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Assessment of soil impacts from lead release by lead-halide perovskite solar cells based on outdoor leaching tests

 Anika Sidler, ^{ab} Felix Schmidt, ^a Bastien Vallat, ^a Fionnuala Grifoni,^c Severin N. Habisreutinger, ^c Riikka Suhonen, ^d Henry J. Snaith, ^e Andreas Schäffer ^b and Markus Lenz ^{*af}

Perovskite solar cells represent a promising technology in the photovoltaic industry due to their high power conversion efficiency, potential for cost-effective manufacturing and versatile applications. The most stable and efficient perovskites to date rely on lead (Pb), raising concerns about leaching into the environment; however Pb release so far has only been quantified under laboratory conditions, and no field-based assessment under real outdoor exposure has yet evaluated this risk. The present study quantified Pb leaching from various metal-halide perovskite compositions, device stacks and encapsulation approaches in a rooftop installation for up to 9 months. Pb leaching was low across all tested configurations, even in intentionally damaged materials. Glass-glass encapsulated tandem devices shattered by hail and plastic-encapsulated samples damaged by 100 μm pinholes released only $0.07\% \pm 0.01\%$ and $0.15\% \pm 0.14\%$ of their initial Pb, respectively, likely due to the slow diffusion of Pb cations in water. The highest leaching ($4.81\% \pm 0.02\%$) occurred in unlaminated laboratory devices, demonstrating the importance of proper lamination. A self-developed freeware web tool was used to calculate predicted soil concentrations and evaluate potential impacts. Even for unlaminated devices, concentrations would only slightly exceed natural background levels (5.6 mg kg^{-1} increase), with negligible effects on soil fertility. A hypothetical worst-case scenario assuming a 1000 nm thick perovskite layer and complete Pb leaching onto a narrow strip of soil predicted a negative impact on soil fertility; however remediation would still not be required under Swiss environmental regulations. Overall, current industry-standard encapsulation limits Pb leaching to levels that almost completely mitigate negative impacts on soil health.

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Broader context

Meeting climate goals requires an accelerated deployment of renewable energy, with solar power playing a central role. Perovskite solar cells are especially promising, combining high efficiency with low production costs. However, concerns about lead (Pb) release have raised doubts about their safe deployment. Much of this debate remains vague: many claim “there is a risk” without addressing either the probability (*e.g.*, of Pb leakage) or its actual impacts (*e.g.*, negative effects on soil quality). This has fueled significant research into Pb-free alternatives (*e.g.* Sn-based devices) and Pb-capture strategies, even though the real risk level is poorly defined. Our study provides a more quantitative foundation for the exposure pathway from field installation to soils. We show that the probability of full Pb leaching is low with industry-standard encapsulation, and that soil impacts remain negligible except under extreme, highly improbable scenarios. To support transparency, we provide the open access PERCENT tool, enabling soil impact assessment for everyone and facilitating communication with policy-makers and the public. However, we also call for impact modeling of other exposure pathways and for further experimental work on environmental fate to strengthen evidence that perovskites are a sustainable solar technology.

^aInstitute for Ecopreneurship, School of Life Sciences University of Applied Sciences and Arts Northwestern Switzerland, Hofackerstrasse 30, 4132 Muttenz, Switzerland. E-mail: markus.lenz@fhnw.ch

^bInstitute for Environmental Research, RWTH Aachen University, Worringerweg 1, 52074 Aachen, Germany

^cOxford PV Ltd, Unit 7–8 Oxford Pioneer Park, Mead Road, Yarnton, UK

^dVTT Technical Research Centre of Finland Ltd, Kaitoväylä 1, 90590 Oulu, Finland

^eClarendon Laboratory, Department of Physics, University of Oxford, Parks Road, Oxford, OX1 3PU, UK

^fDepartment of Environmental Technology, Wageningen University, 6708 PB, Wageningen, The Netherlands

Introduction

Replacing fossil fuels with renewable energy sources is critical in addressing the global challenge of mitigating the effects of climate change. Solar energy has emerged as one of the more affordable options, with the potential to meet a significant portion of increasing energy demands.^{1–3} Currently, silicon-based technologies account for most of the total production in the field of photovoltaics (PV) (~97%).⁴ However, silicon PV is

