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Sustainable perovskite light emitters

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Perovskite light-emitting diodes (PeLEDs) that use lead (Pb)-based perovskites are promising candidates for the next generation of lighting and display technologies. However, concerns about the toxicity of Pb have delayed their progress toward commercialisation. From this viewpoint, we compare Pb-based, low-Pb and Pb-free perovskite systems, with a focus on toxicity and environmental impact. By calculating the amount of lead in different perovskite systems, we find that Pb-based and low-Pb perovskites have relatively low toxicity that meets the restriction of hazardous substances directive standards. We then highlight the strengths and challenges of each material system and further propose a path for sustainable commercialisation focusing on environmental, social, and governance considerations, along with a development roadmap and strategies for perovskite materials and their devices.

Introduction

Perovskite light-emitting diodes (PeLEDs) have a wide colour gamut with high colour purity and are relatively inexpensive, so they show promise as next-generation display and lighting technologies.[1–3] PeLEDs have been advanced to achieve high external quantum efficiencies (EQEs) > 30%, which is comparable to conventional organic light-emitting diodes (OLEDs) and inorganic quantum dot light-emitting diodes (QDLEDs).[4,5] Furthermore, the operational lifetimes of PeLEDs have been increased significantly. However, most of the PeLEDs include lead (Pb), which is known to be toxic. Therefore, Pb-free PeLEDs, which use metals such as tin (Sn), copper (Cu), bismuth (Bi), or antimony (Sb), which are less toxic than Pb, are being evaluated as candidates for commercialisation. Although numerous studies have evaluated the advantages of Pb-free PeLEDs,[6–9] the development of next-generation displays requires a comprehensive evaluation, including device performance, materials design, and environmental impact.

In the evaluation of PeLEDs, an excessive emphasis solely on the Pb content in the emission layer may be inappropriate: analyses should also consider the overall environmental and social impact including energy consumption and chemical waste such as organic solvents generated during the manufacturing

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process and by the equipment used.[10] Moreover, valid assessment of the toxicity of perovskites must consider their applications, so analyses must be tailored for various environmental conditions.[11,12] These analyses must be conducted for Pb-based, low-Pb and Pb-free systems.

Here we examine the development of sustainable PeLEDs by comparing the performance, Pb concentration, and environmental impact of Pb-based, low-Pb and Pb-free perovskite materials. Specifically, we review recent progress in improving EQE, luminance (L), and operational lifetime (T_x) measures, *i.e.*, the time taken for brightness to decay to x% (usually 95 or 50%) of its initial brightness L_0, while comparing the European Union's Restriction of Hazardous Substances Directive (RoHS) compliance and material-toxicity concerns. We further analyse the effects of PeLEDs on the environment and human health throughout their lifecycle and reveal that the presence of Pb can have minimal significance, depending on applications. Additionally, we discuss the sustainability and commercial viability of low-toxicity PeLEDs, considering environmental management, social responsibility, and regulatory governance perspectives. To support sustainable technology translation, we further propose a development roadmap and targeted strategies by clarifying the respective strengths and challenges of each system. As a comprehensive comparative study, this work aims to broaden the application potential and inform the sustainable development of Pb-based, low-Pb and Pb-free perovskite light emitters.

Current status and comparison of Pb-based, low-Pb and Pb-free PeLEDs

The first evaluated perovskite materials had low exciton-binding energies and long exciton-diffusion lengths, so they were not ideal for use as light emitters.[13] Development of nanocrystalline perovskites achieved PeLEDs that had remarkably increased EQE, L, and T values.

Particularly, the EQE of PeLEDs has improved dramatically. This advance began in 2014, with the development of the first bright PeLED ($L \approx$ 300–400 cd m^{-2}), but it had a low maximum EQE (EQE$_{max}$) of $\sim$0.1%.[14,15] Subsequent development of PeLEDs that use nanoscale polycrystalline perovskites achieved the first high-efficiency PeLEDs in 2015.[3] Since then, substantial progress in Pb-based PeLEDs has increased the EQE$_{max}$ to >30%, which is near their theoretical EQE. Concurrently, Pb-free alternatives, especially Sn-based perovskites, have also been rapidly advanced to EQE$_{max}$ approaching 20% (Fig. 1A).[16,17] The rapid evolution in the EQE has established PeLEDs as strong alternatives to commercial OLEDs and QDLEDs.

Maximum luminance (L_{max}) is a crucial performance parameter in PeLEDs. It has also been significantly increased across different emission colours (Fig. 1B). Pb-based systems cover a wide emission spectrum with wavelengths in the range of $450 \leq \lambda < 900$ nm, in which PeLEDs that emit green have achieved L_{max} up to $\sim$470 000 cd m^{-2}.[1] However, blue and red emitters have relatively lower L_{max} than green emitters, primarily due to differences in photopic luminous efficiency and intrinsic material properties.[13] The high L levels meet the requirements for applications such as displays for indoor or outdoor use (>1000–3000 cd m^{-2}), virtual reality (VR, >10^5 cd m^{-2}) and augmented reality (AR, >10^6 cd m^{-2}).[18–20]

In comparison, Sn-based systems emit predominantly in the red to near-infrared (NIR) spectral region ($630 \leq \lambda \leq 975$ nm), with a particularly dense distribution at $\lambda > 850$ nm. Although they have relatively low $10^2 \leq L_{max} \leq 10^3$ cd m^{-2} in the visible range, many devices achieve notably high NIR radiance > 200 W sr^{-1} m^{-2},[21] so Sn-based PeLEDs are promising candidates for NIR optoelectronic applications including bioimaging, night vision, and infrared communication. Systems that combine Pb and Sn emit primarily in the blue-green ($450 \leq \lambda \leq 550$ nm) region and have $L_{max} \approx 10^4$ cd m^{-2}, which is an order of magnitude greater than those of systems that use Sn or other elements.[22] PeLEDs that use other elements (*e.g.* Cu, Sb, Ce, Eu, Zn, Mn, AgInBi, Tb, and La) than Pb and Sn emit in a broad band in the range $450 \leq \lambda \leq 650$ nm. They also lack clear spectral focus and have limited $L_{max} < 10^3$ cd m^{-2}.

