Manage the environmental risks of perovskites

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**Summary**

Perovskite solar cells may bring an enormous advance in our way towards net zero carbon. However, to achieve their full sustainability potential, we must address the risks to soil, ecology and human health associated with the use of toxic lead in perovskite technology.

# Introduction

The push to net zero is gaining momentum, but we must act quickly to protect our planet and ensure a greener, more resilient future for us all. In December 2020, António Guterres, Secretary-General of the United Nations, gave a stark warning to national governments to declare a climate emergency until the world reaches net zero carbon.1 The Intergovernmental Panel on Climate Change (IPCC) tell us that the way to keep the planet’s temperature under control – limiting the global average temperature increase to 1.5 °C - is to cut global carbon emissions by almost half (45%) from 2010 levels by 2030, before reaching net zero by 2050.2 Decarbonizing energy systems would be the fastest way to achieve the net zero target, as almost 75% of our greenhouse gas emissions have come from the energy sector.3 To do this, the International Energy Authority (IEA) say that we must increase the share of wind and solar in the electricity mix from 9% (2020 data) to 40-70% by 2050.3 However, we desperately need more efficient renewable energy technology to have a better shot at displacing the oil and gas industry - a recalcitrant giant beast of the global economy.

Just at the right time, a revolutionary photovoltaic (PV) technology known as ‘perovskites’ has emerged to push forward the green energy transition. This technology offers much higher power conversion efficiency (greater than 29%) than traditional silicon solar cells (less than 23%).4 However, there is a snag: toxic lead is used in perovskites. Concerns over lead-based perovskites have been voiced echoing historic warnings over other lead-based products: J. Lockhart Gibson first raised the alarm on leaded paint in a 1904 article, alas to little international attention. Many millions of people have been affected by lead contaminants and occupational and environmental exposure remains a major global health issue, accounting for more than one million deaths each year.5 With an energy transformation based on perovskites appearing increasingly likely, the adoption of this lead-based PV technology must be fully debated. We believe that the discussion needs to be informed from an environmental viewpoint, in terms of impacts to soil and broader ecosystems and human health, and how to overcome these while tackling the urgent climate crisis, which forms the aim of this paper.

# The environmental risks

## The lead health issue

Toxic lead has been mined and exploited by humans for many centuries. Water pipes were so commonly made from lead in ancient Roman times that the English word ‘plumbing’ derives from the Latin word for lead ‘*plumbum*’. In the 20th century, lead was routinely used as an additive in paint and as an anti-knocking additive in petroleum. Nowadays, lead is widely used in lead-acid vehicle batteries, ammunition and tin-lead solder in electronic devices. Human exposure to lead contaminants can occur in several ways. For example, inhalation of atmospheric particles emitted from smelting or electronic waste recycling operations, ingestion of contaminated dust and soils holding fragments of weathered leaded paint, drinking water that is conveyed through lead pipes, or ingestion of food grown in lead contaminated soil.

Health problems associated with such occupational and environmental lead exposure can include damage to the brain and kidneys and, ultimately, death. Compiled public health data show that it is the cause of more than one million deaths around the world each year and the loss of more than 24 million disability-adjusted-life years - a measure of overall disease burden.5 Recent academic studies suggest that low-level lead exposure has a great impact as a risk factor for cardiovascular disease, with one study attributing it to more than 400,000 deaths per year in the US alone.6 Moreover, low-level lead exposure affects children far worse than adults, as it can irreparably damage neurological development.7 And while the impact of lead exposure among developed countries is concerning, the impact falls hardest on vulnerable communities and developing countries, particularly in regions where occupational and environmental controls are laxer.7 For example, many south and south-east Asian, African, central and Latin American and east European countries still lack regulatory controls on lead-based paint; or they are weakly enforced if they do exist.7

Curbing lead use is a high priority action and an important aspect of our efforts towards the United Nations’ Sustainable Development Goals (SDGs). However, despite efforts led by the United Nations Environment Programme (UNEP) and the World Health Organization (WHO), there remains a long way to go in bringing the lead health issue to an end. Endeavours are hindered by both extrinsic factors, such as organisational behaviour and perceptions of higher “quality” lead-based products like leaded paint, and intrinsic factors linked to the feasibility of alternative technologies and regulatory controls. As such, lead use and its legacy of environmental pollution remains an enormous global health burden.