limited regarding further improvement of power conversion efficiency and their production requires the use of multiple energy-intensive steps, making it important to identify and develop next-generation technologies to meet society's energy needs in a sustainable and cost-effective manner.⁵ Perovskite solar cells (PSCs) represent a potential breakthrough technology for sustainable energy generation.^{6–9} After slightly over a decade of research, their power conversion efficiency has already surpassed that of other thin-film PV, such as copper indium gallium selenide (CIGS) or organic photovoltaics (OPV) at laboratory scale.¹⁰ Their production promises to be simple and cost effective.¹¹ The perovskite layer is typically processed *via* solution-based or vapor-based approaches.^{12,13} In the former, precursors are applied on substrates through processes such as spin-coating or slot-die coating.^{14,15} Vapor-based methods use no solvent, since the precursor materials are evaporated or sublimed under vacuum conditions and then condensed onto a substrate. The two approaches can also be combined in two-step fabrication processes.^{16,17} A promising opportunity involves combining PSCs with conventional silicon solar cells in a tandem configuration, with PSCs used as top cells and silicon solar cells as bottom cells.^{18,19} Using two different bandgaps enables a more efficient conversion of sunlight into energy by absorbing the different parts of the spectrum separately.¹⁸ Consequently, tandem solar cells have already exceeded the theoretical limit of single-junction solar cells.^{10,15}

Most stable and highly efficient PSCs contain lead (Pb) in the active layer, which may pose a challenge to commercialisation due to environmental concerns and public perceptions.^{20–22} Although the absolute content of Pb in PSCs is relatively low (approx. 0.5 g Pb m⁻²), Pb could still enter the environment from damaged modules during operation or at the end-of-life stage if they are disposed of improperly.

While the use of Pb raises environmental and health concerns, its overall contribution to the environmental footprint of PSCs remains a matter of quantitative evaluation rather than simple assumption. Several life cycle assessment (LCA) studies have shown that, although Pb adds to the toxicity potential of PSCs, its share of the total environmental burden is relatively minor compared to other components such as gold electrodes, solvents or encapsulant materials.^{23–25} These studies suggest that the main sustainability challenges of PSCs may not stem solely from Pb content but also from fabrication steps and the use of critical raw materials. Nevertheless, Pb continues to attract particular attention in environmental regulation and public perception. Recent research has therefore shifted toward developing strategies to minimise Pb emissions, such as improving encapsulation barriers and establishing efficient recycling and Pb recovery processes.^{26,27}

Many papers note the potential environmental hazard of Pb as a concern for this technology, but very few studies to date have gone beyond mere assertions and quantified these risks (*i.e.* the product of probability and impact). Several prior studies^{28–32} have investigated Pb leaching under laboratory or regulatory conditions, highlighting the importance of encapsulation and influence of testing methods on the measured leaching. For example, Su *et al.*,²⁸ Kwak *et al.*,²⁹ and Panthi *et al.*³⁰ conducted regulatory end-of-life leaching tests on discarded PSCs, while Hailegnaw *et al.*³¹

and Yan *et al.*³² performed laboratory studies using unencapsulated or minimally protected devices with complete water immersion or simulated rain, demonstrating rapid and extensive Pb release. These studies illustrate both the importance of encapsulation and the dependence of leaching on test conditions. While these studies provide a basis for estimating how much total Pb could ultimately leach out of perovskites, using unencapsulated materials for risk assessment is of limited usefulness, simply because operational PSCs will need to be encapsulated to withstand environmental stresses to achieve a lifetime of decades.^{33,34} Further, the actual kinetics of leaching matter, as they may allow operators to react (*e.g.* by replacing broken modules and/or covering the soil and collecting the rain runoff). Additionally, bifilms may form on photovoltaic modules, producing microbial products that can impact leaching in real-world conditions.³⁵

Despite the laboratory and regulatory investigations discussed above, no study has quantified Pb leaching and the associated environmental risk under long-term outdoor exposure. Therefore, the current study had two goals: first, to quantify how much Pb can leach from various PSCs over the course of 9 months under real-world outdoor conditions. To this end, several PSC configurations were tested, including glass mini-modules using only 'minimal' encapsulation (UV-curable epoxy and glass cover slip), fully laminated flexible poly(ethylene) terephthalate (PET)-based PSCs and large-area rigid PSCs that were fully encapsulated according to industry standards using a polyolefin hot-melt lamination foil and butyl-rubber edge sealant. To simulate breakage in the field, the PET-based samples were damaged by a laser (simulating pinholes/microdamage) and the large area glass-based samples by hail impact tests, which resulted in cracking of the lamination glass. Collected rainwater was analysed by triple quadrupole inductively coupled plasma mass spectrometry (QQQ-ICP-MS) in the low $\mu\text{g L}^{-1}$ range.

Second, to develop an open-source perovskite leaching assessment tool (PERCENT) using a simple dilution model to estimate predicted environmental concentrations. The tool also allows users to put the calculated concentrations in perspective, relating them to negative impacts on healthy soils according to Swiss regulations on soil protection (guide value, trigger value and clean-up value). Experimental values from the outdoor leaching tests as well as a worst-case scenario (maximal perovskite thickness, maximal leaching, minimal volume of soil affected) were used to calculate predicted environmental concentrations and evaluate the consequences on soil health.