Operational stability remains a significant challenge. For display devices such as televisions and mobile phones, the commercial requirement is typically defined as $T_{95} \approx 10^4$ h at L_0 = 1000 cd m^{-2}. Mobile applications with less frequent usage (*e.g.* camera and watch) than televisions and mobile phones require $T_{50} > 10^6$ h at L_0 = 100 cd m^{-2}.[12] However, both of these lifetime parameters (T_{95} and T_{50}) of PeLEDs have been increased more slowly than their EQEs. In Pb-based systems, the longest reported T_{50} at a constant current density of 100 mA cm^{-2} is 50 317 h in green-emitting PeLEDs,[1] $\sim$3900 h in red-emitting PeLEDs,[1,23] but only $T_{50} \approx 35$ h in blue-emitting PeLEDs.[24,25] However, Pb-free systems generally have $T_{50} < 200$ h at both high and low current densities of 200 and 5 mA cm^{-2}, respectively,[26,27] so this low lifetime is a critical drawback of Pb-free PeLEDs, which is far behind the stability requirement for practical applications (Fig. 1C).

In summary, Pb-based PeLEDs have higher EQE$_{max}$, L_{max} and T_{50} than do Pb-free systems (Fig. 1D). For instance, Sn-based systems exhibit considerably low L; Pb/Sn hybrid systems are hindered by low T_{50}; and PeLEDs that use other elements typically have low EQEs and low L. Despite the significant

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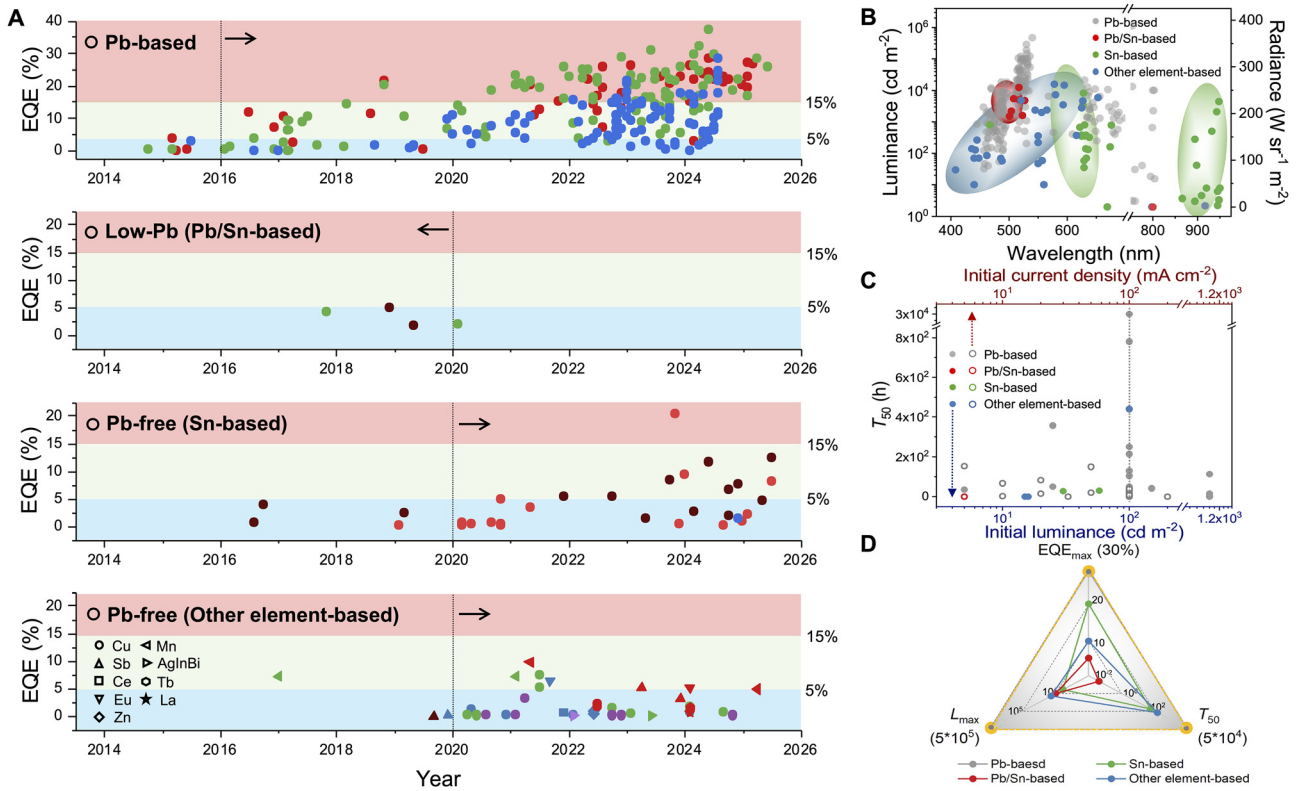

Fig. 1 (A) EQE evolution over time (red, green, and blue markers represent emission colours, brown represents NIR emission, and purple represents white emission), (B) distribution of luminance (cd m^{-2}) across the visible and near-infrared spectrum (375–750 nm) and radiance (W sr^{-1} m^{-2}) across the visible and near-infrared spectrum (750–975 nm), (C) T_{50} *versus* initial J_0. The vertical dashed line indicates 100 cd m^{-2} or 100 mA cm^{-2}. (D) Radar chart showing comparison of three key metrics: L_{max}, T_{50}, and EQE_{max} for PeLEDs that bear Pb, Pb–Sn, Sn, and other elements. Detailed data are shown in Tables S1–S13 (SI).

interest in Pb-free perovskites and their remarkable development, Pb-free PeLEDs still lag behind Pb-based PeLEDs, as a result of substantial challenges to their development. Therefore, replacing Pb totally or partially with these environmentally-benign Pb-free alternatives requires further advances.

