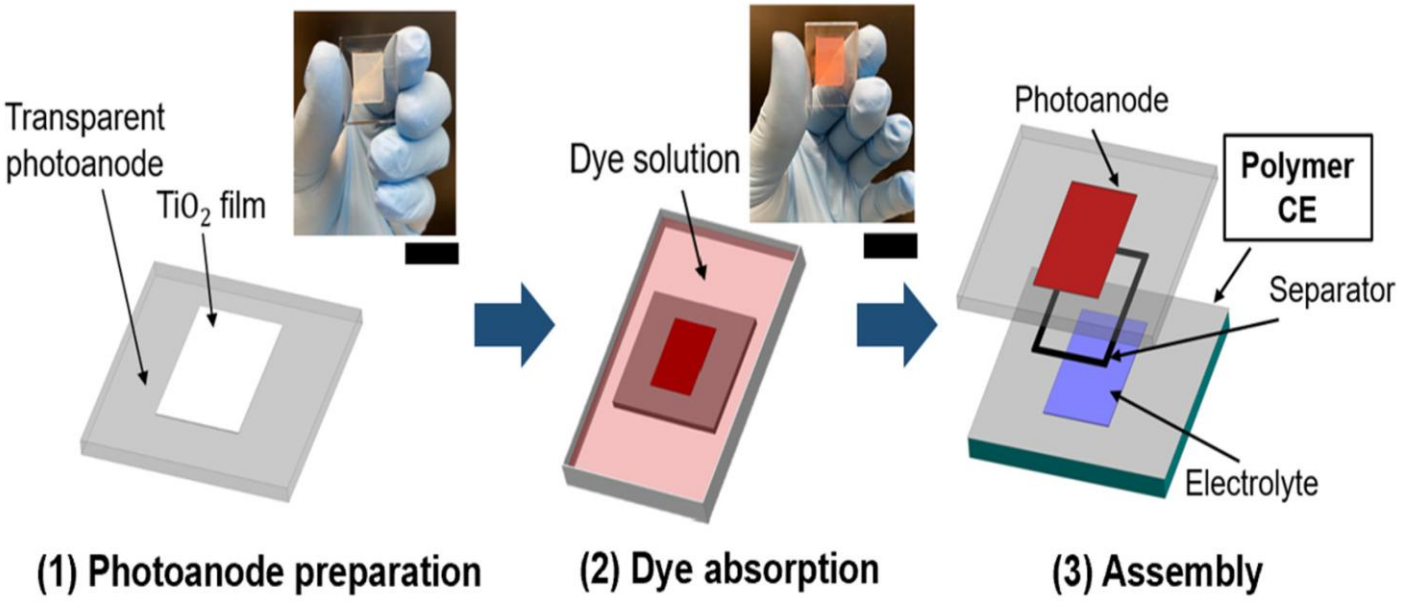


Fig. 2. Schematic of the DSSC preparation process. Reproduced with permission from Ref. [46], Akin, S., Kim, S., Song, C.K., Nam, S.Y. and Jun, M.B.G., **2024**. Fully additively manufactured counter electrodes for dye-sensitized solar cells. *Micromachines*, *15*(4), p.464. https://doi.org/10.3390/mi15040464. Copyright © Creative Commons Attribution (CC BY) license. 2024 MDPI.

© Ariston Publications 2026. All rights reserved.