Materials and methods

Leaching set-up and leachate analysis

An outdoor leaching installation for PSC samples was constructed with stainless steel bars and mounts at the FHNW campus in MuttENZ, Switzerland (47° 32' 5.7696" N, 7° 38' 32.4024" E). Details on the set-up are provided in the SI (Fig. S1). The samples were centred using magnets, and the mounts were tilted (30°) to ensure proper rain runoff through a drain adapter with a runoff pipe. Schott bottles (1 L) were attached at the end of the runoff pipe to collect rainwater. Sampling occurred within a few days of a given rain event by logging the total

volume and taking a 10 mL aliquot. The aliquot was filtered to remove biomass and dirt (0.45 μm polypropylene filter, Macherey-Nagel, Düren, Germany) and acidified to a final concentration of 3% HNO_3 prior to analysis. The samples were exposed outdoors over the course of 7 to 9 months. ICP-MS analysis was performed on an 8800 QQQ-ICP-MS system (Agilent, Basel, Switzerland) using general-purpose operational settings. Metal analysis was carried out on the isotope with the highest natural abundance, using helium as a collision gas (5 mL min^{-1}) for $^{52}\text{Cr}^+$, $^{107}\text{Ag}^+$, $^{115}\text{In}^+$, $^{118}\text{Sn}^+$, $^{197}\text{Au}^+$ and $^{208}\text{Pb}^+$. The instrument was tuned daily according to operational standards. Quantification was performed using matrix-matched external calibration from a single-element standard solution ranging from 0 to 50 $\mu\text{g L}^{-1}$, prepared in milliQ water (18.2 $\text{M}\Omega\text{ cm}^{-1}$). Calibration was deemed acceptable with an R^2 value of >0.995 . $^{103}\text{Rh}^+$ was monitored as an internal standard to account for possible matrix effects.

PV samples

PSCs on small glass substrates ($3 \times 3\text{ cm}^2$ each; hereinafter 'mini-glass samples'), composed of glass/fluorine-doped tin oxide (FTO)/poly-TPD/ $\text{FA}_{0.83}\text{CS}_{0.17}\text{Pb}(\text{I}_{0.9}\text{Br}_{0.1})_3/\text{PCBM}/\text{BCP}/\text{Cr}/\text{Au}$, were encapsulated by a UV-curable epoxy and glass cover slip, as is typical in indoor solar cell stability assessment.³⁶ PSCs on a PET substrate ($10 \times 3\text{ cm}^2$ each; hereinafter 'plastic samples') were composed of PET/indium tin oxide (ITO)/ $\text{SnO}_2/\text{MAPbI}_3/\text{spiro-OMeTAD}/\text{Ag}$ and were fully laminated on both sides using a 25 μm thick pressure sensitive adhesive (PSA, ARcare 92 734; supplier Adhesives Research, Glen Rock, US) and a 80 μm thick barrier foil including a UV-protective layer (ATCJ, Rayotec UB4 + UV; supplier Amcor, Zurich, Switzerland). The PSA was first laminated on the barrier foil, and the stack was then laminated on to the PSC, both as front and back sheet, under inert atmosphere (N_2). No dedicated edge sealing component was used in this process. Lastly, large-area tandem PSCs on glass ($11.2 \times 11.2\text{ cm}^2$; hereinafter 'large-area samples') were composed of glass/FTO/PEDOT:PSS/ $\text{FA}_{0.83}\text{CS}_{0.17}\text{Pb}_{0.5}\text{Sn}_{0.5}\text{I}_3/\text{PCBM}/\text{BCP}/\text{ITO}/\text{poly-TPD}/\text{FA}_{0.83}\text{CS}_{0.17}\text{Pb}(\text{I}_{0.6}\text{Br}_{0.4})_3/\text{PCBM}/\text{BCP}/\text{ITO}$ and were fully encapsulated using a polyolefin hot-melt polymer lamination foil and butyl-rubber edge seal according to industry standards; section S1 lists the layer thicknesses. Two large-area modules included the all-perovskite tandem material stack, and two included all layers of the tandem except the Pb-containing perovskite layers ('large-area samples blank'). Large-area samples were subjected to hail impact testing after 180 and 243 days. Testing was carried out using the ISO 9806 norm. Briefly, ice balls with a mass of $12.7 \pm 0.5\text{ g}$ (30 mm diameter) or $30.0 \pm 1.0\text{ g}$ (40 mm diameter) were fired at the PV samples at velocities of $23.9 \pm 2.0\text{ m s}^{-1}$ and $27.5 \pm 2.0\text{ m s}^{-1}$, respectively. To simulate micro-damages on plastic samples, they were damaged with a laser beam ($5 \times 100\text{ }\mu\text{m}$ holes).

