Materials Today 90 (2025) 495–518

Contents lists available at ScienceDirect

Materials Today

journal homepage: www.elsevier.com/locate/mattod

Advances in perovskite indoor photovoltaics for intelligent Internet of Things

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ARTICLE INFO

Keywords:
Perovskite
Indoor photovoltaics
Energy harvesting
Intelligent Internet of Things

ABSTRACT

Currently, perovskite indoor photovoltaics (PIPVs) exhibit a power conversion efficiency exceeding 40% under artificial illumination, outperforming conventional silicon-based counterparts. Given this capability, this review emphasizes the transformative role of PIPVs in the intelligent Internet of Things (IIoT), particularly their integration of energy harvesting, light sensing, and optical communication, which underpin ubiquitous intelligence. We further examine PIPVs' capability to drive distributed IIoT nodes, encompassing wearable electronics, environmental sensors, and visible light communication terminals. Although challenges remain regarding stability, lead toxicity, and scalable manufacturing, emerging approaches like lead-free materials and machine learning-driven optimization show significant promise. Integrated with energy storage and edge computing, these innovations could provide the last-mile solution for PIPV commercialization. As costs decline and policy support grows, PIPVs may redefine sustainable energy solutions for IIoT applications. Future research should focus on standardized testing, large-scale production, and practical deployment to fully realize their potential in smart cities, healthcare, and industrial automation.

Introduction

Through the integration of physical devices, sensors, intelligent control systems, and network connectivity, the evolution towards the Intelligent Internet of Things (IIoT) signifies the seamless unification of once-isolated functionalities into a dynamic, interconnected ecosystem [1]. This transformation elevates standalone devices into adaptive, collaborative components, enabling real-time data acquisition, intelligent processing, and enhanced automation. By unlocking unprecedented levels of insight and operational efficiency, IIoT redefines technological possibilities across diverse domains, from personal applications to complex industrial systems. With the rapid evolution of intelligence and ubiquitous connectivity, IIoT applications have proliferated, especially in smart homes and smart cities, where they reveal immense potential [2–4]. Leveraging deep connectivity and efficient data exchange, IIoT enhances the convenience and personalization of home environments, refines healthcare services to better meet individual needs, and optimizes resource allocation and management efficiency in urban governance [5–7].

As of 2024, the global IoT network had encompassed over 18 billion connected devices, and this figure is projected to surge to 25.4 billion by 2030 [8], with this number projected to surge to 25.4 billion by 2030 [9]. Such rapid expansion marks a transformative shift toward deeply integrated digital ecosystems while also raising concerns about the energy pressures stemming from the sustained increase in sensor nodes [10]. Battery power is critical in the IIoT realm, especially for remote or hard-to-reach devices, providing durable and portable energy support as the primary power source for autonomous terminals. Nevertheless, the limited capacity and lifespan of batteries, coupled with the growing number of devices, result in frequent replacement and maintenance demands [11]. Replacement costs are on the rise, and the environmental disposal of used batteries presents additional challenges. In response to these challenges, an expanding body of research is pioneering advancements in energy harvesting (EH) technologies. By capturing ambient energy sources—such as solar [12], thermal [13], vibrational [14], and electromagnetic energy [15], and even unconventional sources like wind [16] and sweat [17], pervasive IoT devices can move toward partial energy autonomy. However, these EH techniques generally struggle to meet the growing cost and power supply demands of IIoT technologies, particularly under low or dynamic light conditions.

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https://doi.org/10.1016/j.mattod.2025.08.028
Received 1 June 2025; Received in revised form 8 August 2025; Accepted 24 August 2025
Available online 4 September 2025
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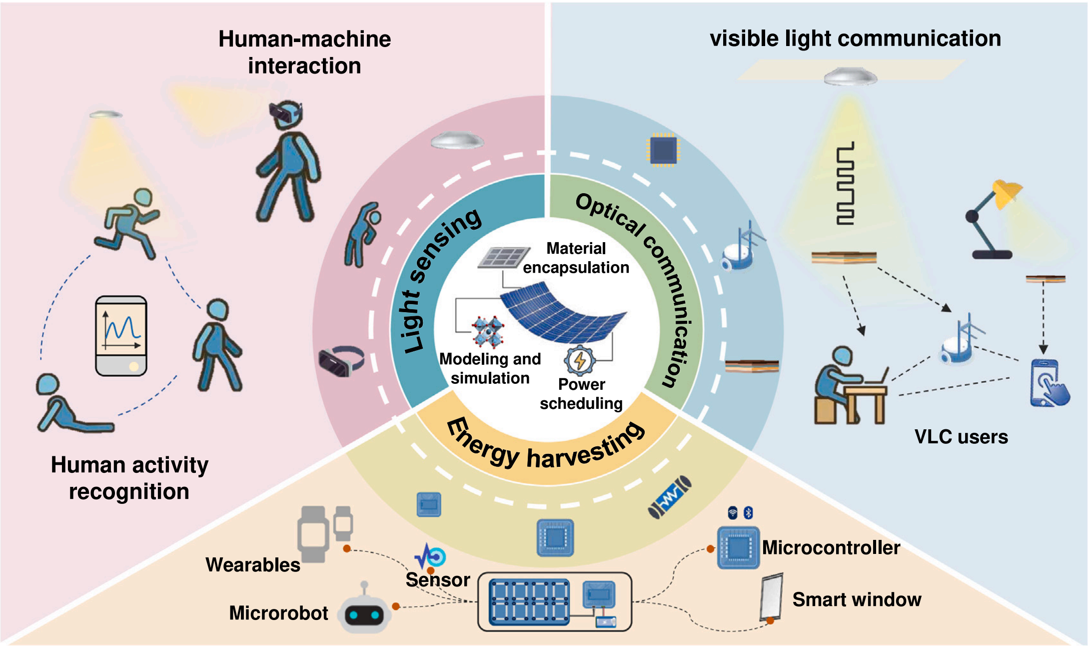

Fig. 1. Advancing the IIoT ecosystem through PIPVs.

In this context, indoor photovoltaics (IPVs) efficiently convert light energy into electricity by harnessing lighting devices in the indoor environment, potentially eliminating the dependence of IIoT on batteries [18–21]. Current research on CuInGaSe (CIGS)-based solar cells, dye-sensitized solar cells (DSSCs), organic solar cells (OSCs) and other emerging thin-film PV technologies has been progressively explored for IPV applications [22–24]. It is noteworthy that solar radiation and indoor light sources exhibit substantially different spectral distributions [25,26]. This spectral disparity necessitates tailored absorber bandgaps and device architectures to optimize photovoltaic performance under indoor illumination.

Perovskite materials offer advantages such as a tunable bandgap, efficient carrier transport, and low manufacturing costs [27–29]. These properties make perovskite-based indoor photovoltaics (PIPVs) a compelling candidate for IIoT systems operating under weak illumination (Fig. 1). With their thin and lightweight design, PIPV components can be seamlessly integrated into smart terminals such as sensors and wearables [30,31]. This compact integration significantly reduces maintenance requirements while extending IIoT system longevity. The technology further demonstrates adaptive EH capabilities, dynamically optimizing efficiency across varying indoor lighting conditions [32]. Furthermore, their exceptional optoelectronic properties position PIPV components as promising enablers for seamless integration with low-power processors and communication modules [33] (Fig. 2a). This inherent compatibility confers a strategic advantage for advancing 6G-enabled infrastructure and integrated sensing and communication (ISAC) systems, positioning them as pivotal enablers for next-generation smart networks.

In this review, the integration of PIPV technology with the IIoT is critically examined (Table 1). The review begins by elucidating the principles of PV energy conversion and its significance in powering IoT devices, with particular emphasis on the distinct advantages of perovskite materials. Subsequently, we systematically examine the progress in perovskite-based systems for indoor low-light energy conversion and their integration with wireless sensing-communication functionalities. Lastly, the review highlights key challenges, including concerns regarding device stability and environmental sensitivity, while providing an overview of emerging strategies aimed at optimizing performance and ensuring the sustainable, self-sufficient operation of IIoT systems.