Sustainability of perovskite light emitters: from RoHS limits to biotoxicity

The primary contributors to toxicity in perovskite light emitters are heavy metals from raw materials, especially Pb. During prolonged operation, Pb-based perovskites tend to decompose into lead halide (PbX_2) when exposed to light, heat, air, or humidity. PbX_2 is $\sim 10^9$ times more water-soluble than PbS and PbSe because it can easily form hydrogen bonds with water.[29] Consequently, if the device is damaged, even rainfall lasting >10 min can completely dissolve the perovskite film.[28,29] To assess the environmental impact, the Pb content ([Pb]) of the perovskite layer in both PeLEDs and perovskite colour conversion layers (PeCCLs) with different compositions is estimated. The RoHS standard permits a maximum [Pb] = 0.1% (=1000 ppm) by weight in homogenous materials (European Union (EU), 2011).[30]

In Fig. 2A, we report [Pb] for various types of perovskites. Assuming typical LED devices contain a perovskite-layer thickness of 20 nm, *in situ* Pb-based and low-Pb perovskites exhibit the highest [Pb] ($\sim$14 000 ppm and $\sim$1500 ppm), exceeding the RoHS limits. Followed by nanocrystals, [Pb] decreases to $\sim$472.11 ppm in Pb-based systems and $\sim$47.30 ppm in low-Pb systems, and for core–shell nanocrystals, [Pb] further decreases to $\sim$442.57 ppm and $\sim$44.14 ppm, respectively; all nanocrystal LEDs meet the RoHS standard. Pb-free PeLEDs, as expected, contain no Pb. Importantly, when the PeLED is evaluated as a complete device unit incorporating a 1.1 mm glass substrate (dashed blue bars in Fig. 2A), [Pb] decreases dramatically—for example, to $\sim$0.210 ppm in Pb-based and $\sim$0.0211 ppm in low-Pb NC devices—because the 20 nm perovskite layer is negligible relative to the overall thickness.

A comparable trend is observed for PeCCLs used in displays with a blue-LED backlight, which typically comprise a 100 μm polymer matrix containing 0.1 wt% perovskite, encapsulated between two 100 μm PET barrier layers (Fig. 2B). Here, [Pb] decreases from $\sim$107.03 ppm in Pb-based to $\sim$12.41 ppm in low-Pb systems, and to 0 ppm in Pb-free formulations. For nanocrystals, [Pb] is reduced to $\sim$16.00 ppm in Pb-based systems and $\sim$1.63 ppm in low-Pb systems. With core–shell nanocrystals, [Pb] further decreases to $\sim$12.82 ppm for Pb-based variants and $\sim$1.32 ppm for low-Pb variants, both of

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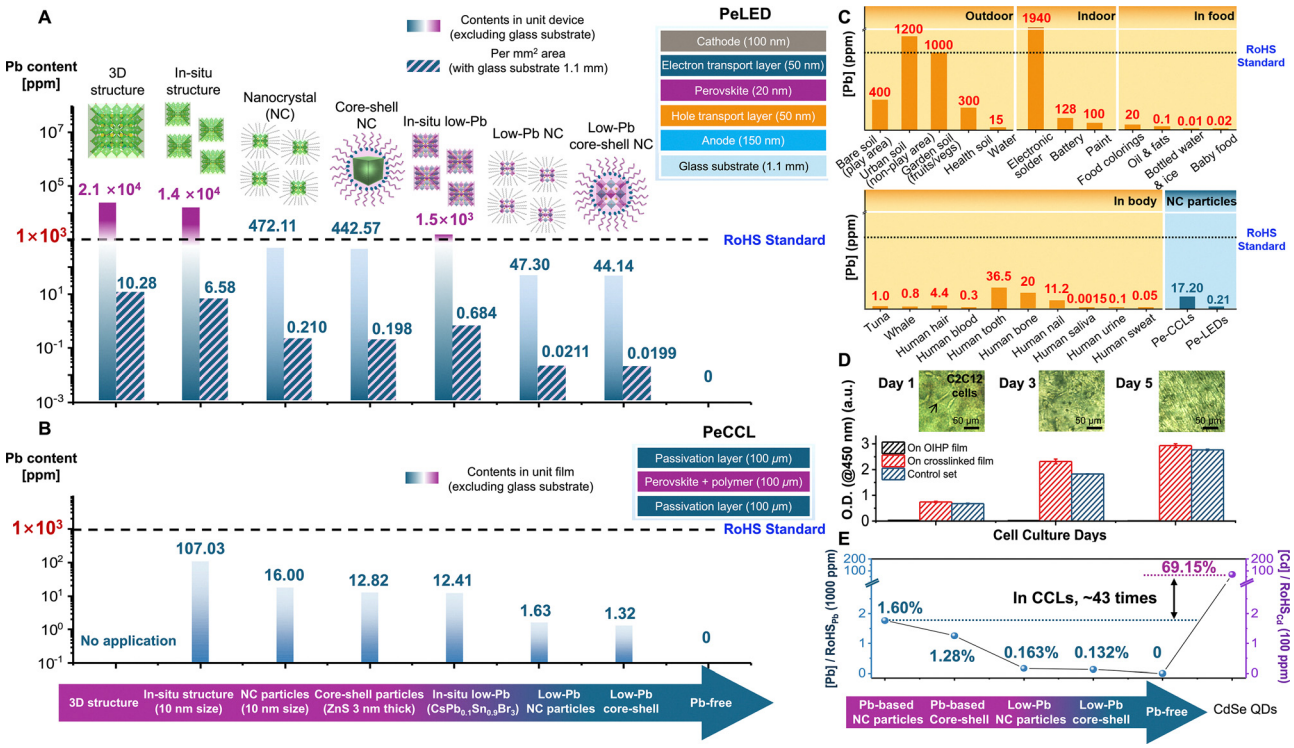

Fig. 2 Quantitative analysis of Pb content in PeLEDs (A) and PeCCLs (B), compared to the RoHS standard (1000 ppm). The inset shows the device structure (*in situ* perovskite refers to PeCN particles without the modification of ligands, and NC particles denote PeCN particles with the modification of ligands).[1] Here, a Pb/Sn hybrid composition of $CsPb_{0.1}Sn_{0.9}Br_3$ (10% Pb fraction) is used as a representative low-Pb system. (C) Comparison of Pb content in outdoor, indoor, food and in-body applications with RoHS standards and perovskite-based devices. (D) Toxicity assessment of perovskite materials in C2C12 cell culture on different substrates (optical density indicates the volume density of cells).[43] Adapted with permission from ref. 43. (E) A relative regulatory content ratio ([Pb]/RoHS limit for Pb and [Cd]/RoHS limit for Cd) for Pb-based, low-Pb, and Pb-free systems with NP particles and core–shell structure and CdSe QDs. The detailed calculation process is shown in SI1–SI3 (SI).

which are well within RoHS limits. These findings show that, in practical devices, the effective Pb content of PeLEDs and PeCCLs is very low and fully compliant with RoHS, confirming the feasibility of their safe commercial deployment.