## The perovskite lead issue

In one of the most celebrated scientific discoveries of recent years, scientists found a way to improve solar cells using hybrid organic/inorganic crystalline materials.8 The discovery of perovskites has rendered power conversion efficiencies as high as 25% as a single junction and more than 29% as a perovskite-silicon tandem structure.4,8 Their high performance, coupled with ease of manufacture, promises commercialization at a time when solar electricity generation must ramp up to meet net zero targets. The IEA predict that 70,000 terawatt-hours of electrical power will be generated globally in 2050: almost triple the current level.3 They also say that in order to produce this output and still achieve net zero, we will need solar cells installed on 240 million rooftops by 2050, compared to just 25 million at present.3 The development of perovskites makes this challenge somewhat more achievable.

The advanced perovskite solar cell design has a thin layer of a lead-based perovskite compound that harvests solar energy. That perovskite layer lies beneath other layers including an outer transparent contact usually made of glass. Whilst the solar cell remains intact, the lead is safely stowed with no exposure route and no environmental risk. However, broken perovskite cells with loosened frames or cracked outer layers can release lead compounds into rainwater - a process known as leaching - with breakage rates in the operational phase of traditional PV cells being low but notable: Roughly 1 in 100 solar cells break over a 25-year life.9 Nevertheless, the possible scale of perovskite solar cell deployment suggests that millions of proprieties could be affected by lead leaching.

Human and ecosystem exposure to lead contaminants is often conducted via a contaminated environmental medium. In the case of leached lead, rainwater acts as a vector, carrying lead contaminants to the wider local environment. As shown in Figure 1, there is a direct route from broken perovskites installed on residential building rooftops to garden soil, which poses a particular risk because of hand-to-mouth activity among young children displaying pica behaviour (eating objects which are not suitable to be eaten). Moreover, leached lead accumulation in soil would introduce a pathway for lead uptake by plants. Climatic simulation has suggested that perovskites may only affect soils with relatively small amounts of lead, with the lead leached from a broken 1 m2 solar panel calculated to increase soil lead content to 70 mg kg-1.10 However, such simulation does not necessarily represent a “worst-case” scenario, for example, multiple cell breakages on one roof or leached lead directed to a specific location. Water quality issues can also result from infiltration (water entry into soil) affecting groundwater aquifers and surface runoff carrying leached lead to watercourses and affecting aquatic ecosystems.

Importantly, concerns over perovskite lead heighted after it was discovered that perovskites can release certain chemical forms of lead - including lead iodide and methylammonium lead iodide - which are prone to leach due to their high solubility and are particularly harmful to humans and ecosystems owing to high bioavailability - the degree to which a contaminant interacts with a living organism. Initial toxicity research (e.g., assays and electron microscopy) conducted on human cells exposed to perovskite methylammonium lead iodide has revealed massive apoptotic death;11 follow-up research is needed to fully understand the implications for human health. An important study found that plants can absorb certain forms of perovskite lead at rates that are an order of magnitude higher than other common lead contaminants found in the environment,12 which is a concern for food safety if taken up by edible plants. Other studies, including aqueous and dietary exposure tests conducted on both zebrafish larvae and adults as model organisms,13 have reported perovskite lead to be highly bioavailable to aquatic organisms, thus, indicating its potential to adversely affect aquatic ecosystems.

Such environmental studies are a stark warning of the potential environmental risks of lead-based perovskites. Although we do not yet know whether these early signs scale up to extensive human health impacts through contaminated soil exposure or affected foodstuffs, or severe damage to ecosystems through trophic chains, the highly bioavailable nature of the chemical forms of perovskite lead points toward that direction. Therefore, we need comprehensive environmental risk assessments to understand the environmental impacts better. In the meantime, we ought to be cautious about installing perovskites on millions of buildings around the world.

# Managing the risk

## Environmental risk management

Environmental risk management aims to manage risks posed by contaminants at affected sites based on an evidence base of known toxicity effects. Where an environmental risk is deemed high, we may be able to mitigate that risk by breaking the source-pathway-receptor contaminant linkage.

One way to mitigate the risk of leached lead affecting garden soil would be to place lead-based perovskites away from residential areas, for example, as PV power stations, also known as “solar farms”. However, if perovskites were to be installed on rural farmland combined with crops, this may create a food safety concern due to leached lead uptake. Moreover, risks to aquatic ecosystems from lead leaching would remain. Therefore, whenever possible, it may be prudent to build perovskite PV power stations on unproductive degraded land e.g., desert areas.