Coupling foundations of PIPVs and IIoT

Research history of perovskite in the IPV field

The essence of the PV effect is that semiconductor materials absorb photon energy to separate and collect photogenerated carriers (electron–hole pairs), thereby directly converting it into electrical energy. When the incident photon energy ($E = h\nu$) is greater than the band gap (E_g) of the semiconductor material, the photon is absorbed and the valence band electrons are excited to the conduction band, forming electron–hole pairs. Under the drive of the built-in electric field within the material (such as in p–n junctions, heterojunctions, or the energy level gradient in perovskites), the photogenerated carriers separate, with electrons migrating towards the cathode (such as TiO_2 or SnO_2) and holes moving towards the anode (such as Spiro-OMeTAD or NiO_x), generating photocurrent. Since the performance of photovoltaic devices is highly spectrum-dependent, their spectral response must be matched to the illumination source. Standard solar AM 1.5G covers a broad emission spectrum (300–1200 nm), while indoor light sources such as fluorescent lamps (FL) and light-emitting diodes (LED) typically emit primarily in the 400–700 nm range (Fig. 2b). Consequently, IPV technology demands efficient light-absorbing materials with optimized bandgaps to guarantee that its Shockley-Queisser (SQ) limited power conversion efficiency (PCE) substantially exceeds the theoretical maximum achievable under standard solar spectrum [36] (Fig. 2c).

The chemical formula of metal halide perovskites is ABX_3 (A=monovalent cation, such as Cs^+, $[CH_3NH_3]^+$ (MA^+), $[CN(NH_2)_2]^+$ (FA^+); B = bivalent cations, such as Pb^{2+}, Sn^{2+}; X^- = halogen anion, such as I^-, Br^-, Cl^-) [37] (Fig. 2d). The high light absorption coefficient and low exciton binding energy of perovskite materials make them suitable for low-light scenes [38] (Fig. 2e), and maintain a high open-circuit voltage (V_{OC}) under low light intensity (200–1000 Lux, typical indoor environment), and IPV efficiency can reach 30%–45%, far more than amorphous silicon (a-Si) and OPVs. And the wide spectrum adjustable band gap of perovskite better matches the spectral range of indoor light sources [39] (Fig. 2f). Table 2 summarizes representative perovskite material systems employed in indoor photovoltaics over the past decade, underscoring the diversity in material composition and structural design.

Table 1
Comparative perspective analysis of this review with existing literature in the field of PIPV.

Comparison criteria	Existing reviews	Current review
Primary focus	Primarily investigates perovskite-based power supply applications for devices [19]	Perovskite's promise in integrated EH, light sensing, and optical communication
Scope of technology	Primarily focused on improving EH efficiency [21]	Integration from EH to ambient sensing
Indoor applications	Optimize the applicable parameters of perovskite in IPVs [34]	Discussion on the integration of PIPV into intelligent systems
Challenges Addressed	Focuses on PV stability, efficiency, and environmental adaptability [33]	Device stability, environmental adaptability, optimization for intelligent system integration
Emerging Strategies	Focuses on material optimization strategies for improving PV efficiency [35]	Proposes new strategies for optimizing PIPV performance in intelligent, self-sustaining systems

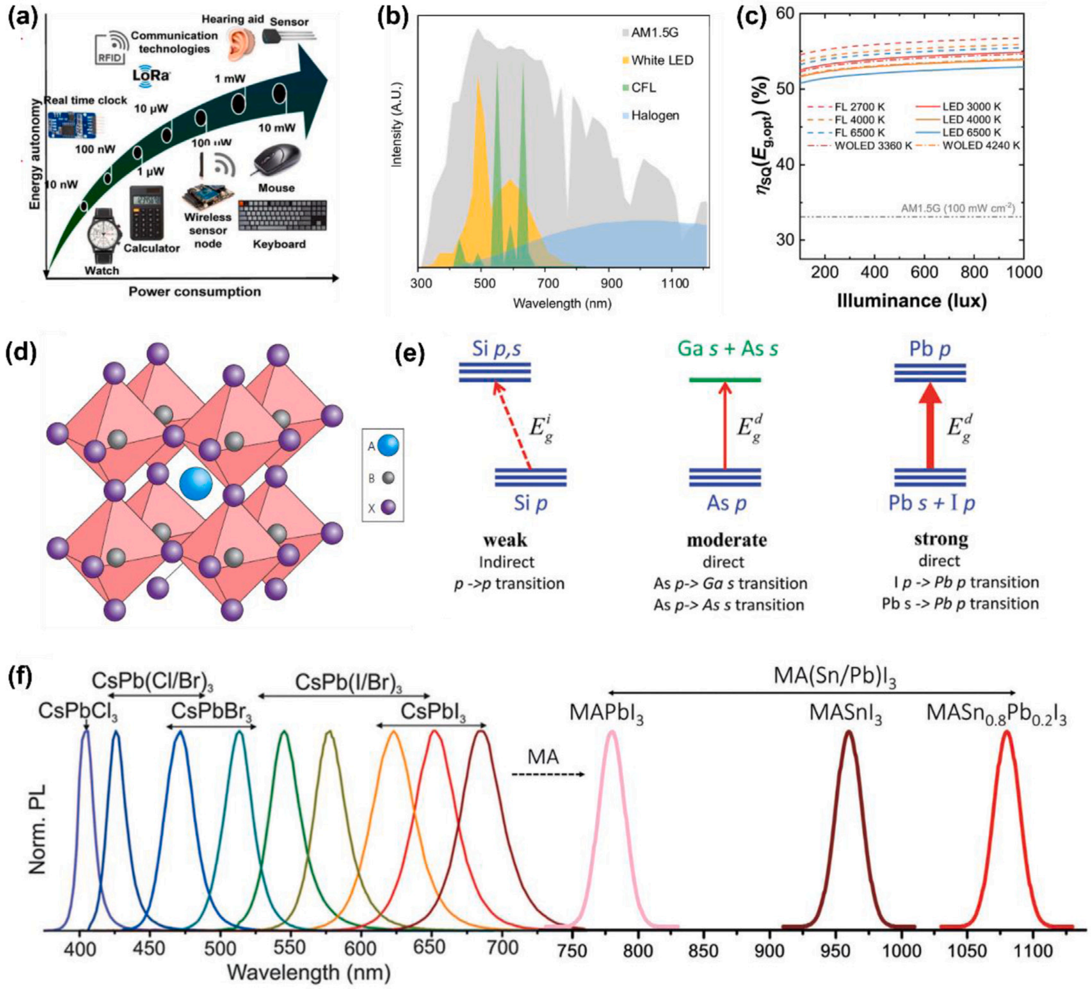

Fig. 2. Spectral matching of perovskite solar cells under indoor lighting. (a) Power requirements of low consumption electronics targeted by indoor PV harvesters. Reproduced with permission from Ref. [33]. © 2024 Elsevier Ltd (b) The standard solar spectrum (AM1.5G) and typical spectra from White LED, CFL, and Halogen sources. Reproduced with permission from Ref. [18] © 2019 Elsevier Ltd (c) The Shockley–Queisser limited PCE at the optimal bandgap energy for various cold light sources at different color temperatures vs. illuminance. Reproduced with permission from Ref [36]. Copyright (2020) by Royal Society of Chemistry. (d) Perovskite crystal structure. Reproduced with permission from Ref. [37] © 2014 Springer Nature (e) Optical absorption schematic of different solar cell absorbers. Reproduced with permission from Ref [38]. Copyright (2015) by Royal Society of Chemistry. (f) Representative photoluminescence spectra of perovskites with different bandgaps. Reproduced with permission from Ref. [39] © 2018 Wiley-VCH.

In 2009, Kojima's group first used methylammonium lead iodide ($MAPbI_3$) as a sensitizer in dye-sensitized solar cells, achieving an efficiency of 3.8% [51]. At this time, the studies focused on the synthesis and light absorption properties of the material, but the high absorption coefficient (>10^4/cm) and wide spectral response (300–800 nm) have been noted. In 2012, Kim et al. used a small molecule (spiro-OMeTAD) as a hole transport material to prepare all-solid perovskite solar cells (PSCs) for the first time and obtained 9.7% PCE [52]. In 2013, Snaith's

Table 2
Representative materials and device architectures for PIPVs.