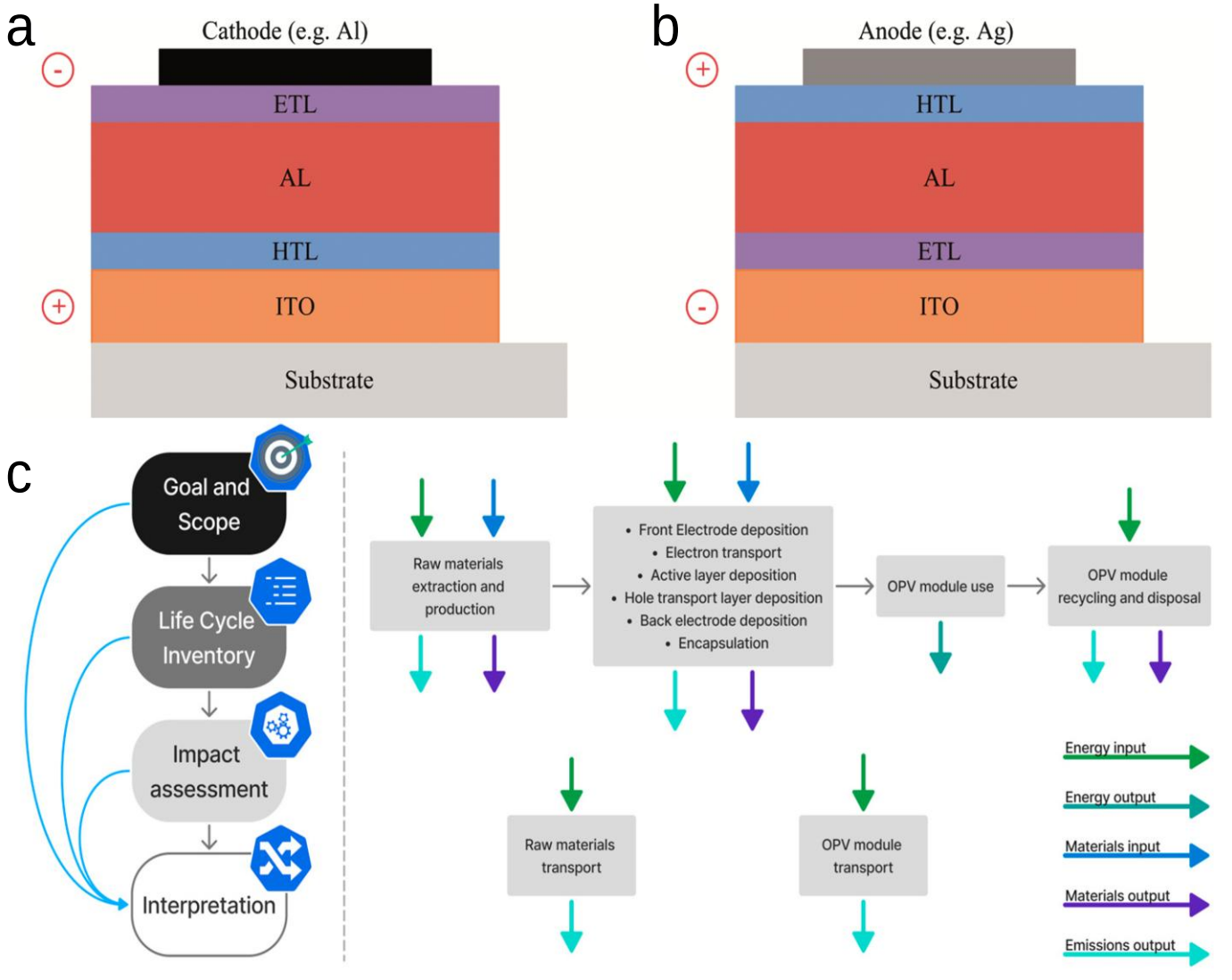


Fig. 3. (a) Representation of the conventional OPV cell structure, indicating the cathode, ETL, AL, HTL, ITO, and substrate. (b) OPV cells with inverted structure, showing the inverse arrangement of the charge-transport layers and electrodes. Reproduced with permission from Ref. [48]. Copyright © 2013 Royal Society of Chemistry. (c) LCA scheme for OPV modules, including the definition of the goal and scope, life-cycle inventory, impact assessment, and evaluation stages, along with materials and energy inputs, as well as the manufacturing, distribution, use, recycling, and disposal stages. Reproduced with permission from Ref. [49]. Kiskira, K., Kalkanis, K., Coelho, F., Plakantonaki, S., D'onofrio, C., Psomopoulos, C.S., Priniotakis, G. and Ioannidis, G.C., **2025**. Life cycle assessment of organic solar cells: Structure, analytical framework, and future product concepts. *Electronics*, *14*(12), p.2426. https://doi.org/10.3390/electronics14122426. Copyright © Creative Commons Attribution (CC BY) license. 2025 MDPI.

Polymer solar cells can be manufactured in either conventional or inverted designs through changes in the order of the electron and hole transporting layers (Figure 3a, b). The environmental impact of these solar cells can be analyzed through a life cycle analysis (LCA) that includes production, manufacturing, transportation, use, recycling, and disposal phases (Figure 3c) [48]. According to LCA studies, fullerene derivatives have been found to be major environmental hotspots in some specific OPV systems; however, this does not mean that all fullerene or non-fullerene systems have the same environmental effects [11].

The environmental performance of OPVs is greatly influenced by the active layer loading, synthesis yield, solvent recycling, OPV lifetime, and disposal procedures [12]. The small amount of energy required to process OPVs should not be considered an indicator of low environmental impact when the synthesis of the active material is complicated and when the lifetime is short, causing repeated replacement of OPVs [9]. Green chemistry approaches include the reduction of synthetic processes, the use of non-stoichiometric toxic reagents, catalytic syntheses, bio-derived feedstocks, when possible, and the use of safe

 © Ariston Publications 2026. All rights reserved.

solvents in place of dangerous ones [13].

3.4 Polymer solar cells

Polymer solar cells are generally viewed as part of OPV systems, in which conjugated polymers are used as donor materials, acceptors, or charge carriers [48]. In standard experimental setups, a donor polymer is used with either a fullerene or a non-fullerene acceptor [50]. Their production is compatible with the roll-to-roll coating process and flexible substrates, which can lead to lower material usage and novel applications [51]. However, their environmental impact depends on polymer chemistry, molecular weight distribution, synthesis method, solvents, and electrodes used [48, 49].

Potential hazards include exposure to residual monomers, catalysts, coupling agents, and organic solvents used in polymer formation and coating applications [52]. Polymerization reactions can lead to the formation of hazardous metals. Chlorinated aromatic solvents pose inhalation risks and are problematic for disposal [53]. Polymers remain in the environment, and the decomposition products of organic compounds are not always clear. Hazard assessments must consider all chemicals, from synthesis reaction intermediates to process aids [48].

The environmental impact of polymer solar cells can be reduced by choosing safer chemicals and improving their preparation methods [54]. Studies are investigating less harmful solvent substitutes, water-based processing methods, and solvent recycling to minimize chemical waste [55]. Improvement of polymer synthesis processes and reduction of energy used in production may also help [56]. The use of renewable raw materials is another possible approach, although the environmental benefits of such an approach need to be assessed considering the resources required for their production [11, 48].

3.5 Quantum dot solar cells

QDSCs use semiconductor nanocrystals as light-harvesting components [57]. The ability to tune the bandgap of these semiconductors and process them in solution offers possibilities for tunable optical absorption and potentially inexpensive production methods [58]. The materials studied include PbS, CdS, CdSe, and other metal chalcogenides [59]. Other materials that can be used in this type of cell include ligands, surface passivators, charge transport layers, electrodes, and encapsulation materials [59]. Consequently, the environmental impact depends on the composition of the quantum dots and the chemistry used in their manufacture and assembly into devices [10].

Metal-containing quantum dots, such as those based on cadmium, lead, and selenium, require strict hazard evaluation because of the possibility of the release of metal-containing nanomaterials or their byproducts and their impact on aquatic and terrestrial life [60]. Exposure routes include inhalation of the powder or aerosol form during the synthesis process, skin or eye exposure to the precursor solution, discharge of wastewater containing nanoparticles, and release of nanoparticles from damaged or disposed-of devices. The toxicity of nanoparticles cannot be predicted based on the toxicity of bulk elements alone; factors such as size, coatings, and dissolution affect their behavior and bioavailability [11].

There is considerable literature on the LCA of quantum dot solar cells, which identifies heavy-metal-based absorber materials as environmental hotspots. Safer-by-design approaches include using less toxic compositions, improving synthesis yields, recovering excess precursors, collecting nanoparticle-containing effluents, and strong encapsulation [10, 11]. Lead- and Cd-free alternatives should not be considered environmentally safe until comparative data on the toxicity of the precursors, resource demands, product lifetime, and end-of-life scenarios are available [11]. Figure 4 illustrates the solar cell structure using PbS quantum dots (QDs). Panels (a) and (b) represent various solar cell structures using gold (Au) electrodes, a hole transport layer (HTL), PbS QD layer, TiO2, and ITO. The energy level alignment of the different materials in the structure is illustrated in panel (c), whereas the absorption coefficient for the PbS QD layer at varying wavelengths is shown in panel (d) [30].

4. COMPARATIVE ASSESSMENT OF TOXIC MATERIALS AND CHEMICALS IN EMERGING SOLAR CELLS

The materials and chemicals used in new types of solar cells depend on the cell structure, production method, and photoactive layer [10]. Although these cells were developed as an alternative to conventional silicon solar cells, their production process may use materials that require special handling because of their hazardous nature [35]. These materials include heavy metals, organic solvents, metallic compounds, nanomaterials, and special electrode materials. However, the environmental impact depends not only on the photoactive material [11].

In the comparative analysis of different solar cell technologies, different environmental problems can be identified. PSCs are linked to the presence of absorbers containing lead and solvents used in the production process [34]. In the case of dye-sensitized solar cells, there is a need for concern because of the presence of metal dyes, electrolyte solutions, and platinum counter electrodes [11]. In the case of organic and polymer solar cells, there are special types of organic compounds, synthesis materials for polymers, and organic solvents [48]. QDSCs are characterized by the presence of Cd, Pb, and Se nanoparticles.

The level of concern associated with the environment depends on the nature of the chemical involved, the amount used, the means of exposure, and the possibility of its release into the immediate environment. For example, a hazardous metal contained within an encapsulated device may have a

© Ariston Publications 2026. All rights reserved.

lower risk of exposure than the same metal in production plant effluent or waste from a discarded device [35]. In addition, the use of organic solvents in production may pose risks to both employees and the environment due to their emissions and improper disposal [48]. Therefore, the evaluation of such technologies requires both risk and exposure conditions [35].