Open-source tool for predicted environmental Pb concentrations

An open-source tool, PERCENT (derived from PERovskite leaChing assEssmeNt Tool; available at [https://](https://percent.lifesciences.fhnw.ch/)

percent.lifesciences.fhnw.ch/), was developed to determine predicted environmental Pb concentrations in soils. The web tool employs a dilution model to estimate Pb concentrations in soil based on user-defined inputs, including the dimensions and composition of the PSC, as well as the selected leaching scenario (for details, refer to the SI, Section S2). The tool also gives guidance to the user on the probability of different leaching scenarios and the interpretation of possible negative impacts on soils. We determined impacts based on the legislation on soil protection issued by the Swiss Federal Office for the Environment (FOEN), as it is well advanced and documented.^{37,38}

Predicted environmental concentrations and impact assessment

Multiple scenarios were considered to calculate predicted environmental concentrations. The scenarios denoted as 'real' (*i.e.* mini-glass_{real}, plastic_{real}, large-area_{real}) accounted for the cumulative leached Pb at the end of the experimental time. Leaching from the damaged samples was considered *i.e.* micro-damaged samples for plastic_{real}, and samples after hail impact tests for large-area_{real}. The 'catastrophic' scenarios (*i.e.* mini-glass_{catastrophic}, plastic_{catastrophic}, large-area_{catastrophic}) considered 100% Pb leaching from the samples tested in this study. A further theoretical worst-case scenario (worst-case_{theoretical}) was assumed in which every parameter in PERCENT was set to maximize the resulting Pb concentration in soil, specifically a high perovskite thickness with maximum Pb content (see the SI for details, Tables S1 and S2). The concentrations from the scenarios were used to assess impacts beyond soil health, in particular, food plant and fodder plant cultivation. In this, FOEN's 'expert system' was used,³⁷ which is defined for soil Pb concentrations between 200–2000 mg kg^{-1} . Soil parameters (pH 6.2, organic matter content 5.45% and clay content 19.5%) were chosen according to average values in Swiss soils.³⁹

Results

Extent of Pb leaching

We calculated the total amount of Pb in the various samples based on the perovskite film dimensions and density in each sample, thus neglecting Pb that may have been in other, non-perovskite components. The highest Pb release was observed in the mini-glass samples, with a cumulative leaching of $4.81\% \pm 0.02\%$ of Pb during 7 months of outdoor exposure (Fig. 1a). Plastic samples exhibited almost no Pb release over the course of the exposure time ($0.04\% \pm 0.01\%$) (Fig. 1b). Damage to the plastic samples (100 μm holes) did increase Pb emissions, but the Pb concentration remained low $0.15\% \pm 0.14\%$ (Fig. 1b). Large-area samples were tested over 9 months, including hail impact tests after 6 months and 8 months with increasing size of hail (indicated by the dotted line in Fig. 1c). Pb emissions were very low throughout the exposure: $0.056\% \pm 0.011\%$ before the first hail impact, $0.070\% \pm 0.010\%$ before the second hail impact and $0.072\% \pm 0.008\%$ at the end of testing (Fig. 2c). The hail impact tests damaged the encapsulation, causing surface cracks spaced a few centimetres apart (Fig. 2c). Despite

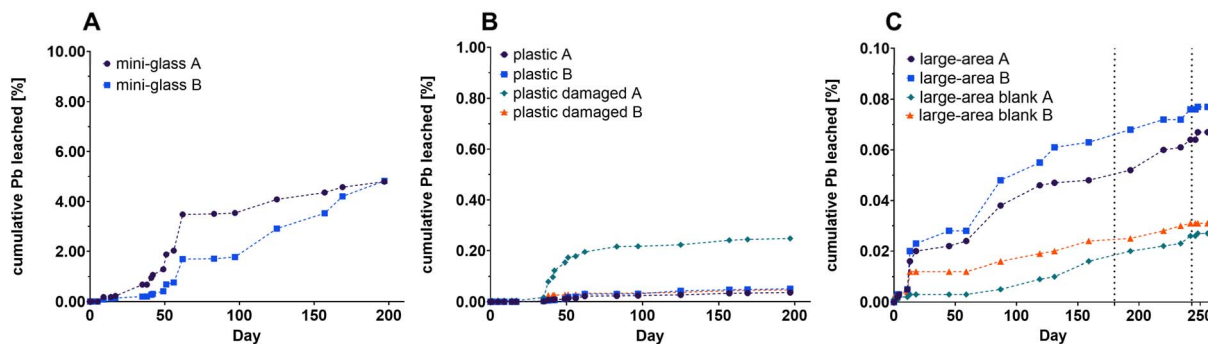


Fig. 1 Cumulative Pb leaching (in % of total Pb) for different PSCs under natural outdoor conditions. Mini-glass samples (A) plastic samples (B) and large-area samples and blanks (C). Dotted lines indicate hail tests after 180 and 243 days. Note the difference in scale (factor of 10 each from left to right) in the y-axis.