Absorber	Light Intensity (Lux)	Configuration	V_{OC} (V)	J_{SC} (μA/cm^2)	FF (%)	PCE (%)	Year	Ref.
$MAPbI_{3-x}Cl_x$	1000	p-i-n	0.85	132.4	77.0	27.40	2015	[40]
$MAPbI_{3-x}Cl_x$	400	n-i-p	0.66	33.7	77.3	12.10	2017	[41]
$MAPbI_3$	1000	p-i-n	0.87	150.1	75.2	35.20	2018	[42]
$FA_{0.75}MA_{0.25}SnI_2Br$	1000	p-i-n	0.28	280.0	67.0	12.81	2021	[43]
$Cs_{0.17}FA_{0.83}Pb(I_{0.7}Br_{0.3})_3$	1000	n-i-p	0.93	159.0	82.5	30.90	2022	[44]
$Cs_{0.05}MA_{0.05}FA_{0.90}PbI_{2.85}Br_{0.15}$	1000	n-i-p	1.06	155.0	81.5	41.23	2022	[45]
Cs_2AgBi_2I	1000	n-i-p	0.643	54.0	72.2	7.60	2024	[46]
$FA_{0.92}Cs_{0.04}MA_{0.04}PbI_3$	1000	n-i-p	0.979	139.7	84.32	41.33	2024	[47]
$Cs_{0.18}FA_{0.82}Pb(I_{0.8}Br_{0.2})_3$	1000	p-i-n	1.07	301.0	79.0	42.05	2024	[48]
$Cs_{0.05}FA_{0.70}MA_{0.25}PbI_{2.25}Br_{0.75}$	1000	p-i-n	1.07	172.0	82.3	44.72	2024	[24]
$Cs_{0.1}FA_{0.85}MA_{0.05}PbI_{2.88}Br_{0.12}$	1000	n-i-p	1.02	158.5	80.7	42.10	2025	[49]
$Cs_{0.4}DMA_{0.2}FA_{0.2}MA_{0.2}PbI_3$	1000	p-i-n	0.99	137.8	84.28	41.05	2025	[50]

group proposed a planar heterojunction structure (no mesoporous TiO_2 required) with an efficiency of more than 15%, verifying the potential of perovskite as an independent light-absorbing layer [53]. At this time, studies in the field of perovskite have not paid attention to low-light properties, but the low excitation binding energy (<50 meV) and long carrier lifetime (>100 ns) of perovskite lay the foundation for subsequent studies on low-light response.

After 2015, as the outdoor efficiency of perovskite approached 20%, researchers began to focus on its performance under non-standard lighting conditions. In 2015, Chen et al. first demonstrated that defect engineering in the absorption layer enables highly efficient indoor PSCs, achieving a PCE of 27.4% under 1000 Lux illumination [40]. In 2017, researchers reported the first flexible indoor perovskite solar cells (PSCs) fabricated on a polyethylene terephthalate/indium tin oxide (PET/ITO) substrate [41]. These perovskite cells achieved PCEs of 10.8% at 200 lux and 12.1% at 400 lux under low-light conditions. In 2018, Li et al. used the ionic liquid of 1-butyl-3-methylimidazole tetrafluoroborate ($[BMIM]BF_4$) as the modified layer of [6,6]-phenyl-C61-methyl butyrate (PCBM) in inverted perovskite solar cells to promote electron transport and extraction, and obtain 35.2% PCE (at 1000 Lux) [42]. In 2022, Teixeira et al. compared three flexible PSCs structures for IPV [44]. At 1000 Lux (200 Lux), the maximum efficiency of PSCs with gold electrodes was 30.9% (30.0%), and that of PSCs with HTM and carbon electrodes without HTM was 25.4% (24.7%) and 23.1% (22.3%), respectively. The HTM-free carbon electrode PSCs maintained an initial efficiency of 84% after 1000 h, with almost no performance loss after 1000 h at 85°C. In 2024, Liu et al. passivated interface defects by introducing additives, improved charge transfer and extraction efficiency, and obtained a flexible indoor solar cell with a PCE of 41.33% and FF of 84.32% at 1000 Lux [47]. At the same time, Shi et al. modified NiOx films with different self-assembled monomolecular layer materials (SAMs) to improve interface defects, and obtained more than 42% PCE (at 1000 Lux) on wide-bandgap PSCs ($Cs_{0.18}FA_{0.82}Pb\ (I_{0.8}Br_{0.2})_3$) [48]. Recently, Dong et al. enhanced the moisture resistance and bending stability of flexible perovskite photovoltaic modules by introducing a polymer network. Under an indoor light intensity of 1000 Lux, the flexible PSCs they prepared achieved a PCE of 42.1% (0.07 cm^2) and 40.1% (23.25 cm^2) [49]. Fang et al. doped PCBM with ethylenediamine iodide ($PDAI_2$) to construct a "defect passivation-electron transport" dual-optimized interface. The 1 cm^2 device they fabricated achieved a PCE of 41.05% under an indoor light intensity of 1000 Lux [50].

In summary, over the past decade, the development of perovskite materials in the field of indoor photovoltaics (IPV) has advanced rapidly—from early research focused on outdoor performance to the realization of high-efficiency indoor devices with power conversion efficiencies exceeding 40% under low-light conditions. These advancements underscore the significant potential of perovskite materials in self-sustained indoor applications, particularly for emerging autonomous electronics and smart systems.

Application potential and market development of PIPVs

The application of traditional PV technology in indoor low-light intensity and narrow spectrum environments is subject to certain limitations. There is obvious efficiency attenuation at low light intensity. For example, crystalline silicon (c-Si) has a bandgap of ~1.1 eV, which exhibits severe spectral mismatch with indoor light sources (e.g., LED/fluorescent lamps, photon energy ~1.8–2.2 eV). This results in significant thermalization losses due to excessive photon energy. C-Si provides only about 4%–10% PCE under indoor light sources of 200–1000 Lux, and has low V_{OC} and fill factor (FF) [33] (Fig. 3a-b). Although c-Si has a mature technical foundation and superior stability, its application in the IPV field is ultimately limited. Amorphous silicon (a-Si): Although the band gap is wide (~1.7–1.8 eV), there is a certain market in the IPV field, and the maximum PCE reaches 30%, but due to the optical attenuation effect and low carrier mobility (<1 cm^2/V s), the current density is insufficient in low light [33].

For other thin-film solar cells, such as DSSCs, GaAs solar cells and OSCs, they all exhibit more well-matched band gaps and better weak light response under indoor light sources compared to c-Si solar cells. However, at present, DSSCs still need to pursue new types of dyes that are lower in cost and environmentally friendly. Moreover, liquid electrolytes have problems such as volatilization, leakage and corrosion of metal electrodes, which will affect long-term stability. The PCE of DSSCs is lower compared to other new thin-film photovoltaic technologies [54,55]. III-V compound semiconductor cells represented by GaAs have an extremely high PCE, but their core bottleneck lies in the high manufacturing cost [56]. For large-scale commercial use, the compatibility issues between cost and flexible substrates still need to be addressed. Research on OSCs in the IPV field is quite in-depth, and they have achieved a PCE of over 30% under indoor light intensity [23, 57,58]. Moreover, it can be prepared by the low-temperature solution method, which makes it have great commercial potential. The development of these new thin-film photovoltaic technologies has facilitated rapid improvement of PCE and stability of PSCs. Various strategies have been developed, such as the perovskite quality and properties can be enhanced by adding additives, the non-radiative recombination loss can be reduced through interface passivation, the long-term stability can be improved by optimizing the packaging process, and large-scale industrial production can be achieved through scalable preparation processes such as slot-die coating or roll-to-roll.

The light absorption and photoelectric response of PSCs have obvious advantages. The absorption coefficient of perovskite is much higher than that of c-Si, and only needs ~300 nm thickness to absorb >90% of visible light to reduce the amount of material. By adjusting the halogen ratio (I/Br/Cl) or the A-position cation (MA/FA/Cs), the perovskite band gap can be continuously adjusted at 1.2–2.3 eV. The exciton binding energy of perovskites is low (<50 meV), and the excitons can spontaneously dissociate into free carriers under low light, which improves the charge collection efficiency. Perovskite devices can be