This comparison indicates that no single material or chemical is responsible for all the environmental concerns associated with emerging solar cells. While some technologies are more strongly associated with heavy metal toxicity, others raise concerns related to solvent use, complex synthesis procedures, electrolyte leakage, and material recovery. These differences highlight the need for technology-specific safety measures and appropriate waste-management practices. Therefore, a life cycle approach is essential to identify major environmental hotspots and support the development of safer and more sustainable solar cell technologies [11].

5. ENVIRONMENTAL AND HEALTH HAZARDS

5.1 Occupational exposure during manufacturing

Manufacturing-related exposure may occur during precursor weighing, solution preparation, coating, annealing, electrode deposition, cleaning, and waste handling [33]. The routes of exposure include inhalation of vapors, aerosols, or dust, dermal contact, and accidental ingestion from contaminated surfaces [35]. Workers may be exposed to solvents, corrosive reagents, metal salts, nanomaterials, and process gases [33, 35]. Risk management should include the substitution of hazardous chemicals where feasible, closed transfer systems, local exhaust ventilation, appropriate personal protective equipment, training, spill procedures, and segregated waste collection [33]. The adequacy of the controls should be verified through exposure monitoring and documented risk assessment [35].

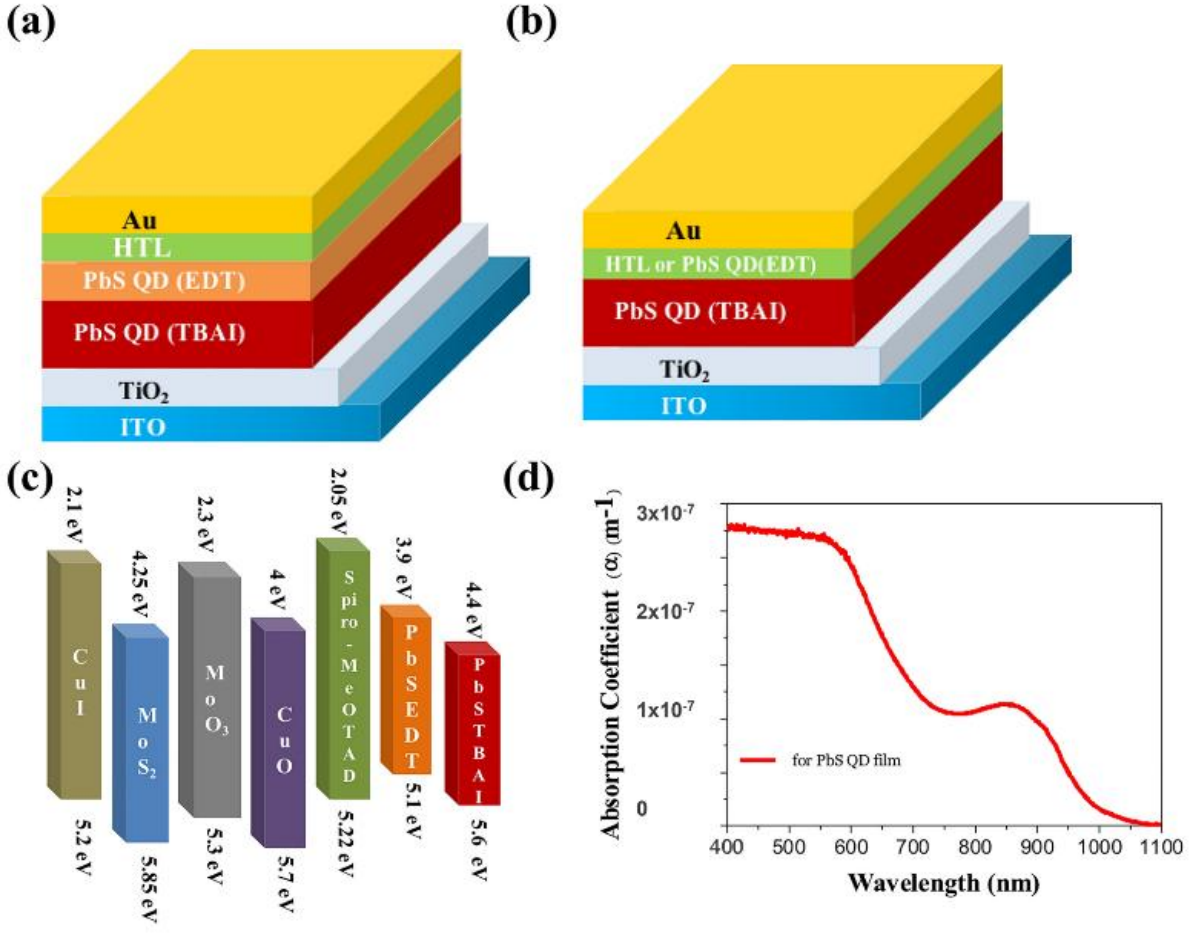


Fig. 4. Schematic diagrams of (a) architecture-1: ITO/TiO_2/PbS-TBAI/PbS-EDT/HTL/Au and (b) architecture-2: ITO/TiO_2/PbS-TBAI/HTL/Au. (c) Energy band diagrams of PbS QDSCs using various HTLs. (d) Absorption coefficient of PbS quantum dot film as a function of wavelength. Reprinted with permission from Ref. [30]. Neupane, K., Kabel, J., Uddin, J., Dubey, R., Ojha, R., Zhang, D. and Yap, Y.K., **2026**. Quantum Dot Solar Cells: Background, Progress, and Perspective. *Micromachines*, *17*(4), p.474. https://doi.org/10.3390/mi17040474. Copyright © Creative Commons Attribution (CC BY) license. 2026 MDPI.

 © Ariston Publications 2026. All rights reserved.

5.2 Soil and water contamination

Soil and water contamination can occur when wastewater from solar cell manufacturing is not properly treated, chemicals are accidentally spilled, or damaged and discarded modules are exposed to rainwater [34]. Improper disposal of manufacturing residues and end-of-life devices may also allow hazardous substances to enter the environment [11]. Once released, metals can be present in water and soil in different forms, and their movement depends on factors such as pH, oxygen availability, organic matter, and soil composition. The behavior of nanomaterials is also influenced by processes such as dissolution, aggregation, and changes in their surface properties [60].

These processes determine how easily materials move through soil and water and how long they remain in the environment [11, 60]. Therefore, suitable leaching tests are important for assessing the possibility of chemical release from solar cell materials under different environmental conditions [34]. Where possible, these tests should measure both the total amount of metals released and the fraction that is dissolved [60].

5.3 Air emissions and fire-related hazards

Air pollution may occur during solar cell manufacturing through solvent evaporation, thermal processing, and the release of exhaust gases [33]. Some volatile organic compounds released during these processes can affect worker health and contribute to air pollution [33]. Additional concerns may arise if solar cell modules are exposed to fires or high temperatures [35]. Under these conditions, polymers, encapsulating materials, and semiconductor components may decompose and release potentially harmful substances [64]. The nature of these emissions can vary depending on the type of solar cell technology and materials used in the module [35, 64]. Therefore, fire-related risks should be assessed by testing complete module structures and analyzing the emissions produced, rather than considering only the photoactive material [64].