## Perovskite design

Designing perovskite solar cells to robustly encapsulate the lead content and reduce their lead leaching potential would be one obvious way to lessen the environmental risk. It has already been discovered, in laboratory tests, that epoxy resin encapsulation may reduce lead leaching levels significantly compared to perovskites that have glass outer layers with UV-cured resin edges.14 Covering solar cells with a hydrophobic (waterproof) chemical, such as polytetrafluoroethylene (PTFE), has also been investigated as a way to protect perovskites.8 However, robust designs must be tested for different environmental stresses and climate extremes due to climate change.

According to the hierarchy of controls, replacing a hazard with a substitute is better than isolating people from the hazard by encapsulation. Therefore, some researchers propose that lead should be avoided and that alternative divalent cations (i.e., metals with oxidation state II), such as tin, should be substituted into the perovskite compound as environmentally-friendly alternatives.12 However, it is reported that non-lead perovskites generally display inferior power conversion efficiencies than those of lead-based perovskites (tin perovskites have displayed less than 10% efficiency so far),8 restricting their ability to push forward the green energy transition. Moreover, non-lead perovskites tend to degrade quickly by oxidation processes (for example, tin is less stable in its divalent state than lead is),8 which raises another threat to their commercialisation. From an environmental perspective, alternative metals themselves also pose environmental risks. For example, while it is generally accepted that the risk of poisoning from tin or tin salts (inorganic tin) is much lower than for lead or lead salts, tin still poses an environmental risk. Indeed, tin–based perovskites have shown higher levels of toxicity to zebrafish embryos than lead-based perovskites due to an acidification effect.15 Human neurotoxicity and carcinogenicity associated with tin exposure is still under investigation:8 We know surprisingly little about environmental tin exposure, which is widely used in industrial and consumer products, such as food cans, transportation and construction materials, as well as electrical equipment.

A full evaluation of production factors and pollution and toxicity risks is lacking. Holistic life-cycle sustainability analyses that incorporate factors such as material costs, resource availability, and production processes as well as the environmental impacts of contaminant leaching, need to be conducted to compare lead-based perovskites with non-lead alternatives so that a clearer view can be formed of the extent of the potential risk.

# Conclusions and Outlook

The push to net zero energy is gaining momentum with more and more world leaders making serious commitments on carbon peak and carbon neutrality.16 In the battle against climate change, perovskites may play a vital role, catalysing further energy transition effort. However, perovskites contain lead. Highly bioavailable lead compounds can leach from broken perovskites and enter the environment at potentially harmful levels, particularly in residential areas where children might be affected. The most sustainable way to manage that risk cannot be judged because we lack comprehensive environmental risk assessments for perovskite lead compounds in the environment. Until then, a precautionary approach should arguably be taken, wherein policies favour the deployment of perovskites at non-residential sites, for example, as solar farms. With a concerted effort, perovskites may not only bring a new energy revolution, but also bring a cleaner and healthier environment.

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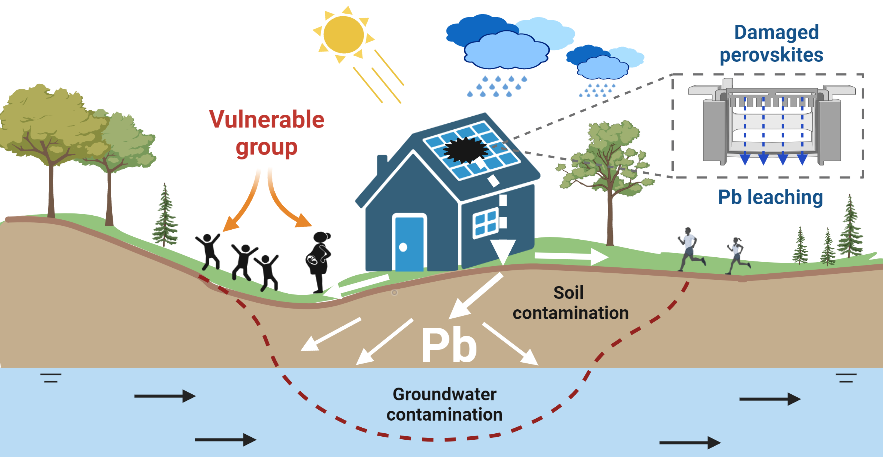
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# AUTHOR CONTRIBUTIONS

Both co-authors developed the ideas presented in this paper. DO’C took a lead on writing the first draft, and both authors contributed to later revisions.

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**Figure 1**. Perovskite solar cells can be damaged by natural events, such as hail storms and freeze-thaw seasonal cycles. Toxic lead can leach from damaged perovskites and concerns have arisen regarding environmental contamination and human health concerns.