Assessment of the [Pb] of PeLEDs and PeCCLs should be categorised into application classes—outdoor, indoor, food and in-body applications—because permissible limits differ significantly (Fig. 2C).[29,31–34] In outdoor environments, [Pb] often exceeds both the RoHS standard (1000 ppm) and the health advisory limit for soil (300 ppm). For example, bare soil in play areas may contain up to 400 ppm, urban soils in non-play areas up to 1200 ppm, and garden soils used for growing edible plants up to 1000 ppm.[31] For water sources, the regulatory limit for [Pb] is significantly lower at approximately 15 ppm because it is directly related to the ecosystem and human health.[32]

For indoor applications, there is a relatively high Pb amount in conventional electronic materials such as electronic solder (6200 t per year, 174–1940 ppm) and batteries (up to 1 000 000 t per year, 127.7 ppm).[35,36] In particular, for batteries, more than 40 000–70 000 t per year of Pb waste remains even after processing and recycling.[33] For consumer products with direct human exposure—such as paints—[Pb] must be kept substantially lower (<100 ppm). For food-related applications, [Pb] must be extremely low to ensure human health and safety, ranging from <20 ppm (such as food colourings, and oil and fats) to as low as <0.01 ppm (such as bottled water and ice).[32]

For Pb-based PeLEDs, [Pb] nearly meets the safety requirements for all indoor and outdoor applications. For low-Pb core–shell devices, [Pb] is somewhat similar or sometimes even lower than the levels typically detected in different organisms, such as in tuna (<1.0 ppm) and whale (<0.8 ppm),[37,38] as well as various human body structures, including hair (<4.4 ppm), blood (<0.3 ppm), tooth (<36.5 ppm), bone (<20 ppm), nail (<11.2 ppm), urine (<0.1 ppm), and sweat (<0.05 ppm), except for saliva (<0.0015 ppm).[39–44] These low [Pb]s suggest that PeLEDs and PeCCLs pose negligible risks in practical applications, which is compliant with the safety requirements for nearly all application scenarios, excluding stricter categories such as baby food (<0.02 ppm) and bottled water (<0.01 ppm). Perovskite-based devices that have [Pb] less than the RoHS standard and Pb-free devices can be freely commercialised.

The amount of Pb in PeLEDs and PeCCLs is comparable to, or even lower than, that in materials used in everyday life and the biological tissues in the human body. This suggests that the decade-long concerns surrounding Pb in PeLEDs may have been overstated. Even those exceeding the RoHS limit can still be used in specific domains like electronic solder and batteries with high [Pb].

To verify that Pb-based perovskites meeting RoHS limits are also biologically safe, we investigated their biocompatibility

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in vitro. Mouse skeletal myoblasts (C2C12) were cultured for 3 and 5 days on (i) pristine perovskite-nanocrystal films, (ii) cross-linked perovskite-nanocrystal films, and (iii) a standard tissue-culture plate (control) (Fig. 2D).[45] After 3 and 5 days of culturing, bright-field images directly showed well-grown cells on the crosslinked films, and optical density (OD), which represents the number of living cells, increased significantly on this film from 0.7 to 3.0, which was even slightly higher than that of the control sample (OD increased from 0.7 to 2.8). In contrast, cells failed to proliferate on the pristine perovskite nanocrystal film owing to the decomposition of perovskite crystals. These results demonstrate the excellent biocompatibility and exceptional stability conferred by core–shell encapsulation. Consequently, well-controlled PeLEDs and PeCCLs with extremely low [Pb] that meet the RoHS standard without Pb leakage can be regarded as biocompatible and therefore suitable for in-body or biomedical applications.

In CCLs, the film must absorb a sufficient portion of the blue backlight to achieve efficient colour conversion. Accordingly, for a material with a high absorption coefficient, the required absorber concentration to reach the target absorption is lower, thereby reducing the amount of hazardous constituents. From this perspective, perovskites are promising candidates for CCLs, as they typically exhibit higher absorption coefficients than alternative emitters, including inorganic quantum dots and organic emitters.

Perovskites exhibit absorption coefficients of 10^4–10^5 cm^{-1} (*e.g.*, $\alpha_{CH_3NH_3PbBr_3} \approx 100\,000$ cm^{-1} and $\alpha_{CsPbBr_3} \approx 86\,000$ cm^{-1})[46]—approximately an order of magnitude greater than those of most inorganic QDs from II–VI, IV–VI, and III–V families, which typically lie in the 10^3–10^4 cm^{-1} range (*e.g.*, $\alpha_{GaP} \approx 1000$ cm^{-1}, $\alpha_{CdSe} \approx 12\,000$ cm^{-1}).[47] Consequently, the perovskite concentration in a CCL can be significantly reduced compared with that in a conventional QD CCL, while still sufficiently absorbing the blue backlight and achieving equivalent brightness.