Table 3. Comparative overview of potentially hazardous materials and chemicals used in emerging solar-cell technologies and their potential environmental and health concerns

Solar-cell technology	Representative materials and chemicals	Major environmental and health concerns	Ref.
PSCs	Lead halides (PbI_2, $PbBr_2$), tin halides in lead-free formulations, organic cation salts, DMF, DMSO, NMP, GBL, chlorobenzene, and metal electrodes (Ag, Au, Pt)	Potential lead release during manufacturing, module damage, and end-of-life disposal; occupational exposure to hazardous processing solvents; resource consumption associated with electrodes and substrates; and possible soil and water contamination through leaching.	[10, 35]
DSSCs	Ruthenium-based dyes, organic dyes, TiO_2 photoanodes, iodide/triiodide redox electrolytes, organic solvents, and platinum counter electrodes	Resource depletion associated with ruthenium and platinum, potential electrolyte leakage, solvent use and emissions during fabrication, and environmental impacts associated with glass substrates and dye synthesis are also drawbacks.	[61]
OSCs/OPVs	Conjugated organic semiconductors, fullerene derivatives (PCBM), non-fullerene acceptors, donor materials and processing solvents, including halogenated solvents	Environmental impacts associated with the synthesis of organic semiconductors and fullerene derivatives include hazardous solvent use and emissions during fabrication, chemical waste generation, and uncertainties regarding the environmental fate of some organic compounds.	[49]
OPVs	Conjugated polymer donors, polymeric or small-molecule acceptors, monomers,	Potential occupational exposure to residual monomers, catalysts, and processing solvents; solvent emissions during film preparation; energy and chemical requirements of polymer synthesis; and limited	[48]

© Ariston Publications 2026. All rights reserved.

	polymerisation reagents and organic casting solvents	information on long-term polymer degradation and end-of-life behavior.	
QDSCs	Lead sulfide (PbS), cadmium sulfide (CdS), cadmium selenide (CdSe), copper indium sulfide ($CuInS_2$), surface ligands, and metal precursor salts were used.	Potential toxicity associated with lead- and Cd-containing quantum dots; release of metal ions during degradation or improper disposal; environmental concerns associated with nanoparticle transformation, surface ligands, and precursor chemicals; and possible soil and water contamination.	[62, 63]

5.4. End-of-life waste and resource depletion

The disposal of solar cell modules at the end of their service life raises concerns regarding waste generation and the loss of valuable resources. These modules contain materials such as glass, metals, semiconductor compounds, polymers, and other critical elements that can be recovered and reused [65, 66]. When discarded in landfills or dismantled without proper handling, these materials may be lost, and potentially hazardous substances may be released into the surrounding environment [65]. Recycling provides an opportunity to recover valuable components and reduce dependence on the extraction of raw materials. However, material recovery may involve energy-intensive processes, substantial water consumption, and the use of chemical reagents to separate individual components [66]. Furthermore, poorly managed recycling processes can generate secondary waste and create additional opportunities for environmental contamination. Thus, the environmental benefit of recycling depends not only on the amount of material recovered, but also on the purity of the recovered products, the resources consumed during processing, and their potential to replace virgin materials in the manufacture of new solar cell components [67].

6. STRATEGIES TO REDUCE ENVIRONMENTAL IMPACTS

6.1 Green chemistry and safer material design

Green chemistry focuses on reducing environmental pollution by selecting safer materials and improving product manufacture [33]. In emerging solar cells, this can be achieved by replacing hazardous materials with safer alternatives, reducing the use of harmful solvents, minimizing the number of processing steps, and improving the material yield. However, an alternative material should not be considered environmentally friendly simply because it replaces a hazardous chemical [48]. Its toxicity, environmental persistence, availability, and energy requirements during production should also be considered [10, 48].

Researchers are exploring safer solvent systems, solvent recovery methods, and alternative deposition techniques that may reduce the use of chemicals and waste [33]. Approaches to prevent lead leakage through effective capture or immobilization are also important [34]. In organic and polymer solar cells, the use of safer coating solvents, improved polymer synthesis methods, and alternatives to conventional fullerene-based materials may help reduce environmental concerns [48, 54]. For DSSCs, the development of metal-free dyes, less hazardous electrolytes, and reduced use of platinum are being investigated [48]. Similarly, QDSCs require safer absorber materials and effective methods to prevent the release of nanoparticles during manufacturing and disposal [10, 60].

6.2 Waste minimisation and cleaner production

Reducing waste during manufacturing is an important step towards making emerging solar cells more sustainable [33]. This can begin with simple measures, such as using the correct quantity of raw materials, improving coating methods to avoid material loss, and recovering solvents for reuse [33]. Recycling process water, separating metal-containing waste from organic waste, and recovering usable materials from rejected products can further reduce the amount of waste generated [11]. Maintaining proper records of chemical use, wastewater generation, air emissions, and solid waste also helps manufacturers identify where losses occur and implement suitable corrective measures. These practices can reduce environmental pollution while also lowering production costs [67].

6.3 Encapsulation, durability and service-life extension

Improving the durability of solar cell modules is another important way to reduce their environmental impact [37]. Encapsulation and protective barrier layers help prevent moisture and oxygen from reaching sensitive materials and can reduce the possibility of hazardous substances being released if a module is damaged [35]. In lead-containing PSCs, researchers have investigated lead-absorbing or lead-immobilizing layers and improved edge sealing to minimize the risk of lead leakage [34].

However, the materials used for encapsulation should also be considered during recycling, as they may make the separation of individual components more difficult [67]. Therefore, their ability to provide long-term protection

 © Ariston Publications 2026. All rights reserved.

should be tested under realistic conditions, including exposure to sunlight, moisture, temperature changes, mechanical damage, and fires [64]. Developing solar cells that last longer and can be repaired when necessary may reduce the frequency of replacement and lower the overall environmental burden associated with electricity generation [37, 48].

6.4 Reuse and recycling

Recycling helps recover valuable materials from solar cell modules and reduces the need to extract new raw materials [66]. The process generally involves removing the frames and electrical components, separating the glass and polymers, and recovering metals and semiconductor materials [65]. Different approaches, including mechanical, thermal, and chemical methods, have been investigated. Mechanical methods help separate major components but may produce mixed material fractions. Thermal treatment can remove encapsulating materials, although it requires energy and proper emission control [66]. Chemical methods can recover selected materials more effectively, but may involve acids, alkalis, oxidizing agents, and/or organic solvents. Therefore, the choice of recycling method should consider not only the amount of material recovered, but also its purity, energy consumption, chemical requirements, wastewater generation, and overall cost [66, 67].