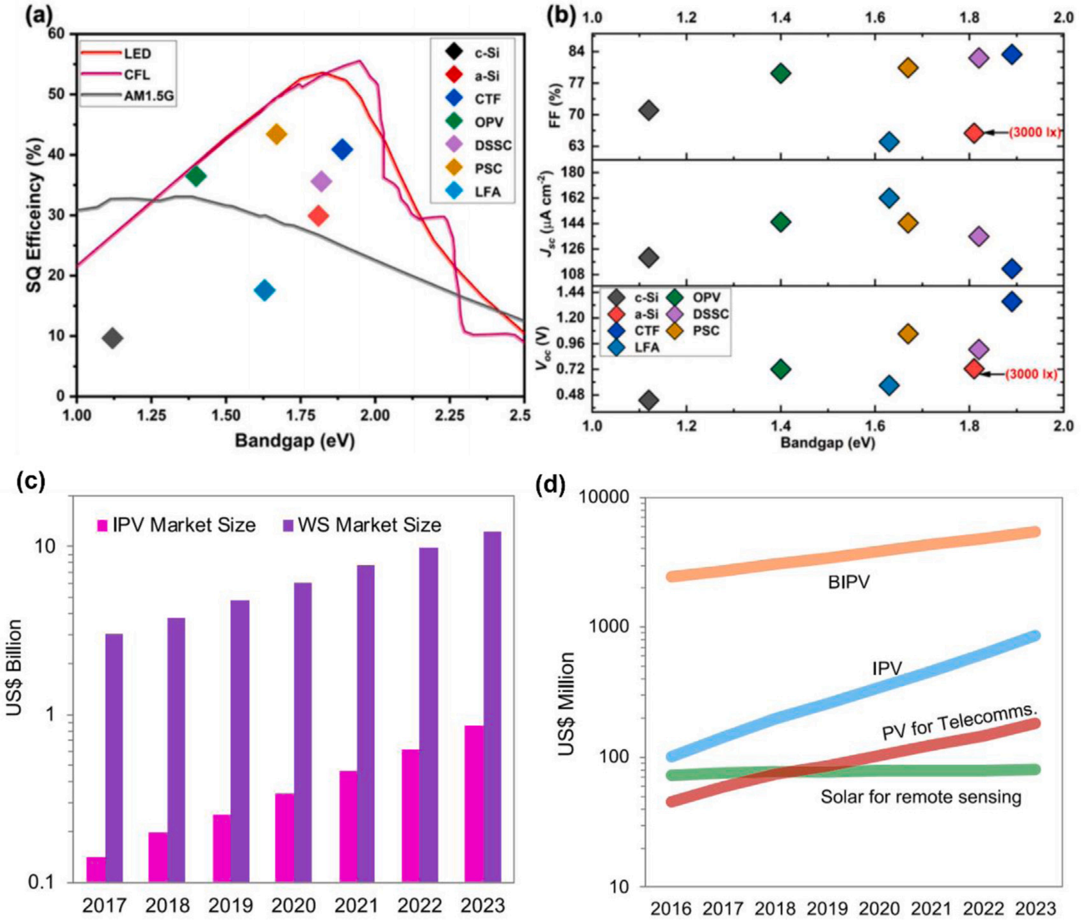

Fig. 3. Photoelectric performance of perovskite solar cells under indoor lighting. (a) Highest reported efficiencies of all IPV technologies under 1000 Lux illumination with respect to their bandgaps. Reproduced with permission from Ref. [33] © 2024 Elsevier Ltd (b) V_{OC}, short-circuit current density (J_{SC}) and FF of the highest reported efficiencies. Reproduced with permission from Ref. [33] © 2024 Elsevier Ltd (c) The projected size of the wireless sensor and IPV market in billions of dollars. Reproduced with permission from Ref. [18] © 2019 Elsevier Ltd (d) The expected sizes of alternative markets for PV technologies over the coming years. Reproduced with permission from Ref. [18] © 2019 Elsevier Ltd.

fabricated via low temperature (<150°C) solution processing on flexible substrates such as PET or PI, achieving a thickness below 1 μm and a bending radius under 5 mm, while retaining over 90% of their efficiency. Translucent perovskite components (visible light transmittance >30%) can be integrated into windows, screens and other surfaces to enable invisible EH systems. Due to the continuous development of the IoT industry, the market size of IPV will continue to grow and is the fastest growing among all non-traditional PV markets [18] (Fig. 3c-d). In recent years, the scientific community has shown increasing interest in IPV. The global IPV cell market was valued at $140 million in 2017—a marginal share compared to the $100 billion PV module industry. However, it developed rapidly and grew to a scale of one billion US dollars within a few years. Meanwhile, compared with BIPV, PV for telecomms and solar for remote sensing, the market size of IPV has grown the fastest in the non-traditional photovoltaic market. As IPV equipment plays a key role in the IIoT revolution, its cumulative output is expected to grow rapidly. It is estimated that by 2030, the market size of IIoT connected devices will reach $30 billion, among which the market size of wireless sensors will reach $8 billion [33]. Powering these Internet of Things devices with batteries will eventually become a huge market. At this point, IPV technology will play a key role in this field by providing efficient and sustainable solutions. And the development of perovskite photovoltaics will provide a stronger impetus for it.

The prerequisites for long-term compatibility between PIPV and IIoT devices

IIoT devices powered by IPVs must be engineered for ultra-low power consumption to facilitate sustained operation under constrained light conditions. This necessitates that the device's power consumption be minimized to the milliwatt or even microwatt scale [59,60]. The device's utilization of ultra-low-power processors, sensors, and communication modules contributes to a notable decrease in energy consumption, thereby extending the lifespan of the perovskite cells and elevating the overall user experience. Through the implementation of advanced modulation, optimized power settings, and extended sleep states, low-power protocols like Bluetooth Low Energy (BLE) and Long Range (LoRa) have substantially reduced energy consumption during data transmission, enabling longer operational lifetimes for devices powered by IPV systems. In energy-autonomous wireless sensor networking, the STM32L microcontroller, responsible for control and power management, consumes approximately 3.6 mW in run mode, while the BLUENRG-2 system-on-chip (SoC), used for low-power Bluetooth communication, consumes around 18.5 mW during non-connectable undirected events [61]. The system's total energy consumption in the transmission phase is about 50 μJ, and it can drive a minimum illuminance of 200 Lux. In a particular study, perovskite materials were utilized in a mechanical energy converter, offering an innovative solution for remote and autonomous IIoT applications powered by LoRa technology [62]. Unlike traditional Wi-Fi communication, where devices actively generate and transmit signals, in a

Wi-Fi backscatter system, devices leverage existing Wi-Fi signals (from routers or access points), modulating and reflecting them to convey information [11,63]. The signal modulation and protocol management require only a minimal amount of power, with the wake-up receiver and backscatter uplink power consumption controlled at an extremely low level of 30 μW [64]. Thus, the integration of PIPVs with backscatter communication establishes a technical framework for achieving energy-autonomous IIoT operation, addressing both power generation and ultra-low-power transmission requirements.

Impedance matching is paramount in power systems to ensure optimal energy transfer [65]. For PIPV-based energy supply systems, proper impedance matching is crucial to maximize the efficient delivery of harvested energy to devices and minimize energy dissipation. Recent advancements in semitransparent perovskite solar cells have utilized impedance matching to improve the efficiency of transmissive colors [66]. By incorporating a dielectric functional layer over traditional optical microcavities, researchers have achieved enhanced device performance. This approach enhances light transmission and EH while maintaining color purity, enabling efficient operation across a broad range of incident angles and preserving the visual quality of the transmitted colors. Gao et al. [67] pioneered a novel approach to enhance electromagnetic attenuation, utilizing CoFe/$LaFeO_3$ and CoFe/$LaFeO_3$/La_2O_3 perovskite composites. Through strategic structural engineering, dielectric and magnetic property optimization, and impedance matching, they achieved impressive absorption bandwidths of 4.88 GHz and 3.36 GHz. Yadav et al. [68] demonstrated an integrated perovskite solar-supercapacitor system achieving 87% storage efficiency (0.8 V overpotential) through optimized series-connection and illumination control. The device maintained stable performance over 200 cycles, highlighting impedance matching as a key design principle for photorechargeable energy storage.

On the other hand, perovskite devices, when employed as sensing elements, present an efficient solution that can partially or even completely eliminate the energy consumption of the sensing layer, thereby significantly improving overall energy efficiency [69]. The specific technical details will be further elaborated in the subsequent sections.

Progress of PIPVs in IIoT applications

Perovskite-based energy harvesting

Leveraging the unique properties of perovskite materials, various perovskite-based devices have demonstrated significant potential in constructing indoor wireless self-powered IIoT nodes. With a highly sensitive perovskite absorption layer as the core component, n-i-p and p-i-n type perovskite cells can be fabricated by adjusting the positions of the electron transport layer (ETL) and hole transport layer (HTL) on both sides [70]. Through ongoing technological advancements and extensive research, certain single-junction solar cells have achieved V_{OC} approaching or even surpassing 1.2 eV [71–73] (Fig. 4a). For IIoT applications, however, further power output optimization is critically required to meet demanding performance benchmarks.