For example, assuming identical photoluminescence quantum yield (PLQY), a typical CdSe CCL would require a weight fraction of 0.717 wt% to achieve the same PL intensity as a $CsPbBr_3$ PeCCL containing 0.1 wt%. This results in a cadmium (Cd) content [Cd] of 69.15 ppm, while [Pb] is 16.00 ppm for a $CsPbBr_3$ CCL with the same optical performance (the detailed calculation is shown in SI3, SI). Given that the RoHS threshold for Cd is 100 ppm, whereas that for Pb is 1000 ppm, the regulatory burden differs markedly: $[Pb]/RoHS_{Pb}$ = 1.60% for perovskites, *versus* $[Cd]/RoHS_{Cd}$ = 69.15% for CdSe QDs. As depicted in Fig. 2E, Cd QDs therefore present a substantially greater hazard potential than their perovskite counterparts.

Sustainability of perovskite light emitters: from environment to society and governance

Until now, most concern regarding Pb-based perovskites has focused on the effect of Pb on human health. However, to evaluate the comprehensive impact of perovskite light emitters, environmental, social, and governance (ESG) factors must all be considered. From an environmental perspective, analyses must consider the energy consumption and materials usage, which are related to the total used amount and [Pb] in a certain volume. The social perspective includes potential health and safety risks, particularly those associated with Pb exposure. Finally, governance addresses the regulatory frameworks, standards and industry practices that ensure responsible development and deployment of PeLED and PeCCL technologies. Together, the ESGs provide a holistic framework for guiding the sustainable commercialisation of both Pb-based and Pb-free perovskite light emitters.

The energy consumed during the operation of PeLED- and PeCCL-incorporated displays, and the amount of materials used during the manufacture of the PeLEDs and PeCCLs have significant environmental impact (Fig. 3A). Therefore, light-emitting devices must be fabricated efficiently with minimal use of materials. The EQE_{max} ($\sim$30%) of PeLEDs is comparable to those of OLEDs and QDLEDs and the very EQE_{max} of hybrid tandem PeLEDs with OLEDs ($\sim$37%) is beneficial in reducing energy consumption. PeLEDs can achieve high brightness at voltages <3 V by using the high carrier mobility of the perovskite layers together with high-mobility charge transport layers.[1]

Electricity consumption should also be considered from an environmental perspective. Electricity accounts for over 99% of the total energy consumed during the manufacturing stage, which involves the extensive use of vapour deposition of common transport materials and metal electrodes.[10] Therefore, transitioning to renewable energy sources such as wind and solar power and adopting large-area fabrication techniques such as printing, blade coating, and roll-to-roll processing are expected to reduce the energy cost and facilitate practical industrialisation.

Furthermore, significant material waste is generated during the fabrication of PeLEDs and PeCCLs, including metal electrodes, ITO glass substrates, organic cleaning solvents and perovskite materials. Particularly, organic cleaning solvents, including 4.4 g of deionised water, 3.480 g of acetone and 3.454 g of 2-propanol, account for approximately 98% of the total mass of substances required to clean a 2000 mm^2 substrate. In contrast, for the emissive perovskite layer, only 0.01–0.02 g dimethyl sulfoxide, chlorobenzene or toluene is used.[10] Therefore, recycling materials used in PeLEDs (*e.g.* organic solvents) are crucial and can further reduce the environmental impact of their manufacture. Although determining operational processes and standards remains challenging, the relative environmental effects of PeLEDs and PeCCLs can still be significantly reduced.

Society imposes strict requirements on health and safety. Historically, the relationship between humanity and Pb spans over 6000 years, with documented history of Pb poisoning dating back 2500 years.[29] Two well-known sources of Pb exposure are paints and leaded gasoline (Fig. 3B). Considering the widespread use, the hazards persisted for an extended period until governments imposed restrictions (Fig. 3C). The first

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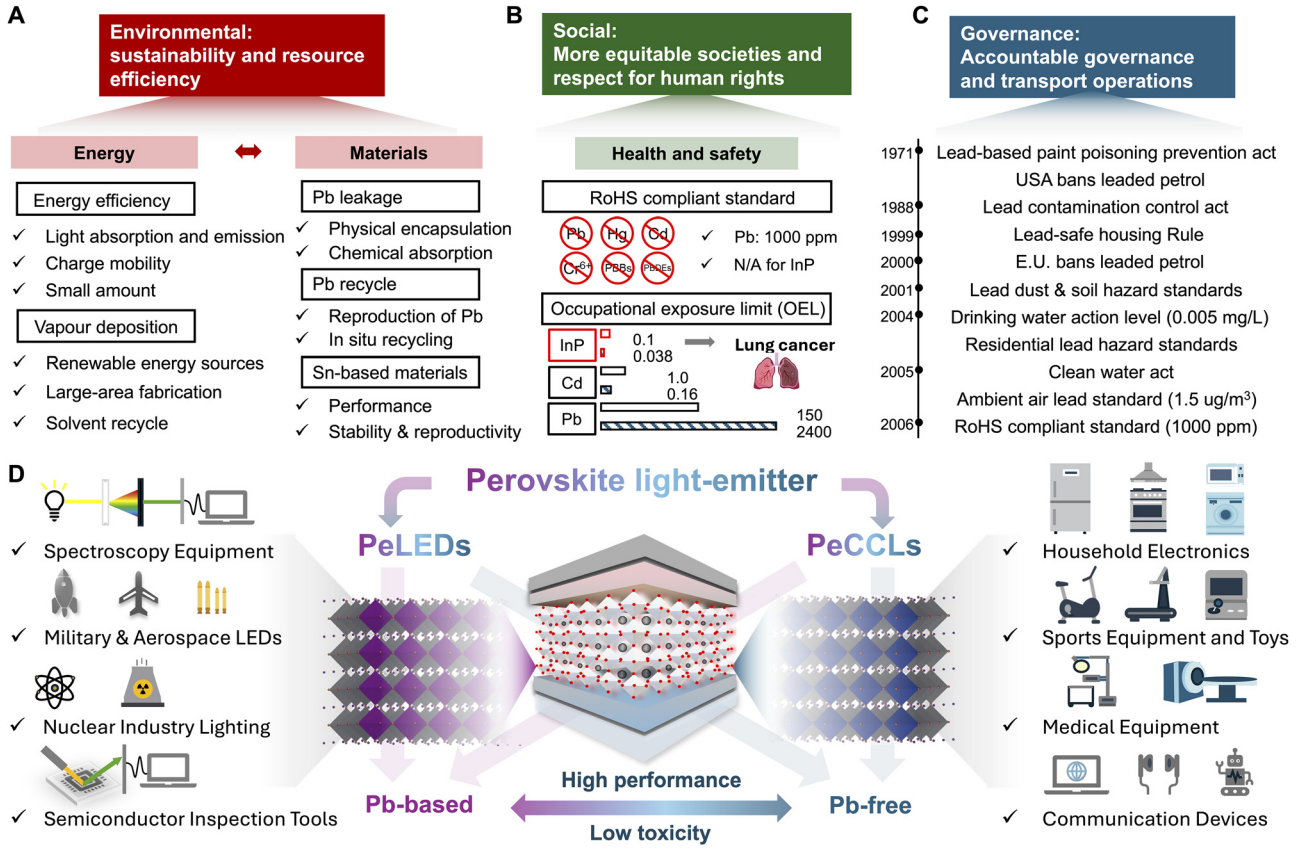