Fig. 2 Mini-glass samples (A), plastic samples (B) and large-area samples (C) at the end of outdoor experiments.

resulting in complete discoloration and bleaching of the perovskite film in the cracked samples, this did not lead to a considerable increase in Pb leaching (resulting in only a 0.002% increase after the second hail impact test). It should be noted that some Pb was also measured in the large-area samples blank. For comparison, assuming the large-area samples blank had the same total amount of Pb as the large-area samples, this would amount to an emission of $\sim 0.03\%$ (Fig. 1c). Other elements (In, Sn, Ag, Al and Cr) were detected only at the trace level ($<0.1 \mu\text{g L}^{-1}$ in the leachate), hence they were not considered for subsequent impact assessments.

Predicted environmental concentration and risk scores

To estimate the feasible concentration of Pb that could accumulate in the soil, we assumed that all the runoff would deposit any rainwater containing Pb into a small trench (10 cm in width, 5 cm in depth) running the length of a 1.5 m long and 1 m high tilted module. 'Real' scenarios increased the Pb concentration by 0.1–5.6 mg kg^{-1} in comparison to the background concentration of 24.2 mg kg^{-1} in Switzerland (Fig. 3). As a result, Pb leaching from mini-glass samples, plastic samples and large-area samples would result in predicted environmental concentrations of 29.8 mg kg^{-1} , 24.3 mg kg^{-1} and 24.3 mg kg^{-1} , respectively, which are still below the guide value (50 mg kg^{-1}). The predicted environmental concentration in 'catastrophic' scenarios for mini-glass samples (140.2 mg kg^{-1}), plastic samples (110.5 mg kg^{-1}) and large-area samples (192.7 mg kg^{-1})

kg^{-1}) would exceed the guide value but still be lower than the trigger value for agricultural uses (200 mg kg^{-1}). Only the worst-case_{theoretical} scenario (408.7 mg kg^{-1}) would exceed the trigger value for agricultural uses. The risk scores for food plant

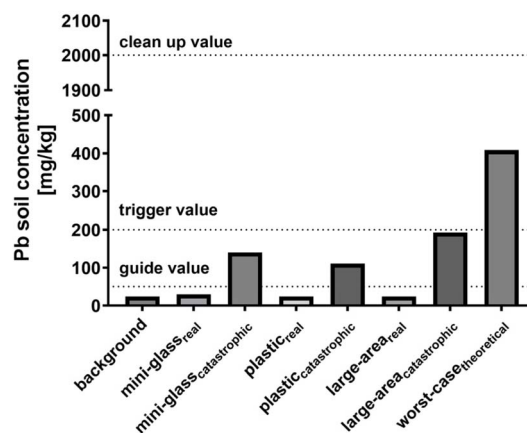


Fig. 3 Resulting Pb soil concentrations for the leaching scenarios considered (for details refer to text). Legislative values in terms of soil protection in Switzerland (*i.e.* guide value, trigger value and clean-up value) are indicated by dotted lines. Note that the y-axis is broken, and even the theoretical worst-case would result in Pb soil concentrations approximately four times lower than the clean-up value specified by Swiss regulations.

Table 1 Risk scores for food plant cultivation depending on plant contaminant uptake for worst-case_{theoretical} leaching scenario

Plant uptake	Risk score
Low	0.58
Medium	1.58
High	2.58

Table 2 Risk scores for fodder plant cultivation depending on soil uptake factor for worst-case_{theoretical} leaching scenario

Soil uptake factor (%)	Risk score
1	1.09
2.5	2.72
5	5.45
10	10.90
15	16.35
20	21.80
30	32.70

cultivation in the worst-case_{theoretical} scenario are all below 3 (Table 1). For fodder plant cultivation, the risk scores range from 1–33 for worst-case_{theoretical} scenarios depending on the soil uptake factor (Table 2).