Expanding the area can produce more photogenerated carriers, yet it encounters limitations due to increased recombination losses from longer carrier transport distances. In contrast, modular designs employing series-parallel and stacked configurations effectively address diverse application requirements [35]. Due to their superior spectral matching with indoor illumination, wide-bandgap perovskites are highly suitable as sub-cells in these PV modules. For example, an indoor EH module, utilizing series-connected 1.8 eV bandgap perovskite PV cells, achieves self-powered backscattering and high-frequency data acquisition at 14.5 μW output power [74] (Fig. 4b). Furthermore, wide-bandgap perovskite cells, optimized with bromide-enriched bulk and surface passivation, attain a remarkable PCE of 41.58% under 1000 Lux LED illumination [75] (Fig. 4c). Even at 400 Lux, the perovskite module demonstrably sustains adequate power output to actuate onboard sensors and BLE chips, facilitating environmental sensing and data dissemination. A commercial Gen-2 RFID IC interfaces with a perovskite PV module (4-series cells, 10.1% PCE) to establish a self-powered wireless sensing platform [76] (Fig. 4d). Through backscatter modulation, the system achieves energy-positive operation with an energy gain ratio (operation time/charging time) exceeding 4.

Recent advancements have further expanded the potential of perovskite materials in the integration of EH and wireless power transfer (WPT) [77]. Dispensing with intricate circuitry, energy can be wirelessly transmitted between perovskite devices via an optical transceiver. During this process, one perovskite unit discharges photons in the light emission mode, while another absorbs photons in the light absorption mode, thereby erecting a perovskite-based thing-to-thing optical WPT system [78]. In a single-input single-output (SISO) WPT system, perovskite nanocrystals (PNCs) function as the core for energy conversion and light emission [79]. Upon absorbing ultraviolet (UV) light, they undergo internal energy transitions, emitting visible green light to achieve remote illumination. However, the inherent energy-communication trade-off in WPT nodes fundamentally limits system stability [80]. This challenge is addressed through dynamic toggling between photoconductive and PV modes, enabling adaptive EH without compromising operational robustness [81].

The lightweight and flexible characteristics of perovskite devices ensure their seamless integration with other hardware components [82,83]. These properties enable a breakthrough self-powered wearable biosensor that simultaneously achieves 29.64% PCE under 600 Lux illumination and continuous metabolic monitoring, advancing personalized healthcare diagnostics [84] (Fig. 4e). Additionally, perovskite nanowires embedded in a flexible matrix exhibit strain-adaptive piezoelectricity [85]. Synergizing these with perovskite's triboelectric-photosensitive dual functionality enables wearables with enhanced environmental and biomechanical responsiveness [86,87](Fig. 4f-g). Nevertheless, flexible perovskite PV cells typically exhibit lower efficiency than their rigid-substrate counterparts, and the durability of perovskite-based nodes degrades significantly after repeated bending cycles. Optimizing the electrode materials and ensuring material compatibility can significantly improve the energy level alignment and interfacial contact between the perovskite film, electrodes, and transport layers, thereby mitigating these issues to a considerable extent [88]. Furthermore, by precisely optimizing substrate thickness and identifying the fracture point, crack-free, high-efficiency ultra-flexible perovskite PV devices with a PCE of 17.03% can be fabricated, representing a significant leap in both performance and mechanical resilience [89] (Fig. 4h).

Beyond EH for IoT nodes, perovskite materials also demonstrate remarkable capabilities in self-powered sensing applications. In the perovskite-based self-powered sensing platform, photoconversion generates electrical signals, which are modulated by the target substance interacting with the perovskite active layer, altering its electronic structure and charge distribution [90]. This mechanism seamlessly integrates PV and sensing functions, revealing exceptional potential for near-zero power consumption and highly efficient operation at ambient temperature. Gas sensors play a crucial role in IIoT systems by providing real-time monitoring and intelligent solutions. Nitrogen oxides (NO_x) are indoor air pollutants significant for disease diagnosis in trace amounts. However, commonly used metal oxide semiconductors (MOSs) have limited sensitivity and require high operating temperatures for detection [91]. One strategy involves integrating p-type hybrid halide perovskite with n-type MOS thin film, where the V_{OC} under illumination acts as an output signal that sensitively reflects changes in NO_2 concentration [92] (Fig. 5a). A gas sensor based on triple-cation perovskite operates self-sufficiently under light exposure [93]. It responds to NO_2 concentrations as low as 0.2 ppm within approximately 17 s, while showing negligible sensitivity to other gases, thus overcoming typical cross-sensitivity challenges. The self-powered gas sensor based on two-dimensional (2D) perovskite photoferroelectric materials has demonstrated spontaneous polarization and visible-light

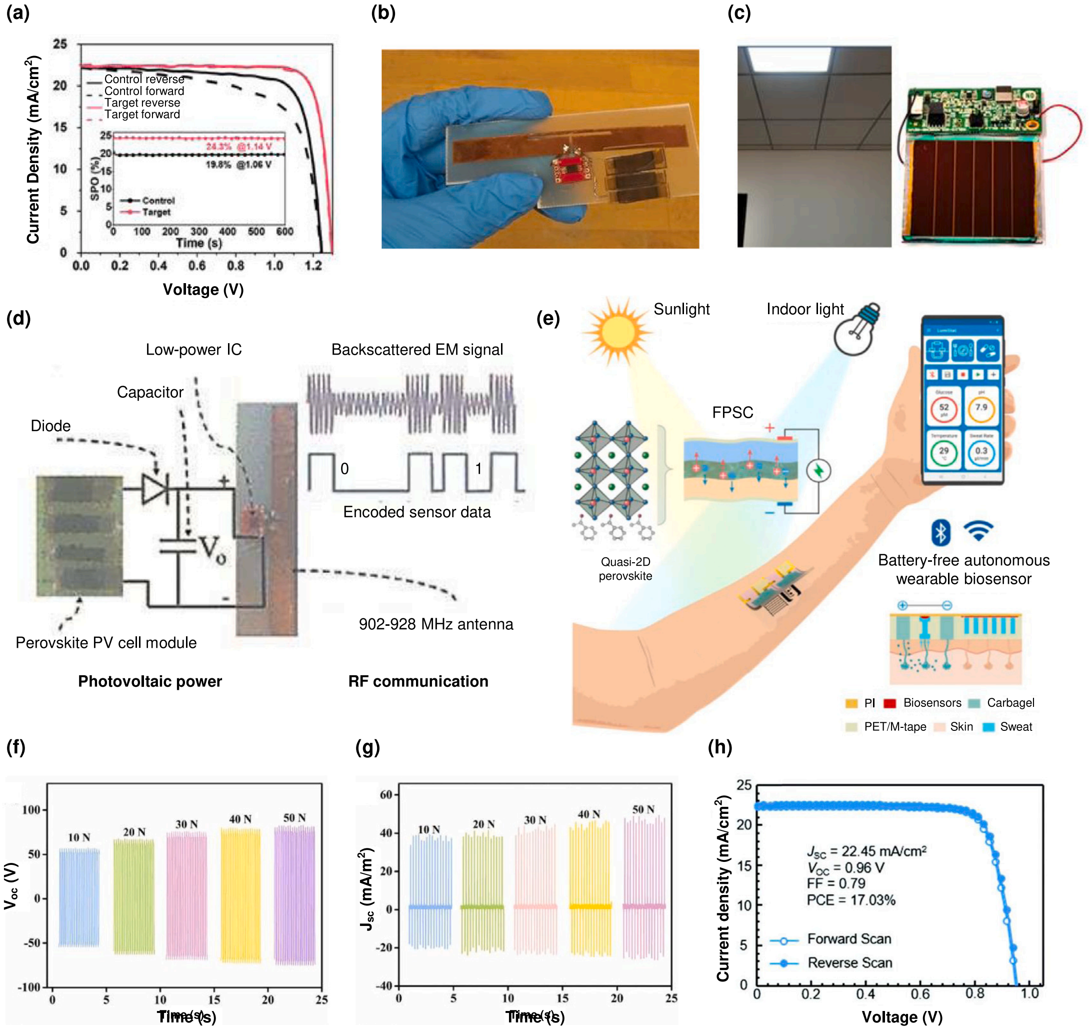

Fig. 4. Perovskite-based devices for indoor wireless self-powered IIoT nodes. (a) Wide-bandgap perovskite solar cell with rubidium thiocyanate as an additive exhibits V_{oc}s of 1.29 V and 1.30 V under forward and reverse scanning, respectively. Reproduced with permission from Ref. [73] © 2024 Wiley-VCH (b) IPV-backscatter sensor fabricated from tandem perovskite PV cells. Reproduced with permission from Ref. [74] © 2019 Wiley-VCH (c) Wide-bandgap perovskite PV module powering the IoT board indoors. Reproduced with permission from Ref. [75] © 2024 Wiley-VCH (d) Perovskite-powered wireless node integrating PV EH and RF communication. Reproduced with permission from Ref. [76] © 2020 IEEE (e) Illustration of an autonomous perovskite-based wearable device for non-invasive detection of metabolic biomarkers. Reproduced with permission from Ref. [84] © 2023 Springer Nature (f,g) Perovskite materials enhance the power generation performance of TENG through the PV pathway. Reproduced with permission from Ref. [87] © 2023 Elsevier Ltd (h) Perovskite thin films with a thickness of only 2.5 μm pave the way for the development of flexible and portable power sources. Reproduced with permission from Ref. [89] © 2019 RSC Publishing.