Fig. 3 The sustainability assessment of perovskite devices: (A) environmental strategies target energy and materials; (B) social considerations focus on health and safety; (C) governance highlights global lead-related regulations; (D) application scenarios from Pb-based to Pb-free perovskite light emitters.

major ban on Pb was in 1971, specifically concerning its use in commercial paint products. Researchers found that children were being poisoned by ingesting deteriorating Pb-based paint in 1909, yet it took over 60 years to push for the introduction of nationwide regulatory bans. In gasoline, Pb-containing materials were initially added as anti-knocking agents in 1925, but the Pb level was later found to be far beyond normal thresholds in the 20th century. After decades of legal, political, and scientific disputes, it was eventually banned in both the USA and the EU.[29] Since then, numerous restrictions have been developed and enforced for various applications involving Pb-containing materials, including housing, dust, soil, water, and air. When Pb-containing materials were initially used for specific technological purposes, the associated health and environmental risks were often overlooked, but as they became apparent, regulations were introduced.

In 2006, the RoHS standard was implemented for human health and product applications. To comply with the RoHS standard, [Pb] is generally required to be very low (Fig. 2), and this limit can give the impression that Pb is exceptionally toxic even though other elements are also toxic to human health because the RoHS only regulates a specific list of certain hazardous materials, including Pb, mercury, Cd, and hexavalent chromium. Many materials are exempt from RoHS restrictions, such as indium phosphide (InP), which is regarded as an ideal alternative to Cd-free QDs in commercial displays. This resulted in numerous manufacturers laboring under the false assumption that InP is a non-toxic compound. However, InP-based QDs exhibit significantly higher cytotoxicity than Cd-based QDs in some aspects, which have been classified as materials that are "probably carcinogenic to humans".[48] Moreover, the accepted occupational exposure limit (OEL) for the element In (0.1 μg m^{-3}) is 1/1500 of that for Pb (150 μg m^{-3}), and the required concentration of In (0.038 μg m^{-3}) in the air to represent a certain risk of lung cancer is 1/5th that of Cd (0.16 μg m^{-3}) and 1/100 000 of that for Pb (2400 μg m^{-3}).[49–51] Therefore, although public fears Pb poisoning, the health risks should consider the actual exposure scenarios and product-specific applications.

Rather than simply distinguishing between Pb-based and Pb-free materials, the primary focus should be on minimising environmental impacts while maximising the performance of systems. Pb-free perovskites are generally regarded as safer and more environmentally benign than their Pb-based counterparts, with potential suitability for consumer applications including even toys (Fig. 3D). Pb-based PeLEDs and PeCCLs also appear RoHS-compliant, suggesting their possible applicability in commercial products with frequent human contact, such as household electronics, sporting goods, medical devices, and communication equipment, without posing significant

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environmental and health concerns. In addition, given their superior device performance, including high EQE, high L, and extended operational stability (Fig. 1), Pb-based devices are well-suited for specialised high-performance technical markets such as spectroscopy equipment, military and aerospace LEDs, nuclear industry lighting, and semiconductor-inspection tools (Fig. 3D). As the potential for widespread adoption of PeLEDs and PeCCLs grows over the next 20–30 years, the long-term environmental accumulation and human exposure must be considered, and regulations for the safe and sustainable implementation of perovskite light emitters must be established.[29,32,52]

Roadmaps for sustainable perovskites

Fig. 4A shows that full width at half maximum (FWHM), PLQY, luminance, EQE, and T_{50} exhibit a clear trade-off along the compositional gradient from Pb-based to Pb-free systems. In fact, every display-relevant parameter deteriorates as the lead content is lowered. Notably, the FWHMs of Pb-based systems are clustered around 20 nm, indicative of high colour purity, whereas those of Pb-free systems range from several tens to over one hundred nanometres. In addition, most research studies of Pb-free perovskites have focused on red and NIR emissions in Pb-free systems. There is, therefore, a pressing need for further work aimed at narrowing the FWHM and achieving precise colour tuning in Pb-free perovskites. Pb-free systems also require substantial advances in performance, stability and reproducibility.

To achieve high EQEs in Pb-free and low-Pb perovskite devices—such as Sn perovskites—several critical challenges must be addressed.[16,53,54] First, Sn-based perovskites inherently suffer from deep-level, nonradiative defects (*e.g.*, vacancies and interstitials). These can be mitigated by coordinating unsaturated Sn centres with Lewis base molecules (*e.g.*, thiocyanates, thiols, and carbazole derivatives) and by applying halide-rich or antioxidant post-treatments to suppress trap-assisted recombination.[16] Second, poor energy alignment and non-ideal interfaces hinder charge injection and extraction. This can be improved by optimising charge transport layers (*e.g.*, NiO_x and SnO_2) for better energy level alignment and by introducing interfacial dipole layers (*e.g.*, PEAI and polymer additives) to reduce exciton quenching.[53] Third, low-dimensional and core–shell structures can confine carriers, enhance radiative recombination, and suppress ion migration. Developing quasi-2D Sn-based perovskites using bulky organic cations (*e.g.*, PEA^+ and BA^+), as well as core–shell or quantum well architectures, can significantly improve performance.[54] Finally, other Pb-free candidates typically suffer from low PLQYs and indirect bandgaps. Strategies such as ligand-assisted structural reorganisation,