Discussion

Extent of Pb leaching

The outdoor data presented in this study show that less than 5% of Pb leached within 7 months from mini-glass samples that were encapsulated using only UV-curable epoxy and a glass cover slip. Assuming a linear trend in leaching (Fig. S2), one could carefully extrapolate that it might take as long as ~145 months (assuming an average leaching rate of 0.69% per month) to fully leach all Pb from such devices. Using fully laminated plastic samples, hardly any leaching ($\leq 0.05\%$) was observed. Though the double-sided encapsulation of the plastic samples already resulted in sufficiently low cumulative Pb leaching, the leaching could possibly be further reduced by utilizing edge sealing and a state of the art encapsulant such as cross-linkable ethylene vinyl acetate (EVA). The EVA processing, however, typically requires temperature up to 150 °C and should thus be adapted to be compatible with the flexible PET substrate which has an upper processing temperature limit of 140 °C. In large area samples, encapsulation according to industry standards prevented leaching nearly entirely ($< 0.06\%$ over 6 months in large-area samples before hail impact). Together, these results underline the importance of proper encapsulation to prevent Pb leaching. To achieve enhanced lifetime energy yields, the operational lifetimes of PSCs must be comparable to those of crystalline silicon modules. However, the ingress of humidity is a well-known degradation pathway for perovskites.⁴⁰ Since the performance and longevity of a PSC depend on the structural integrity of the perovskite layer, a fully functional device should not exhibit any Pb leaching.

This study also found that Pb does not immediately leach fully when the plastic and/or glass encapsulation is damaged. This is in contrast to previous outdoor leaching experiments with OPV in which samples that were severely damaged (cut with scissors) showed continuous, linear leaching until all the Zn from a ZnO layer was leached out.⁴¹ ZnO is relatively soluble⁴² and may thus serve as a potential proxy for Pb in PSCs. In the present study's experiments, physical damage of the plastic samples was limited to microscopic pinholes in the encapsulation. In comparison to severely damaged samples, we assign the different leaching kinetics to a lower contact area with water due to the hydrophobic nature of the encapsulant and the high surface tension of water. For plastic-based PSCs, this suggests that small-scale mechanical defects (a possible result of careless installation) are unlikely to create a significant source of leaching yet may provide an entry point for humidity that could impact their lifetimes. Hail impact tests resulted in visible cracking of the glass and discoloration of the perovskite phase (Fig. 2c), but the large-area samples still emitted only an additional 0.017% of total Pb afterwards. In general, for full Pb leaching to occur, water must penetrate the substrate (glass/plastic) through holes or cracks and reach the active perovskite layer in sufficient amounts to solubilize Pb. Subsequently, the Pb cation must be transported back to the original entry point to cause leaching. To understand the time required for a Pb ion to be transported a given distance, one must consider that the liquid is confined between two thin layers of glass and that there may be no bulk flow for the back transport. Then, one can use a simple approximation of the diffusion time in bulk water with $t = x^2/2D$, where x is the distance and D the diffusion coefficient.^{43,44} Considering the various dimensions of PV modules (Fig. 4), the diffusion processes are clearly slow at metre (panel dimensions) scale. For a panel with a single crack, it would take almost 20 years for all the Pb to leach out by diffusion alone and assuming cations in bulk solution. For leaching to occur within a day, a module must be largely shattered, with cracks occurring at intervals of less than 1 cm from one another across the entire surface. In the large-scale samples after hail impact, the cracks were spaced within a range of centimetres from one another, although not covering the entire module (Fig. 2), yet almost no leaching was observed after 70 days (from the second hail impact tests until the end of the experiment). The small amount of Pb leached compared to the model can be explained by several factors. The diffusion-controlled transport in bulk water is certainly oversimplified considering the capillary environment within the two glass plates (with some hundreds of nm space). Here, capillary effects may initially accelerate water ingress while preventing any advection for the transport back. The solubility product of PbI_2 ($K_{\text{sp}} = 4.41 \times 10^{-9} \text{ M}^3$) limits the amount of dissolved Pb available for diffusion locally. Electrostatic interactions of the Pb^{2+} cation with the surfaces will then slow down migration kinetics in contrast to bulk diffusion.⁴⁵ Furthermore, during dry periods without rain, drying cycles can disrupt the continuous water film within the samples, potentially temporarily stopping ion diffusion. Indeed, after the second hail impact test (40 mm diameter hailstones), only four rain events occurred, delivering

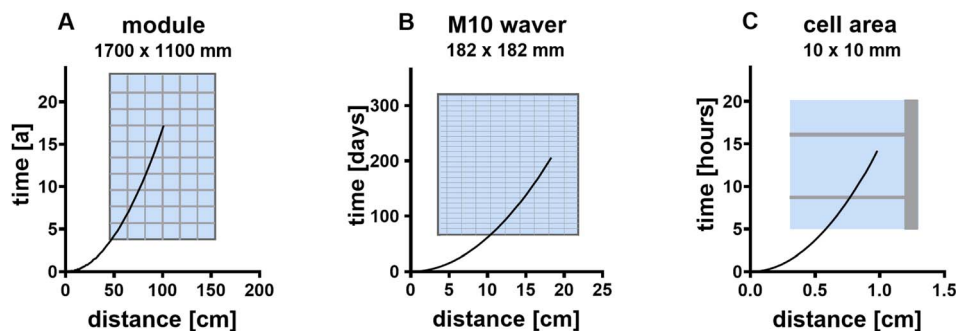


Fig. 4 Diffusion times for the Pb cation in pure H₂O in relation to typical dimensions in PV such as a full module (A), a single wafer (B) and a cell area of 1 cm² (C). Note that fingers and busbars are not drawn to dimension.