The recycling process must also be adapted to the materials used in each solar cell technology. Recent studies on PSCs have explored water-based methods for recovering and reusing different device components, offering possibilities for more sustainable recycling [68]. However, their suitability for large-scale applications, repeated recycling cycles, and safe management of lead-containing residues still needs to be evaluated. In DSSCs, the recovery of glass, conducting layers, dyes, and electrode materials requires careful removal of the electrolyte [66]. Recycling organic and polymer solar cells is more challenging because their thin organic layers and polymer components are closely integrated [67]. In quantum dot solar cells, particular care is required to prevent the release of heavy metal-containing nanoparticles while recovering valuable materials [10, 60].

6.5 Life-cycle-informed procurement and regulation

The environmental impact of solar cell technologies depends not only on how they are manufactured but also on the materials selected during production and how the products are handled after their useful life. Therefore, greater attention should be paid to material selection and responsible procurement practices. Manufacturers and suppliers should provide detailed information on the materials used, potential chemical hazards, recycled content, emissions during manufacturing, and recommended end-of-life management procedures. Such transparency would help manufacturers and industries make informed choices and identify materials and products with lower environmental impacts [35, 69]. Regulatory measures play an important role in ensuring the responsible management of solar cell waste. Approaches such as extended producer responsibility, product take-back schemes, and proper tracking of discarded modules can encourage manufacturers to consider the environmental consequences of their products beyond the manufacturing stage. Clear procedures are also required for the safe collection, transportation, storage, recycling, and disposal of damaged or end-of-life modules [35, 69]. In addition, the use of standardized testing methods to evaluate chemical leaching, emissions under fire conditions, and material toxicity would facilitate the assessment and comparison of the potential environmental risks associated with different solar cell technologies. This would also provide a stronger scientific basis for developing appropriate safety standards and regulatory guidelines [35]. Taken together, combining transparent material procurement, effective waste management policies, and consistent safety standards can help reduce environmental risks and support the responsible development of emerging solar cell technologies [69].

7. RESEARCH GAPS AND FUTURE PERSPECTIVES

One of the major challenges in evaluating the environmental impact of emerging solar cells is the lack of LCA studies that allow direct comparison between different technologies [11, 16]. Existing studies often use different assessment methods, system boundaries, functional units, geographical conditions, manufacturing scales, and assumptions about device lifetime and disposal [16]. These differences make it difficult to identify the technology with the lowest overall environmental impact [11]. Future research should provide more complete information on the materials and energy used during manufacturing, production efficiency, solvent recovery, device performance, degradation, and end-of-life management [11]. The use of sensitivity and uncertainty analyses would also help identify the factors that have the greatest influence on LCA results [16].

Another important area requiring further attention is the assessment of toxicity and the possibility of hazardous material release into the environment [35]. Simply identifying the presence of a toxic element is insufficient to understand its environmental risk [34]. Factors such as chemical form, rate of release, environmental availability, and possible routes of human exposure must be considered [34, 60]. For solar cells containing nanomaterials, it is particularly important to determine whether the released substances are present as dissolved ions, intact nanoparticles, or transformed products [60]. Therefore, future studies should examine modules under different conditions, including normal use, aging, physical damage, and exposure to fire. Such investigations would provide a better understanding of the potential risks to workers, surrounding communities, and the environment, particularly during manufacturing and disposal [35].

© Ariston Publications 2026. All rights reserved.

Future research and development should focus not only on improving the efficiency of emerging solar cells but also on making their materials and manufacturing processes safer and more sustainable [33]. This necessitates considering toxicity, material availability, durability, energy consumption, and recyclability in the early stages of device development [10]. The development of solar cells with longer service lives, safer processing chemicals, efficient resource use, and better recovery of valuable materials can help reduce their overall environmental burden [10, 67]. By considering these factors, researchers can develop solar technologies that support clean energy generation while minimizing the potential risks to human health and the environment.

8. CONCLUSION

Emerging solar cell technologies offer promising opportunities to expand the use of solar energy through lightweight, flexible, and potentially cost-effective devices. However, their environmental performance depends not only on energy conversion efficiency but also on the materials, chemicals, and manufacturing processes involved throughout their life cycle. As discussed in this review, different technologies present distinct environmental concerns: PSCs are associated with lead-containing compounds and fabrication solvents; dye-sensitized solar cells may involve metal-based dyes and liquid electrolytes; organic and polymer solar cells require specialized chemical processing; while QDSCs may contain potentially hazardous elements such as cadmium, lead, and selenium. These concerns extend beyond the active materials to include the substrates, electrodes, charge transport layers, and other device components. Therefore, a life cycle perspective is essential to identify potential impacts associated with raw material extraction, manufacturing, use, and end-of-life management. The adoption of safer materials, green chemistry, cleaner production methods, solvent recovery, effective encapsulation, and improved device durability can help reduce environmental and occupational risks. Similarly, appropriate strategies for repair, reuse, and recycling are important for preventing the release of hazardous substances and for recovering valuable resources. Nevertheless, further research is needed to establish comparable LCAs, improve toxicity and leaching evaluations under realistic conditions, and develop efficient recycling methods with minimal secondary waste. Overall, the future development of emerging solar cells should focus not only on improving device performance but also on material safety, resource efficiency, and responsible end-of-life management to ensure that these technologies contribute to the clean energy transition without creating avoidable risks to human health and the environment.

DECLARATIONS

Ethical Approval

We affirm that this manuscript is an original work, has not been previously published, and is not currently under consideration for publication in any other journal or conference proceedings. All authors have reviewed and approved the manuscript, and the order of authorship has been mutually agreed upon.

Funding

No funding.

Availability of data and material

Data will be made available upon request.

Conflicts of Interest

The authors declare that there is no conflict of interests.

Authors' contributions

All authors contributed equally to this work,

REFERENCE

[1] Pourasl, H.H., Barenji, R.V. and Khojastehnezhad, V.M., **2023**. Solar energy status in the world: A comprehensive review. *Energy Reports*, *10*, pp.3474-3493. https://doi.org/10.1016/j.egyr.2023.10.022

[2] Abdelkareem, M.A., Elsaid, K., Wilberforce, T., Kamil, M., Sayed, E.T. and Olabi, A., **2021**. Environmental aspects of fuel cells: A review. *Science of The Total Environment*, *752*, p.141803. https://doi.org/10.1016/j.scitotenv.2020.141803

[3] Aliari, Y. and Haghani, A., **2016**. Planning for integration of wind power capacity in power generation using stochastic optimization. *Renewable and Sustainable Energy Reviews*, *59*, pp.907-919. https://doi.org/10.1016/j.rser.2016.01.018

[4] Sebastian, R.M. and Louis, J., **2021**. Understanding waste management at airports: A study on current practices and challenges based on literature review. *Renewable and Sustainable Energy Reviews*, *147*, p.111229. https://doi.org/10.1016/j.rser.2021.111229

[5] Homod, R.Z., Togun, H., Ateeq, A.A., Al-Mousawi, F.N., Yaseen, Z.M., Al-Kouz, W., Hussein, A.K., Alawi, O.A., Goodarzi, M. and Ahmadi, G., **2022**. An innovative clustering technique to generate hybrid modeling of cooling coils for energy analysis: A case study for control performance in HVAC systems. *Renewable and Sustainable Energy Reviews*, *166*, p.112676. https://doi.org/10.1016/j.rser.2022.112676

 © Ariston Publications 2026. All rights reserved.