photoactivity [94]. At room temperature, the sensor exhibits exceptional NO_2 detection performance, with a recovery time of merely 0.16 min and a sensitivity of 0.03 ppm^{-1}, outperforming traditional detection systems that rely on external power sources (Fig. 5b).

Interest in the potential application of perovskite-based sensing platforms for detecting food contaminants has recently surged, providing highly sensitive, portable, and eco-friendly solutions. However, the complexity of food products and the trap states introduced during perovskite synthesis present significant challenges for this technology [95]. Extensive research efforts have been dedicated to overcoming these challenges, focusing on structural engineering and material optimization. Notably, the synergistic effect of surface-modified perovskites and Z-type heterojunctions enables the sensing system to detect pesticide residues in food [96]. This capability allows for the detection of pesticide residues at remarkably low concentrations, as low as 0.033 ng/L, under visible light illumination (Fig. 5c). In contrast to bulk perovskite, perovskite nanoparticles (NPs) can effectively mitigate defect states and inhibit charge recombination through sophisticated surface modification or passivation strategies [97,98]. In this context, perovskite NP-based materials efficiently adsorb target pollutants and form in-situ heterojunctions, significantly reducing the recombination of photogenerated charge carriers and enhancing the photocurrent signal [99,100]. Recent advancements have significantly expanded the application horizon of perovskite NPs. Through strategic integration with reaction promoters or support matrices in core–shell or layered architectures, these hybrid systems achieve amplified signals and stabilized sensing performance, enabling ultrasensitive detection of analytes spanning microbial metabolites to pesticides [101–103]. A compelling example is the encapsulation of perovskite-type $LaFeO_3$ nanoparticles with graphitic carbon nitride ($g\text{-}C_3N_4$) to form $LaFeO_3@g\text{-}C_3N_4$, featuring a p-n heterojunction and core–shell structure. Owing to its enhanced visible light utilization (with an absorption band edge extended to 700 nm), $LaFeO_3@g\text{-}C_3N_4$ exhibits a photocurrent signal 2.3 times stronger than $LaFeO_3/g\text{-}C_3N_4$, enabling sensitive streptomycin detection [104] (Fig. 5d-e). Nevertheless, size-dependent surface effects amplify lead toxicity in nanoscale perovskites [105]. This critical concern drives urgent needs for either lead-free designs or effective immobilization approaches to ensure biosafety.

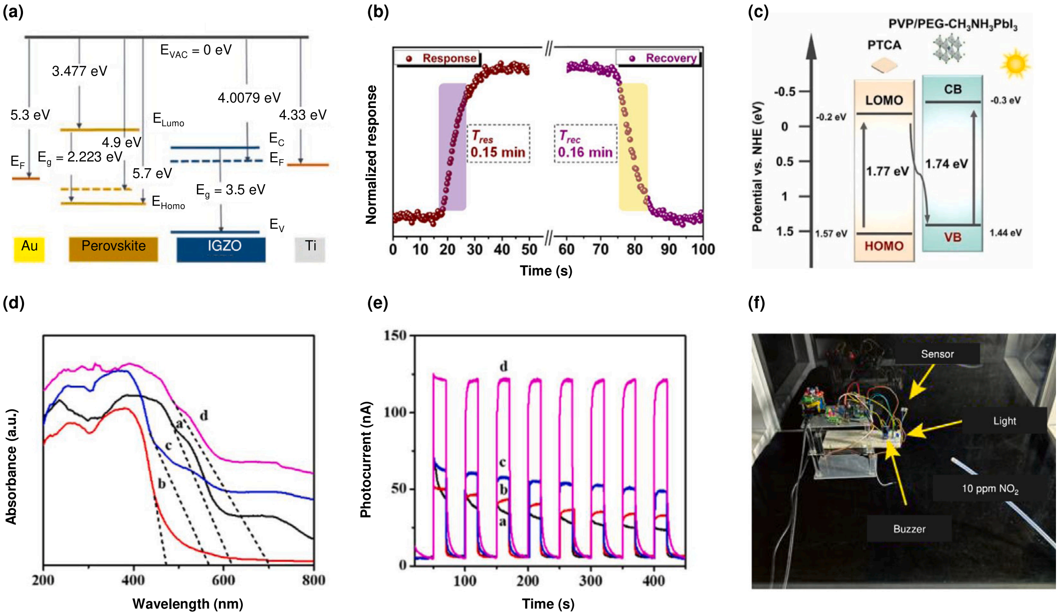

Fig. 5. Perovskite-based self-powered platform for environmental and food contaminant detection. (a) Self-powered heterojunction NO_2 gas sensor fabricated from p-type hybrid halide perovskite and n-type semiconductor metal oxide films. Reproduced with permission from Ref. [92] © 2021 American Chemical Society (b) Perovskite ferroelectric gas sensor ([*n*-pentylaminium]$_2$[ethylammonium]$_2$$Pb_3I_{10}$) exhibits ultra-fast response/recovery speeds. Reproduced with permission from Ref. [94] © 2023 American Chemical Society (c) The PVP/PEG-$MAPbI_3$-PTCA forms a Z-type heterojunction to enable efficient separation of electron–hole pairs. Reproduced with permission from Ref. [96]. © 2024 Elsevier Ltd (d,e) The $LaFeO_3$@g-C_3N_4 exhibits superior light absorption (d) and significantly enhanced photocurrent signals (e) compared to the core ($LaFeO_3$) or shell (g-C_3N_4) materials. Reproduced with permission from Ref. [104]. © 2020 Elsevier Ltd (f) A highly sensitive NO_2 detection alarm system constructed based on TAPA-PDA@Cs_2PdBr_6. Reproduced with permission from Ref. [108] © 2024 Wiley-VCH.

As the concept of smart environments advances, these sensors are expected to integrate seamlessly with smart devices such as smartphones and wearables [106,107]. Through wireless communication technologies, data can be transmitted in real-time to the cloud, enabling instant inference and feedback on indoor environmental quality [106]. The user-end integration of perovskite sensors with alarm systems (such as buzzers and warning lights) offers an efficient solution [108] (Fig. 5f). When the concentration of the target substance exceeds a preset threshold, a light-driven electrical signal triggers the alarm, ensuring prompt protection of public health. However, for large-scale deployment and commercialization, challenges such as the development of lead-free alternatives and selective optimization must still be addressed [109,110].

Perovskite-based photodetectors that integrate optical signal detection and self-powering capabilities represent a breakthrough in optical communications and intelligent sensing. Specifically, these devices decode signals while harvesting energy, enabling low-power, long-term operation of communication nodes. For indoor sensing, their fast response and ultralow dark current ensure precise and continuous performance in IIoT scenarios. This technology lays the foundation for next-generation optoelectronic integration, advancing intelligent sensing networks toward high-efficiency, self-sustained evolution.

Perovskite-based sensing applications

Perovskite-based devices, renowned for their high-efficiency photoelectric conversion properties, have emerged as transformative players in the fields of photodetection. A critical factor in evaluating their performance is their ability to efficiently convert incident light into an electrical signal (Fig. 6a). The spectral response $R(\lambda)$, which characterizes the device's sensitivity to light as a function of wavelength, is a key performance metric for photodetectors [111]. It is defined as the ratio of the photocurrent $I_{ph}(\lambda)$ to the incident optical power $P_{opt}(\lambda)$ at a specific wavelength λ:

$$R(\lambda) = \frac{I_{ph}(\lambda)}{P_{opt}(\lambda)}$$

where $R(\lambda)$ denotes the spectral response (in mA/mW), defined as the ratio of the photocurrent $I_{ph}(\lambda)$ generated at wavelength λ to the incident optical power $P_{opt}(\lambda)$ at the same wavelength.