minor amounts of rain (145 and 156 mL for large-area modules A and B respectively, cumulative) (Table S4). Lastly, despite clear visual degradation, the polyolefin laminate foil may have remained intact after hail impact, and the perovskite may have degraded by diffusing water vapour only. We note that the top side of our films were processed directly on the fluorine-doped tin oxide glass. Notably, in perovskite-on-silicon tandem cells, both sides of the devices would be protected by lamination foil, suggesting that even less Pb leakage should be expected. While our findings indicate limited Pb leaching, the specific mechanisms and contributing factors of cation transport remain insufficiently understood and warrant further systematic investigation. Nevertheless, our results support the conclusion that robust encapsulation can prevent leaching and that, in the use phase, only severe damage scenarios, such as fire and catastrophic failure (complete shattering), are likely to result in more significant Pb release. At decommissioning and end of life (collection, recycling), modules may indeed fully break, and Pb leaching could become an issue. In this context, various approaches to trap Pb from PSCs in damage scenarios have been suggested; for instance, *in situ* Pb sequestration is possible by using a mesoporous hydroxyapatite nanoparticle scaffold,⁴⁶ phosphonic acid-based chelating agents⁴⁷ or a composite of polymer and metal-organic framework.⁴⁸ However, while strong chelating agents may indeed mitigate leaching, their potential impact on the recyclability of PSCs based on extraction (either by organic solvents⁴⁹ or water⁵⁰) requires further investigation.

Predicted environmental concentration and risk scores

Metals in soil are commonly reported in relative units (*e.g.* mg kg⁻¹) to standardise concentration measurements across varying sample sizes, and legislation is based on these relative units. However, it is important to note that the overall amount of Pb in a perovskite use-phase scenario is limited (*i.e.* the maximum content in a module) and that this amount is then 'diluted' in more or less soil upon leaching. After accounting for the natural soil Pb background, the resulting concentration after leaching can be derived. Soil has a natural and finite sorption capacity for cations,⁵¹ which will (amongst other factors as described below) determine the bioavailability of Pb. In this regard, Li *et al.* report that the bioavailability of Pb from perovskite to various plants was higher than that of pure lead

iodide during a 20 days exposure period.²⁰ The authors spiked the soil with 5 to 250 mg Pb kg⁻¹, assuming an infiltration area of 1 m² per m² of PV module and a 15 cm soil depth. Although the relative unit of mg kg⁻¹ suggests that little Pb is needed to increase soil concentrations, the overall amount of Pb is still considerable; the soil volume affected corresponds to 186 kg (assuming an average density of 1240 kg m⁻³) per 1 m² PV module. Assuming a MAPbCl₃ or MAPbI₃ perovskite, the perovskite layer would need to be 19,500–34,800 nm thick to produce an increase of 250 mg kg⁻¹. Most commonly perovskite layers are between 500 and 1000 nm thick, it is therefore doubtful that this hypothetical scenario represents a realistic use-case scenario for perovskite-based solar cells. In addition, it is highly unlikely that rainwater dripping from the edge of a tilted module would infiltrate an area of 1 m² below the module. Furthermore, the assumed penetration depth of 15 cm would be unusually high, considering the high sorptive potential of most soils.^{52,53} Schmidt *et al.* found that Pb is quickly removed from the aqueous phase (dissipation half-lives below 1 h; removal of >90% after 24 h), and most Pb will be part of immobile soil fractions, whereas only a small fraction of Pb remains mobile and bioavailable. To facilitate the calculation of realistic predicted environmental concentrations, we employed PERCENT (<https://percent.lifesciences.fhnw.ch/>). Our worst-case predicted environmental concentrations represent a more conservative approach, considering a much smaller infiltration area (10 cm across the module width, *i.e.* 0.1 m² per m² of PV module width) and a smaller depth of soil affected (5 cm). This results in higher predicted environmental concentrations, yet with a smaller soil mass affected (~9 kg in 5 cm), which allows for easier removal and treatment of soil if needed.