[6] Bademlioglu, A.H., Canbolat, A.S. and Kaynakli, O., **2020**. Multi-objective optimization of parameters affecting Organic Rankine Cycle performance characteristics with Taguchi-Grey Relational Analysis. *Renewable and Sustainable Energy Reviews*, *117*, p.109483. https://doi.org/10.1016/j.rser.2019.109483

[7] Yunna, W., Kaifeng, C., Yisheng, Y. and Tiantian, F., **2015**. A system dynamics analysis of technology, cost and policy that affect the market competition of shale gas in China. *Renewable and sustainable energy reviews*, *45*, pp.235-243. https://doi.org/10.1016/j.rser.2015.01.060

[8] Kasaeian, A.B., Molana, S., Rahmani, K. and Wen, D., **2017**. A review on solar chimney systems. *Renewable and sustainable energy reviews*, *67*, pp.954-987. https://doi.org/10.1016/j.rser.2016.09.081

[9] Tsang, M.P., Sonnemann, G.W. and Bassani, D.M., **2016**. Life-cycle assessment of cradle-to-grave opportunities and environmental impacts of organic photovoltaic solar panels compared to conventional technologies. *Solar Energy Materials and Solar Cells*, *156*, pp.37-48. https://doi.org/10.1016/j.solmat.2016.04.024

[10] Gressler, S., Part, F., Scherhaufer, S., Obersteiner, G. and Huber-Humer, M., **2022**. Advanced materials for emerging photovoltaic systems–Environmental hotspots in the production and end-of-life phase of organic, dye-sensitized, perovskite, and quantum dots solar cells. *Sustainable Materials and Technologies*, *34*, p.e00501. https://doi.org/10.1016/j.susmat.2022.e00501

[11] Cellura, M., Luu, L.Q., Guarino, F. and Longo, S., **2024**. A review on life cycle environmental impacts of emerging solar cells. *Science of the total environment*, *908*, p.168019. https://doi.org/10.1016/j.scitotenv.2023.168019

[12] Vidal, R., Alberola-Borràs, J.A., Sánchez-Pantoja, N. and Mora-Seró, I., **2021**. Comparison of perovskite solar cells with other photovoltaics technologies from the point of view of life cycle assessment. *Advanced Energy and Sustainability Research*, *2*(5), p.2000088. https://doi.org/10.1002/aesr.202000088

[13] Weyand, S., Kawajiri, K., Mortan, C., Zeller, V. and Schebek, L., **2023**. Are perovskite solar cells an environmentally sustainable emerging energy technology? Upscaling from lab to fab in life cycle assessment. *ACS Sustainable Chemistry & Engineering*, *11*(38), pp.14010-14019. https://doi.org/10.1021/acssuschemeng.3c03019

[14] Celik, I., Song, Z., Cimaroli, A.J., Yan, Y., Heben, M.J. and Apul, D., **2016**. Life Cycle Assessment (LCA) of perovskite PV cells projected from lab to fab. *Solar Energy Materials and Solar Cells*, *156*, pp.157-169. https://doi.org/10.1016/j.solmat.2016.04.037

[15] Monteiro Lunardi, M., Wing Yi Ho-Baillie, A., Alvarez-Gaitan, J.P., Moore, S. and Corkish, R., **2017**. A life cycle assessment of perovskite/silicon tandem solar cells. *Progress in photovoltaics: research and applications*, *25*(8), pp.679-695. https://doi.org/10.1002/pip.2877

[16] Pallas, G., Vijver, M.G., Peijnenburg, W.J. and Guinée, J., **2020**. Ex ante life cycle assessment of GaAs/Si nanowire–based tandem solar cells: A benchmark for industrialization. *The International Journal of Life Cycle Assessment*, *25*(9), pp.1767-1782. https://doi.org/10.1007/s11367-020-01791-z

[17] Ziemińska-Stolarska, A., Pietrzak, M. and Zbiciński, I., **2021**. Application of LCA to determine environmental impact of concentrated photovoltaic solar panels—state-of-the-art. *Energies*, *14*(11), p.3143. https://doi.org/10.3390/en14113143

[18] Giannouli, M., **2021**. Current status of emerging PV technologies: a comparative study of dye-sensitized, organic, and perovskite solar cells. *International Journal of Photoenergy*, *2021*(1), p.6692858. https://doi.org/10.1155/2021/6692858

[19] R. Murad, A., Iraqi, A., Aziz, S.B., N. Abdullah, S. and Brza, M.A., **2020**. Conducting polymers for optoelectronic devices and organic solar cells: A review. *Polymers*, *12*(11), p.2627. https://doi.org/10.3390/polym12112627

[20] Solak, E.K. and Irmak, E., **2023**. Advances in organic photovoltaic cells: a comprehensive review of materials, technologies, and performance. *RSC advances*, *13*(18), pp.12244-12269. https://doi.org/10.1039/d3ra01454a

[21] Al-Azzawi, A.G., Aziz, S.B., Dannoun, E.M., Iraqi, A., Nofal, M.M., Murad, A.R. and M. Hussein, A., **2022**. A mini review on the development of conjugated polymers: steps towards the commercialization of organic solar cells. *Polymers*, *15*(1), p.164. https://doi.org/10.3390/polym15010164

[22] Han, J., Park, K., Tan, S., Vaynzof, Y., Xue, J., Diau, E.W.G., Bawendi, M.G., Lee, J.W. and Jeon, I., **2025**. Perovskite solar cells. *Nature Reviews Methods Primers*, *5*(1), p.3. https://doi.org/10.1038/s43586-024-00373-9

© Ariston Publications 2026. All rights reserved.

[23] Muchuweni, E., Martincigh, B.S. and Nyamori, V.O., **2021**. Perovskite solar cells: current trends in graphene-based materials for transparent conductive electrodes, active layers, charge transport layers, and encapsulation layers. *Advanced Energy and Sustainability Research*, *2*(9), p.2100050. https://doi.org/10.1002/aesr.202100050

[24] Korir, B.K., Kibet, J.K. and Ngari, S.M., **2024**. A review on the current status of dye-sensitized solar cells: Toward sustainable energy. *Energy Science & Engineering*, *12*(8), pp.3188-3226. https://doi.org/10.1002/ese3.1815

[25] Wu, J., Lan, Z., Lin, J., Huang, M., Huang, Y., Fan, L., Luo, G., Lin, Y., Xie, Y. and Wei, Y., **2017**. Counter electrodes in dye-sensitized solar cells. *Chemical Society Reviews*, *46*(19), pp.5975-6023. https://doi.org/10.1039/c6cs00752j

[26] Yi, J., Zhang, G., Yu, H. and Yan, H., **2024**. Advantages, challenges and molecular design of different material types used in organic solar cells. *Nature Reviews Materials*, *9*(1), pp.46-62. https://doi.org/10.1038/s41578-023-00618-1