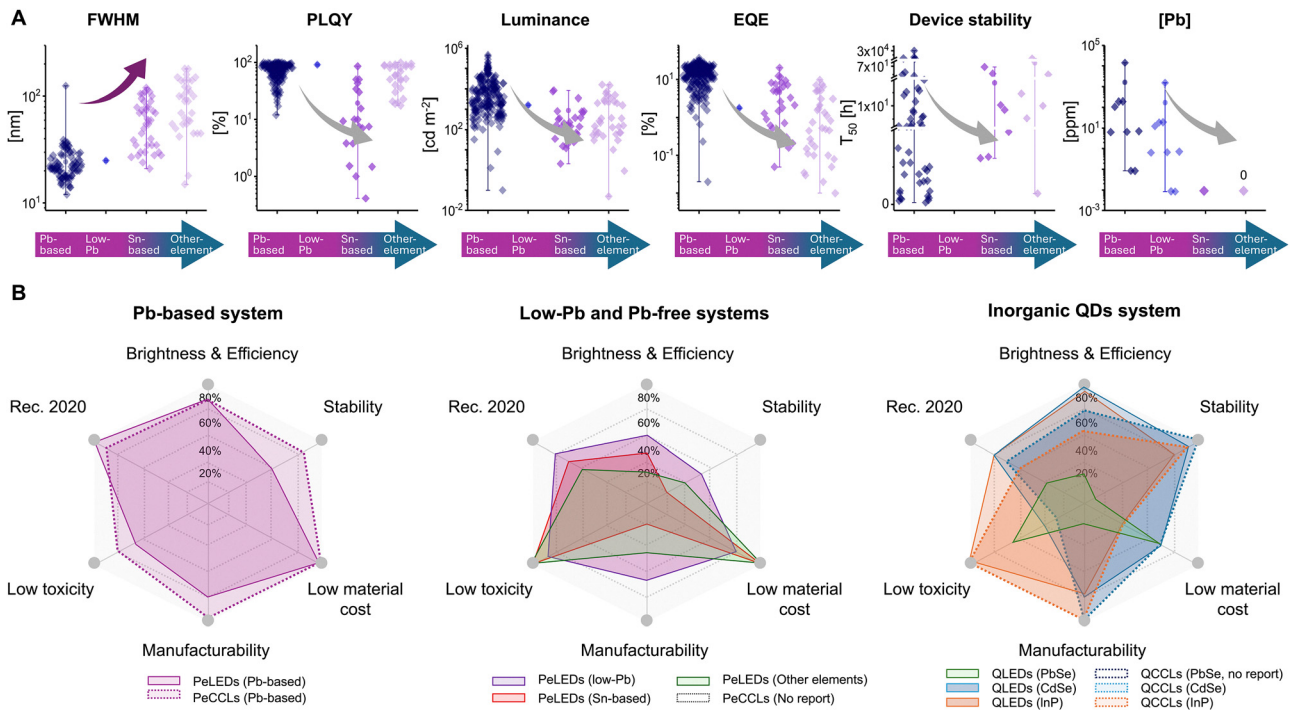

Fig. 4 (A) Trend of performance (FWHM, PLQY, luminance, and EQE), device stability (T_{50}) and Pb content from Pb-based, low-Pb and Pb-free systems (datas from 2020 to 2025) (the range lines represent the maximum and minimum values, and the circles indicate the average values). Detailed information is shown in Tables S1–S13 (SI). (B) Multicriteria evaluation of the technology readiness level (TRL) for Pb-based, low-Pb and Pb-free (Sn-based and other element) perovskite emitters, and II–VI (CdSe QDs), IV–VI (PbSe QDs), and III–V (InP QDs) QD materials: (1) brightness and efficiency; (2) stability (lifetime); (3) low material cost; (4) manufacturability – reflecting device area, fabrication method (spin-coating, blade coating, printing, and evaporation), flexible; (5) low toxicity – assessed by [XX]/$RoHS_{XX}$ (XX = Pb or Cd), reuse or recycle, and regulatory compliant; (6) Rec. 2020 – assessed by wavelength, FWHM and colour coverage. Detailed information is shown in Tables S14–S16 (SI).

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enhancement of self-trapped excitons, and dopant-induced radiative pathways are being explored to overcome these limitations.[55] And from the comparison, incorporating other additional metal elements into Sn-based perovskites may improve the device performance; however, this hypothesis requires further experimental validation.

For stability and reproducibility, for example, $MASnI_3$ is highly susceptible to Sn^{2+} oxidation under ambient conditions, resulting in increased p-type self-doping and rapid degradation. This can be mitigated by incorporating reducing additives (*e.g.*, SnF_2 and hydrazine derivatives) to stabilise Sn^{2+} during film formation and employing encapsulation strategies such as hydrophobic polymers (*e.g.*, PTAA and PMMA) or atomic layer deposition-grown oxide barriers (*e.g.*, Al_2O_3) to prevent environmental exposure.[21,53–55] While Bi^{3+}- and Sb^{3+}-based systems offer greater intrinsic stability, they generally exhibit indirect bandgaps and low dimensionality, restricting efficient charge transport. Dimensional engineering, such as halide bridging and organic spacer optimisation, as well as B-site alloying in double perovskites (*e.g.*, $Cs_2AgBiBr_6$), enable the increase of structural connectivity, thus narrowing the bandgap and enhancing carrier mobility.[17] Moreover, batch-to-batch variability is often caused by precursor oxidation during storage and deposition. To decouple crystallisation from redox reactions, inert atmosphere processing (*e.g.*, glovebox synthesis and N_2 annealing) with oxygen monitoring, and deposition techniques such as vacuum co-evaporation or two-step deposition can be implemented, improving film uniformity. Also, standardising solvent systems, precursor compositions and synthesis temperature can further reduce variations in crystallisation kinetics and improve reproducibility.[56]