Because leaching was low in all the samples tested, the Pb soil concentrations in all real scenarios were also low (easily below the guide value of 50 mg Pb kg⁻¹ soil) (Fig. 3). According to Swiss regulations, the guide value reflects typical concentrations in healthy soil in which no risk to long-term soil fertility is expected. Consequently, the risk posed by Pb leaching in the exposure pathway of encapsulated PSC → rain → soil is zero, since the impacts are zero. The catastrophic scenarios assumed complete leaching of the devices tested. In these scenarios, Pb soil concentrations still remained below the trigger value of 200 mg kg⁻¹. Only the theoretical worst-case scenario increased

the soil concentration to 408.7 mg kg^{-1} , exceeding the trigger value. Exceeding the trigger value does not necessarily imply a factual risk to soil fertility but requires that the possible risk be assessed in detail (this being what is ‘triggered’) and that authorities consider measures to prevent a further increase. Similarly, the European Chemicals Agency determined the predicted no-effect concentration of Pb in soil to be $212 \text{ mg Pb kg}^{-1}$ soil, indicating that concentrations below this threshold are unlikely to negatively impact soil organisms.⁵⁴ The scenario described as worst-case_{theoretical} used a perovskite layer with the highest density of Pb (MAPbCl_3) and assumed a layer thickness of 1000 nm. This composition is not likely to be used in actual PSCs, as it is almost fully transparent, with a bandgap of $>3 \text{ eV}$. Further, we assumed full leaching to a minimal volume of soil. Still, even in the worst-case_{theoretical} scenarios, where all the Pb from a thick perovskite is leached into a minimal volume of soil, the Pb soil concentration did not exceed the clean-up value ($2000 \text{ mg Pb kg}^{-1}$), at which a negative impact is certain, and restriction of soil use or remediation is mandatory.

Regarding the risk assessment, the Swiss FOEN’s ‘expert system’ calculates risk scores for different exposure pathways and different uses (*e.g.* food plant and fodder plant cultivation).³⁷ For food plant cultivation, risk score values below 3 signify no concrete risk. Even in the theoretical worst-case scenario, risk scores remained below (Table 1). For fodder plant cultivation, risk scores depend on the amount of soil taken up by animals (0–30%). Considering fodder plant cultivation with low soil uptake ($<2.5\%$), even the worst-case scenario would result in ‘no risk’ (score <5). Only for fodder plants with more soil uptake in animals could moderate (score 5–8) or even high risk (score above 8) be expected under the large-area_{catastrophic} and worst-case_{theoretical} scenarios (Table 2). In such cases, recommended measures include avoidance of overgrazing and reducing the ratio of contaminated plants in fodder.

While our study provides a long-term outdoor assessment of Pb leaching from PSCs and estimates potential soil impacts using the developed PERCENT tool, some limitations remain. First, we did not directly measure changes in Pb concentrations in soil over time, instead, we relied on modelled predictions. Direct soil monitoring could further validate these estimates. Second, although we simulated certain types of damage such as hail impact and micro-pinholes, extreme device failure scenarios (*e.g.*, complete delamination or full module shattering) were not systematically explored. Future studies could investigate how varying levels of mechanical damage influence Pb leaching kinetics. These limitations highlight possibilities for future work to further refine environmental risk assessments of PSCs.

Conclusion

Given the pivotal role that PSCs may play in the global energy transition, it is certainly premature to issue a general ‘green light’ for all aspects of their widespread deployment. However, our findings across diverse device architectures and encapsulation strategies consistently show that only a small fraction of the total Pb content is likely to leach within the time frame of

months in outdoor conditions in the use phase. Moreover, it is worth emphasizing that the modules examined in this study are research prototypes rather than fully commercialized products. As such, even those with “industry-standard encapsulation” represent conservative stand-ins for future market-ready modules, which will need to meet more stringent reliability and safety standards through certification processes. We strongly advocate for further research into possible failure pathways of perovskite-based cells and modules, as well as leaching mechanisms and the impact of encapsulation strategies on Pb release into the environment, including in catastrophic scenarios such as extreme weather events or fire. Crucially, assessments of possible risks must be made on a comparative basis; the world is already experiencing the impacts of climate change, and waiting to deploy renewables is not an option,⁵⁵ as our carbon budget is dwindling.⁵⁶ One should not forget that other energy technologies (renewable or not) also have associated risks. We recommend refraining from using the term *risk* alone whenever possible, instead providing a statement addressing probability and impacts.

Author contributions

Anika Sidler: conceptualization, methodology, investigation, writing – original draft, visualization. Felix Schmidt: conceptualization, methodology, investigation, writing – review & editing. Bastien Vallat: methodology, software, writing – review & editing. Fionnuala Grifoni: writing – review & editing. Severin N. Habisreutinger: resources, writing – review & editing. Riikka Suhonen: resources, writing – review & editing. Henry J. Snaith: resources, writing – review & editing. Andreas Schäffer: writing – review & editing, supervision. Markus Lenz: conceptualization, methodology, writing – review & editing, visualization, supervision.

Conflicts of interest

There are no conflicts to declare.

Data availability

The data supporting this article have been deposited at Zenodo at <https://doi.org/10.5281/zenodo.17061827>.

Supplementary information (SI) is available. See DOI: <https://doi.org/10.1039/d5el00191a>.

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