Despite advances in perovskite material stability, the complexities of fabrication and quality control remain key barriers to the development of Perovskite-based photodetectors [118]. The resulting high Schottky barrier may further impair the photoelectronic performance of the photodetector. A key innovation to address these challenges is the integration of a typical hybrid organic–inorganic perovskite-coated carbon fiber with CuO-Cu_2O wire, forming a double-twisted fiber structure [112] (Fig. 6b). This design simplifies the fabrication process by eliminating the need for multi-layer composites in traditional structures, while also providing a broad wavelength response (350–1050 nm). Substituting hybrid perovskite with all-inorganic perovskite typically enhances long-term stability and simplifies performance management [119–121]. For example, a breakthrough in all-inorganic metal halide perovskite ($CsPbI_xBr_{3-x}$) devices has led to an ultra-low detection limit of 21.5 pW/cm^2, a 20 ns response time, and exceptional stability, with over 2000 h of reliable operation [113] (Fig. 6c-d). This high sensitivity coupled with long-term environmental stability underscores its significant potential for optical communication applications. Recent work has provided novel insight into solving the aforementioned challenges by employing asymmetric gold (Au) electrodes, thus avoiding the need for additional HTL, ETL, and external electric fields in the complex structural design [122]. Beyond these technological advancements, innovative techniques such as handwriting [114] (Fig. 6e), inkjet printing [123] and molecular modification [124] have enabled the fabrication of Perovskite-based photodetectors on paper, offering a cost-effective solution for flexible and customizable electronics. Taken together, these breakthroughs establish a solid foundation for the precise and versatile detection of various light properties, opening up new possibilities for a wide range of applications.

In optical information processing, the detection of polarized light plays a crucial role in the modulation, demodulation, and signal processing of optical signals, enhancing the performance and flexibility of

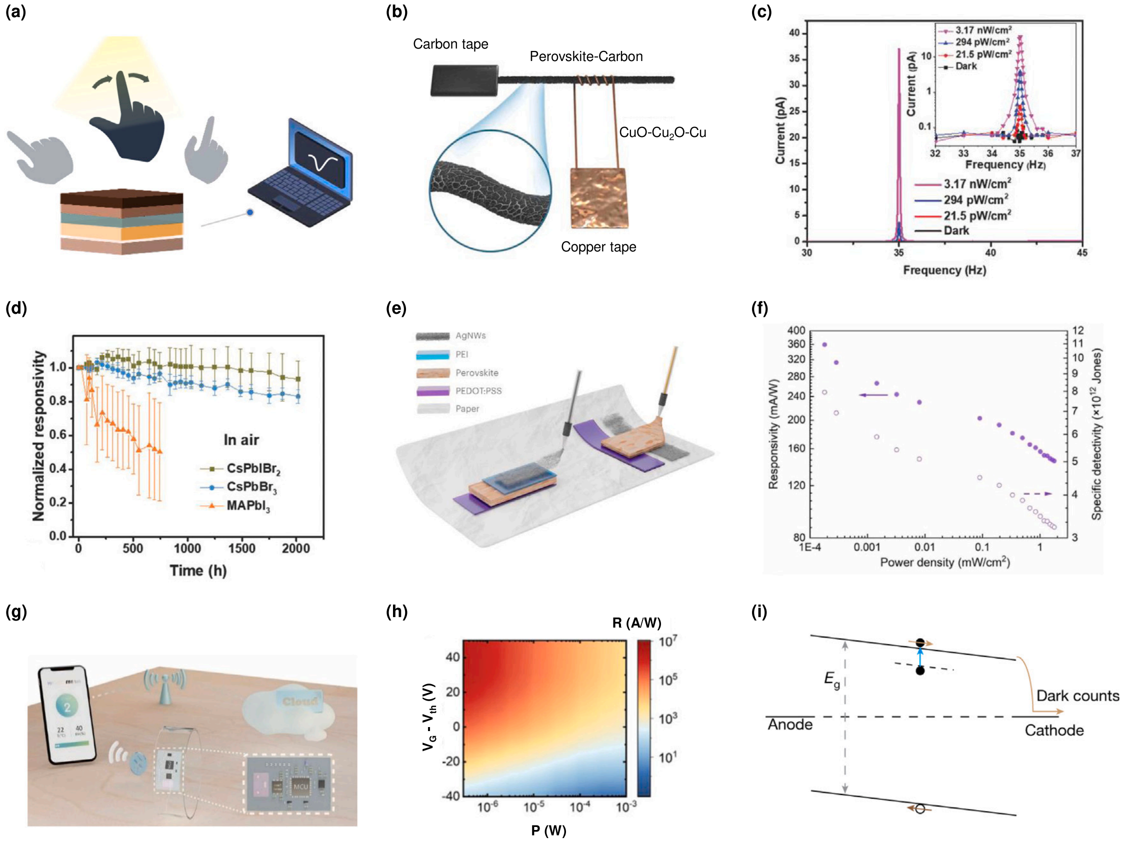

Fig. 6. Recent advances in enhancing the performance of perovskite-based photodetectors. (a) Schematic diagram of a p-i-n type perovskite photodiode. (b) Fiber-shaped photodetector fabricated by integrating perovskite-coated carbon fiber with CuO-Cu_2O wire. Reproduced with permission from Ref. [112] © 2018 WILEY-VCH (c) The current peak generated by incident light with an intensity of approximately 21.5 pW/cm^2 indicates that the $CsPbI_xBr_{3-x}$ photodetector can detect weak light at this low intensity. Reproduced with permission from Ref. [113] © 2018 WILEY-VCH (d) Minimal 7% and 13% decline in device responsivity of $CsPbIBr_2$ and $CsPbBr_3$ photodetectors after over 2000 h. Reproduced with permission from Ref. [113] © 2018 WILEY-VCH (e) Schematic of a handwritten method for fabricating perovskite optoelectronic devices with vertical or lateral structures. Reproduced with permission from Ref. [114] © 2023 Springer Nature (f) Maximum responsivity of 359.03 mA/W achieved by $MAPbCl_3$ film-based device under 395 nm light at 0.18 μW/cm^2 intensity. (g) Schematic of a $MAPbCl_3$ film-based wearable UV wristband transmitting data to a smartphone and cloud. Reproduced with permission from Ref. [115]. © 2022 Elsevier Ltd (h) Responsivity of the PNCs/MoS_2 phototransistor in different gate voltage and laser power. Reproduced with permission from Ref. [116] © 2024 American Chemical Society (i) Contribution of dark count rate in the perovskite photon counting detector at zero bias. Reproduced with permission from Ref. [117] © 2023 Springer Nature.

optical communication systems. A photodiode based on a helical one-dimensional (1D) structure eliminates the need for optical polarizers in traditional photodetectors, thereby preventing losses in light sensitivity and resolution, and achieving a polarization discrimination ratio of 25.4 [125]. Additionally, needle-like perovskite crystal films, fabricated using electric field-assisted droplet jetting 3D printing technology, exhibit high anisotropy. These films enable the detection of changes in the laser polarization direction relative to the angle between the needle crystals through photocurrent generation patterns in both parallel and perpendicular alignment modes [126].

Light quality plays a vital role in indoor activities and workshop production, and the exceptional sensitivity of perovskite-based photodetectors to high-energy short-wave light facilitates precise monitoring and control of light quality. In the field of blue light hazard detection, a self-powered narrowband photodetector based on $Cs_2AgBiBr_6$ has demonstrated high responsivity and specific detectivity around the 450 nm wavelength [127]. This device enables precise evaluation of blue light hazard levels while effectively suppressing interference from other visible light. Another narrowband photodetector, based on $CH_3NH_3PbBrCl_2$, exhibits excellent responsivity, rejection ratio, and linear dynamic range [128]. Integrated with backend circuits, it enables real-time detection and intuitive display of blue light hazard levels, offering support for portable and cost-efficient solutions. For UV monitoring, a wearable photodetector developed using a solution-assisted halide exchange strategy demonstrates a high responsivity of 359.03 mA/W, rapid rise time of 3.91 ms, and fast decay time of 4.55 ms in self-powered mode, alongside excellent stability [115] (Fig. 6f). When integrated with commercial soft circuits, the detector achieves all-weather UV monitoring and environmental data recording, providing real-time personalized health recommendations (Fig. 6g).