For Pb-based perovskite devices, although the actual environmental and health effects of Pb toxicity are negligible during fabrication and use, there is still concern over the toxicity of Pb due to historical fear along with humanity. To eliminate the conceptual concern about the presence of Pb, the development of internal encapsulation techniques such as passivating the perovskite layer with polymerised ligands or external encapsulation methods for the LED or its panel should be prioritised to prevent Pb leakage. During and after the usage, Pb leakage could be a major problem for Pb-based PeLEDs and PeCCLs. For end-of-life devices, landfill disposal could lead to 70% of Pb leaching into soil and water within the first year.[30] To avoid this problem, Pb leakage prevention strategies are critical, which can be divided into physical encapsulation and chemical absorption. Physical encapsulation entails stacking a glass/polymer resin on the perovskite to separate it from the environment. Chemical absorption means the use of Pb-absorbing materials to interact with Pb^{2+}.[57] Both methods can effectively hinder Pb leakage into the environment. Pb can be recycled in two ways: one is to separate and extract waste Pb to return the Pb-containing raw materials into the Pb-trading market; the other is to remove the electrode and transport layers to recycle PbI_2 from pristine PeLEDs and regenerate new devices *in situ*; this approach is more environmentally benign than the recycling approach.[28]

Conclusions and outlook

This review has presented a comparative analysis of Pb-based, low-Pb and Pb-free PeLEDs and PeCCLs from the perspectives of both device performance and sustainability, with the goals of informing materials selection and design strategies for next-generation sustainable perovskite light emitters.

In PeLEDs and CCLs, the actual environmental and health effects of Pb toxicity are relatively negligible during fabrication and use. The amount of Pb itself is minimal because the perovskite layer in a LED is sufficiently thin and has high carrier mobility along with efficient light absorption and emission. Therefore, attention should move beyond the controversial toxicity question and focus on reducing environmental and health impacts throughout the device lifecycle, by drawing lessons from the commercialisation of OLEDs.

We develop a multicriteria radar diagram framework across five critical dimensions: device performance, device stability, material cost, manufacturability, and low toxicity to enable a comprehensive assessment of the technological maturity and scalability (technology readiness level, TRL) for Pb-based, low-Pb, and Pb-free perovskites (Fig. 4B and Table S14, SI). We also evaluate inorganic QD systems from II–VI QD (CdSe and PbSe) and III–V QD (InP) families, recognised as some of the candidates for next generation display emitters. Each emissive material system exhibits distinct strengths and inherent limitations.

While Pb-based perovskites exhibit superior optoelectronic performance, their commercialisation is still restricted by concerns over operational stability, primarily arising from ion migration, phase instability, and environmental sensitivity. Strategies such as compositional engineering, interface passivation, and advanced encapsulation have shown promise in mitigating these issues. However, these stability challenges are further compounded by the complexities of material compositions and manufacturing processes, particularly when considering requirements for material reuse and recyclability alongside compliance with environmental regulations. Based on this, the technology readiness level of these materials remains in the early stages, constraining their practical transition from laboratory research to industrial-scale implementation.

Conversely, Pb-free perovskites align more closely with sustainability objectives due to their low toxicity. Nevertheless, insufficient EQE and instability can increase energy consumption during device operation, offsetting some of the environmental gains achieved by reducing Pb content. Therefore, these materials still require substantial advancements in device performance, stability and manufacturability, which reflects their current status at the laboratory research stage. These contrasting profiles highlight the need for application-specific materials selection, especially in certain niche application scenarios—such as wearable devices, implantable displays, or other direct-contact uses.

For low-Pb systems, due to the limited number of LED-specific studies, we extended our analysis to include reports on perovskite films and solar cells (Tables S15 and S16, SI) to infer

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general performance trends. When the Pb content exceeds approximately 50–60%, device performance can approach that of typical Pb-based perovskites. In contrast, when the Pb fraction falls below ∼10%, the material characteristics become more close to those of Sn-based perovskites—exhibiting reduced toxicity (even below certain Pb levels in the human body) but suffering from markedly lower performance and stability. Guided by this trend, we tentatively define low-Pb systems as those containing roughly 30–50% Pb, representing a compositional window that may offer a balanced trade-off between high performance and reduced toxicity, and thus merits prioritisation for further investigation.

Inorganic QDs such as CdSe and InP have been commercialised in CCL applications, offering excellent stability, mature manufacturing, and competitive performance. However, CdSe faces high toxicity concerns, while InP—though less toxic—has lower performance and narrower Rec.2020 coverage; PbSe combines the drawbacks of both toxicity and poor performance. Moreover, all these systems incur higher material costs than perovskites due to complex synthesis and purification processes. These trade-offs mean that inorganic QDs remain attractive for applications that demand long operational lifetimes and proven reliability, but their environmental and cost limitations reduce their competitiveness in high-colour-gamut, cost-sensitive markets where improved perovskite emitters could offer a more sustainable alternative.

By integrating these considerations—specifically the overlapping region in Fig. 4B—we quantify the practical feasibility of moving from academic research to commercial applications. However, realising the full translational potential of individual material systems remains a formidable challenge. Coordinated efforts in compositional engineering, process optimisation, and regulatory policy development will therefore be essential for advancing the next generation of sustainable emissive materials towards large-scale commercialisation.

Concurrently, the necessary infrastructure and technologies to bring perovskite light emitters to commercialisation must be developed. If these existing challenges can be overcome, these devices can become widely used in daily lives. Particularly, PeLEDs have potential applications in TVs and monitors, and in VR/AR displays, to offer superior immersive experience. These technologies may also have a wide range of applications in various other industries, including smart farming and lighting. An important but often-overlooked aspect of perovskite light emitter development is the need to establish appropriate regulations and policies. As device performance improves and commercialisation nears, attention must also shift toward safe material handling, waste management, and end-of-life recovery, particularly in large-scale application scenarios. Human security and needs will be the subject of future work.

Conflicts of interest

There are no conflicts to declare.

Data availability

No primary research results, software or code have been included, and no new data were generated or analysed as part of this review.

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