[27] Ramoroka, M.E., Yussuf, S.T., Nwambaekwe, K.C., Modibane, K.D., John-Denk, V.S., Douman, S.F. and Iwuoha, E.I., **2024**. Advances in organic photovoltaic cells: fine-tuning of the photovoltaic processes. *Solar RRL*, *8*(7), p.2300982. https://doi.org/10.1002/solr.202300982

[28] Ohkita, H., **2025**. Interface engineering for ternary blend polymer solar cells based on spectroscopic and device analyses. *Polymer Journal*, *57*(10), pp.1067-1081. https://doi.org/10.1038/s41428-025-01064-2

[29] Benten, H., Mori, D., Ohkita, H. and Ito, S., **2016**. Recent research progress of polymer donor/polymer acceptor blend solar cells. *Journal of Materials Chemistry A*, *4*(15), pp.5340-5365. https://doi.org/10.1039/c5ta10759h

[30] Neupane, K., Kabel, J., Uddin, J., Dubey, R., Ojha, R., Zhang, D. and Yap, Y.K., **2026**. Quantum Dot Solar Cells: Background, Progress, and Perspective. *Micromachines*, *17*(4), p.474. https://doi.org/10.3390/mi17040474

[31] Habiba, U., Khan, M.U., Sultan, N. and Saeed Ashraf Janjua, M.R., **2026**. Next-generation quantum dot solar cells: advances in materials, device engineering and performance optimization. *RSC Advances*, *16*(33), pp.30448-30476. https://doi.org/10.1039/d6ra02771g

[32] Goetz, K.P., Taylor, A.D., Hofstetter, Y.J. and Vaynzof, Y., **2021**. Sustainability in perovskite solar cells. *ACS Applied Materials & Interfaces*, *13*(1), pp.1-17. https://doi.org/10.1021/acsami.0c17269

[33] Kim, H.S., An, Y.J., Kwak, J.I., Kim, H.J., Jung, H.S. and Park, N.G., **2022**. Sustainable green process for environmentally viable perovskite solar cells. *ACS Energy Letters*, *7*(3), pp.1154-1177. https://doi.org/10.1021/acsenergylett.1c02836

[34] Ren, M., Qian, X., Chen, Y., Wang, T. and Zhao, Y., **2022**. Potential lead toxicity and leakage issues on lead halide perovskite photovoltaics. *Journal of Hazardous Materials*, *426*, p.127848. https://doi.org/10.1016/j.jhazmat.2021.127848

[35] Torrence, C.E., Libby, C.S., Nie, W. and Stein, J.S., **2023**. Environmental and health risks of perovskite solar modules: Case for better test standards and risk mitigation solutions. *Iscience*, *26*(1). https://doi.org/10.1016/j.isci.2022.105807.

[36] Ma, X., Yao, X., Zhao, Y., Zhu, G. and Zhong, H., **2025**. Life cycle toxicity and reduction potential analysis of perovskite photovoltaic technology. *Journal of Environmental Management*, *393*, p.127170. https://doi.org/10.1016/j.jenvman.2025.127170.

[37] Kim, H.J., Han, G.S. and Jung, H.S., **2024**. Managing the lifecycle of perovskite solar cells: Addressing stability and environmental concerns from utilization to end-of-life. *EScience*, *4*(2), p.100243. https://doi.org/10.1016/j.esci.2024.100243

[38] Su, P., Liu, Y., Zhang, J., Chen, C., Yang, B., Zhang, C. and Zhao, X., **2020**. Pb-based perovskite solar cells and the underlying pollution behind clean energy: dynamic leaching of toxic substances from discarded perovskite solar cells. *The journal of physical chemistry letters*, *11*(8), pp.2812-2817. https://doi.org/10.1021/acs.jpclett.0c00503.

[39] Zhang, C. and Park, N.G., **2024**. Materials and methods for cost-effective fabrication of perovskite photovoltaic devices. *Communications Materials*, *5*(1), p.194. https://doi.org/10.1038/s43246-024-00636-8.

[40] Teixeira, C.O., Castro, D., Andrade, L. and Mendes, A., **2022**. Selection of the ultimate perovskite solar cell materials and fabrication processes towards its industrialization: A review. *Energy Science & Engineering*, *10*(4), pp.1478-1525. https://doi.org/10.1002/ese3.1084.

[41] Lee, D.S., Lee, H.J., Song, Y., Park, J.K., Heo, J.H. and Im, S.H., **2025**. Green solvent strategies for the sustainable development of perovskite solar cells. *Chemical Communications*, *61*(10), pp.2011-2025. https://doi.org/10.1039/D4CC05454G.

 © Ariston Publications 2026. All rights reserved.

[42] Podapangi, S.K., Jafarzadeh, F., Mattiello, S., Korukonda, T.B., Singh, A., Beverina, L. and Brown, T.M., **2023**. Green solvents, materials, and lead-free semiconductors for sustainable fabrication of perovskite solar cells. *RSC advances*, *13*(27), pp.18165-18206. https://doi.org/10.1039/D3RA01692G.

[43] Mahmood, K., Sarwar, S. and Mehran, M.T., **2017**. Current status of electron transport layers in perovskite solar cells: materials and properties. *Rsc Advances*, *7*(28), pp.17044-17062. https://doi.org/10.1039/C7RA00002B.

[44] Webb, T., Sweeney, S.J. and Zhang, W., **2021**. Device architecture engineering: progress toward next generation perovskite solar cells. *Advanced functional materials*, *31*(35), p.2103121. https://doi.org/10.1002/adfm.202103121.

[45] Arumugam, G.M., Karunakaran, S.K., Liu, C., Zhang, C., Guo, F., Wu, S. and Mai, Y., **2021**. Inorganic hole transport layers in inverted perovskite solar cells: A review. *Nano Select*, *2*(6), pp.1081-1116. https://doi.org/10.1002/nano.202000200.

[46] Akin, S., Kim, S., Song, C.K., Nam, S.Y. and Jun, M.B.G., **2024**. Fully additively manufactured counter electrodes for dye-sensitized solar cells. *Micromachines*, *15*(4), p.464. https://doi.org/10.3390/mi15040464

[47] Shalini, S., Balasundaraprabhu, R., Kumar, T.S., Prabavathy, N., Senthilarasu, S. and Prasanna, S., **2016**. Status and outlook of sensitizers/dyes used in dye sensitized solar cells (DSSC): a review. *International journal of energy research*, *40*(10), pp.1303-1320. https://doi.org/10.1002/er.3538

[48] Lizin, S., Van Passel, S., De Schepper, E., Maes, W., Lutsen, L., Manca, J. and Vanderzande, D., **2013**. Life cycle analyses of organic photovoltaics: a review. *Energy & Environmental Science*, *6*(11), pp.3136-3149. https://doi.org/10.1039/c3ee42653j.

[49] Kiskira, K., Kalkanis, K., Coelho, F., Plakantonaki, S., D'onofrio, C., Psomopoulos, C.S., Priniotakis, G. and Ioannidis, G.C., **2025**. Life cycle assessment of organic solar cells: Structure, analytical framework, and future product concepts. *Electronics*, *14*(12), p.2426. https://doi.org/10.3390/electronics14122426.

[50] Meredith, P., Li, W. and Armin, A., **2020**. Nonfullerene acceptors: A renaissance in organic photovoltaics?. *Advanced Energy Materials*, *10*(33), p.2001788. https://doi.org/10.1002/aenm.202001788

[51] Søndergaard, R., Hösel, M., Angmo, D., Larsen-Olsen, T.T. and Krebs, F.C., **2012**. Roll-to-roll fabrication of polymer solar cells. *Materials today*, *15*(1-2), pp.36-49. https://doi.org/10.1016/S1369-7021(12)70019-6.

[52] Tsang, M.P., Sonnemann, G.W. and Bassani, D.M., **2016**. A comparative human health, ecotoxicity, and product environmental assessment on the production of organic and silicon solar cells. *Progress in Photovoltaics: Research and Applications*, *24*(5), pp.645-655. https://doi.org/10.1002/pip.2704.

[53] Luo, S., Li, C., Zhang, J., Zou, X., Zhao, H., Ding, K., Huang, H., Song, J., Yi, J., Yu, H. and Wong, K.S., **2023**. Auxiliary sequential deposition enables 19%-efficiency organic solar cells processed from halogen-free solvents. Nature Communications, 14(1), p.6964. https://doi.org/10.1038/s41467-023-41978-0.

[54] Corzo, D., Rosas-Villalva, D., C, A., Tostado-Blázquez, G., Alexandre, E.B., Hernandez, L.H., Han, J., Xu, H., Babics, M., De Wolf, S. and Baran, D., **2023**. High-performing organic electronics using terpene green solvents from renewable feedstocks. *Nature Energy*, *8*(1), pp.62-73. https://doi.org/10.1038/s41560-022-01167-7.

[55] Xie, C., Heumüller, T., Gruber, W., Tang, X., Classen, A., Schuldes, I., Bidwell, M., Späth, A., Fink, R.H., Unruh, T. and McCulloch, I., **2018**. Overcoming efficiency and stability limits in water-processing nanoparticular organic photovoltaics by minimizing microstructure defects. *Nature communications*, *9*(1), p.5335. https://doi.org/10.1038/s41467-018-07807-5.

[56] Espinosa, N., Hösel, M., Angmo, D. and Krebs, F.C., **2012**. Solar cells with one-day energy payback for the factories of the future. *Energy & Environmental Science*, *5*(1), pp.5117-5132. https://doi.org/10.1039/c1ee02728j

[57] Carey, G.H., Abdelhady, A.L., Ning, Z., Thon, S.M., Bakr, O.M. and Sargent, E.H., **2015**. Colloidal quantum dot solar cells. *Chemical reviews*, *115*(23), pp.12732-12763. https://doi.org/10.1021/acs.chemrev.5b00063.

[58] Shi, G., Ding, X., Liu, Z., Liu, Y., Chen, Y., Liu, C., Ni, Z., Wang, H., Ito, K., Igarashi, K. and Feng, K., **2025**. Overcoming efficiency and cost barriers for large-area quantum dot photovoltaics through stable ink engineering. *Nature Energy*, *10*(5), pp.592-604. https://doi.org/10.1038/s41560-025-01746-4.

[59] Cao, Y., Stavrinadis, A., Lasanta, T., So, D. and Konstantatos, G., **2016**. The role of surface passivation for efficient and photostable PbS quantum dot solar cells. *Nature Energy*, *1*(4), p.16035. https://doi.org/10.1038/nenergy.2016.35.

© Ariston Publications 2026. All rights reserved.

[60] Martínez Muñoz, G., Merinero de los Santos, M., Pérez-Aranda Redondo, M., Pérez-Soriano, E.M., Ortiz Cerda, T.A., Begines Ruiz, B. and Alcudia Cruz, A., **2020**. Environmental Impact of Nanoparticles' Application as an Emerging Technology: A Review. https://doi.org/10.3390/ma14010166.

[61] Parisi, M.L., Maranghi, S. and Basosi, R., **2014**. The evolution of the dye sensitized solar cells from Grätzel prototype to up-scaled solar applications: A life cycle assessment approach. *Renewable and Sustainable Energy Reviews*, *39*, pp.124-138. https://doi.org/10.1016/j.rser.2014.07.079.

[62] Li, F., Shaw, S., Libby, C., Preciado, N., Bicer, B. and Tamizhmani, G., **2024**. A review of toxicity assessment procedures of solar photovoltaic modules. *Waste Management*, *174*, pp.646-665. https://doi.org/10.1016/j.wasman.2023.12.034.

[63] Giroux, M.S., Zahra, Z., Salawu, O.A., Burgess, R.M., Ho, K.T. and Adeleye, A.S., **2022**. Assessing the environmental effects related to quantum dot structure, function, synthesis and exposure. *Environmental Science: Nano*, *9*(3), pp.867-910. https://doi.org/10.1039/D1EN00712B.

[64] Ollagnon, F., Aurrekoetxea-Arratibel, O., Gottis, E., Li, H.Y., Olano-Azkune, X., Despeisse, M., Faes, A. and Ballif, C., **2026**. Advanced Flame Retardant Strategies and Fire Performance Assessment for Safer Photovoltaics in Buildings: A Two-Part Review. *Advanced Functional Materials*, *36*(16), p.e09194. https://doi.org/10.1002/adfm.202509194.

[65] Cheema, H.A., Ilyas, S., Kang, H. and Kim, H., **2024**. Comprehensive review of the global trends and future perspectives for recycling of decommissioned photovoltaic panels. *Waste Management*, *174*, pp.187-202. https://doi.org/10.1016/j.wasman.2023.11.025.

[66] Divya, A., Adish, T., Kaustubh, P. and Zade, P.S., **2023**. Review on recycling of solar modules/panels. *Solar Energy Materials and Solar Cells*, *253*, p.112151. https://doi.org/10.1016/j.solmat.2022.112151.

[67] Sun, R., Yuan, X., Yang, X., Wu, Y., Shao, Y., Wu, X., Brabec, C.J. and Min, J., **2024**. Cost-efficient recycling of organic photovoltaic devices. *Joule*, *8*(9), pp.2523-2538. https://doi.org/10.1016/j.joule.2024.06.006.

[68] Xiao, X., Xu, N., Tian, X., Zhang, T., Wang, B., Wang, X., Xian, Y., Lu, C., Ou, X., Yan, Y. and Sun, L., **2025**. Aqueous-based recycling of perovskite photovoltaics. *Nature*, *638*(8051), pp.670-675. https://doi.org/10.1038/s41586-024-08408-7.

[69] Kwok, K.H., Savaget, P., Fukushige, S. and Halog, A., **2024**. The necessity for end-of-life photovoltaic technology waste management policy: A systematic review. *Journal of Cleaner Production*, *461*, p.142497. https://doi.org/10.1016/j.jclepro.2024.142497.

 © Ariston Publications 2026. All rights reserved.