Inspired by the quantification of photocurrent, perovskite-based photodetectors exhibit the ability to estimate the incident photon flux. Typically, employing transistor architectures enhances gain performance, meeting the stringent requirements for high sensitivity and low noise in photon counting applications [116]. In this research domain, heterojunction phototransistors stand as a pivotal device architecture, with the perovskite and MoS_2 composite structure being particularly exemplary [116,129,130] (Fig. 6h). Exemplified by a type II band alignment, the efficient separation of photogenerated electron–hole pairs within the perovskite layer enables a device responsivity of up to 2.2×10^6 A/W, representing an order-of-magnitude enhancement over conventional designs [116]. Building on this, the meticulous optimization of the perovskite-complementary material interface can effectively exploit the photogating effect, thereby enhancing the phototransistor's gain performance [131]. Unfortunately, the long-term stability of perovskite-based phototransistors remains a significant challenge, as their three-terminal design, coupled with larger electrode spacing, results in slower response times and higher driving bias [132–134]. In comparison, the structurally compact perovskite-based photodiodes, featuring shorter carrier transit lengths, deliver enhanced performance with rapid response times and zero-bias operation [117,135] (Fig. 6i). Zero-bias operation helps reduce noise caused by charge accumulation, but the lack of an external electric field leads to ion migration and charge loss within the material, ultimately compromising the stability of the device. Recent studies demonstrate that optimizing grain size and surface passivation effectively suppresses shallow trap states, reducing the dark count rate from over 20,000 cps/mm^2 to just 2 cps/mm^2 [117]. This improvement enhances both operational stability and device performance in critical applications. Furthermore, space charge buildup during high-flux operation generates radiation polarization, degrading detector count-rate capability [136]. This can be effectively mitigated by applying optimized reverse bias, which simultaneously suppresses polarization effects and reduces pulse rise time, thereby restoring count-rate performance [137].

Perovskite-based integration of optical communication and energy harvesting

Visible light communication (VLC), with its superior capabilities in high data rates and large capacity, plays a pivotal role in the development of 6G-IoT networks [138,139]. It holds the potential to meet the growing demand for high-speed connectivity and massive-scale network connections. Since the first integration of $CsPbIBr_2$ photodetector into VLC systems in 2018, perovskite-based receivers have undergone rapid advances [113]. Substantial advancements have been realized in critical performance metrics, including bandwidth [140], responsivity [141], and detection sensitivity [142].

In open environments, the transmission of optical signals to target detectors is significantly attenuated by factors such as atmospheric scattering and broadband interference, severely impacting signal quality [143]. Traditional wavelength selection techniques utilizing optical components can enhance signal transmission to a certain degree [144]. However, this inevitably introduces additional system complexity. To address these issues, recent efforts have focused on enhancing system robustness against interference through optimized design engineering of perovskite-based photodetectors. A potential approach involves the fabrication of high-quality composite thin films. As a typical example, the sequentially spin-coated $CsPb_2Br_5$-$CsPbBr_3$ PD establishes an HTL-free architecture that effectively reduces grain boundary defects. The resultant enhanced photoresponse and stability enable its implementation in a voice-controlled VLC system [145] (Fig. 7a). Direct physical bonding between compositionally distinct perovskite films proves non-essential for mitigating interference. Instead, vertically stacked detectors comprising oppositely polarized $MAPbBr_3$- and $MAPbI_3$-based PDs form p-i-n-i-p or n-i-p-i-n architectures [146] (Fig. 7b). This configuration exhibits spectral selectivity, effectively minimizing cross-band optical interference. Subsequently, a photodetector composed of two PDs in a back-to-back configuration (Ag/P3HT/perovskite/PEDOT:PSS/ITO) has been demonstrated, effectively suppressing low-frequency interference [140] (Fig. 7c). The perovskite film in the device exhibits a vertical 2D-3D-2D phase distribution, creating a ‘V’-shaped potential, enabling selective optical response within the 0.8–9.7 MHz frequency range. Additionally, through precise modulation of absorption layer thickness and interface electric field strength in perovskite-based photodetectors, the optical communication system’s capability to interpret optical signals can be significantly enhanced [147] (Fig. 7d). This approach enables wavelength and intensity discrimination of monochromatic light solely through photocurrent waveform analysis, eliminating dependence on supplementary optical/mechanical components.

Despite these innovations, the RC time constant, which defines the RC-limited time response (approximately 2.2 times the RC constant for output risetime), remains a critical factor limiting bandwidth performance [148]. The most direct method to reduce the impact of the RC time constant is to minimize the device’s active area, though this inevitably leads to a reduction in sensitivity [97]. A more sophisticated yet promising concept reported involves the array-based design of perovskite-polymer fibers. Cascading the detection area in this architecture reduces the RC constraints imposed on perovskite-based photodetectors [149] (Fig. 7e).

Currently, the integration of perovskite-based photodetectors in low-power receivers offers an innovative pathway to achieve passive VLC systems. By eliminating the need for traditional energy-intensive components such as amplifiers and analog-to-digital converters (ADCs), these systems leverage the efficiency of perovskite PV cells to both harvest energy and receive optical signals (Fig. 7f). For example, comparators can be used to convert the received signal into a binary format, while oscilloscopes can help monitor and analyze the waveform for signal integrity and performance [141,150]. More significantly, unlike conventional SLIPT networks, the perovskite receiver intrinsically combines EH functionality, dramatically streamlining system design [151]. Recent breakthrough in perovskite-based photodetector have achieved record data rates of 56 Mbps, paving the way for deeper integration between PIPV technology and VLC systems [152] (Fig. 7g).

Perovskite-based integration of sensing and energy harvesting

Owing to their exceptional photoelectric conversion efficiency and tunable properties, perovskite-based devices are driving paradigm shifts in intelligent sensing systems. The dynamic photoresponse of perovskite-based photodetectors under dynamic illumination enables precise analysis of critical electrical parameters (e.g., waveform and amplitude), facilitating the development of efficient motion-state inference frameworks [153,154].

Emerging research underscores the potential of these devices for high-precision motion sensing, enhanced by machine learning (ML)-driven data reconstruction [155]. As a prime example, the integrated 2D perovskite oxides, fabricated through a charge-assisted oriented assembly film-formation process, achieve motion trajectory recognition accuracy exceeding 99.8% [156]. Despite their potential in spatiotemporal processing and motion recognition, the research focuses primarily on ultraviolet detection, limiting its applicability for indoor use. In contrast, the wearable shadow recognition sensor based on liquid crystal (LC) doped perovskite is specifically designed for applications under indoor ambient light conditions [157] (Fig. 8a). Under 500 Lux indoor lighting, the system demonstrates an exceptional on-off ratio exceeding 100 times, with millisecond-scale response time in translating gestural inputs into machine control commands. On the basis of enhanced photodetector stability and dynamic response, distinct motion patterns can be classified via intrinsic resistance waveform features, obviating sophisticated algorithm implementation [158]. The invariance of resistance response waveforms to peak frequency variations enables velocity-agnostic motion recognition through waveform pattern matching. Additionally, the bioinspired perovskite hemispherical detectors demonstrates superior wide-angle light-field resolving capability over planar counterparts, achieving enhanced angular robustness in moving-object tracking [159]. Perovskite hemispherical photodetectors have also been demonstrated to facilitate pixel array integration while providing higher-dimensional optical information for ML models [160] (Fig. 8b). However, oriented deposition of high-quality perovskite films on spherical substrates remains challenging, primarily due to non-uniform crystallization during curved-surface fabrication. Spin-coating emerges as a more efficient strategy, enabling precise customization of photosensitive layer thickness through optimized solution concentration and deposition frequency [161]

The sophisticated acquisition and processing of optical signals by photodetectors position them as a cornerstone of intelligent sensing and control within non-contact human-machine interaction systems [157,162,163]. Operating within a dynamic paradigm, this task demands inference systems with temporally-aware architectures and nonlinear computational depth. For real-time detection of dynamic gestures, the perovskite-based photodetector array captures current fluctuations resulting from the cycles of light path obstruction and exposure, facilitating more accurate extraction of key features across both temporal

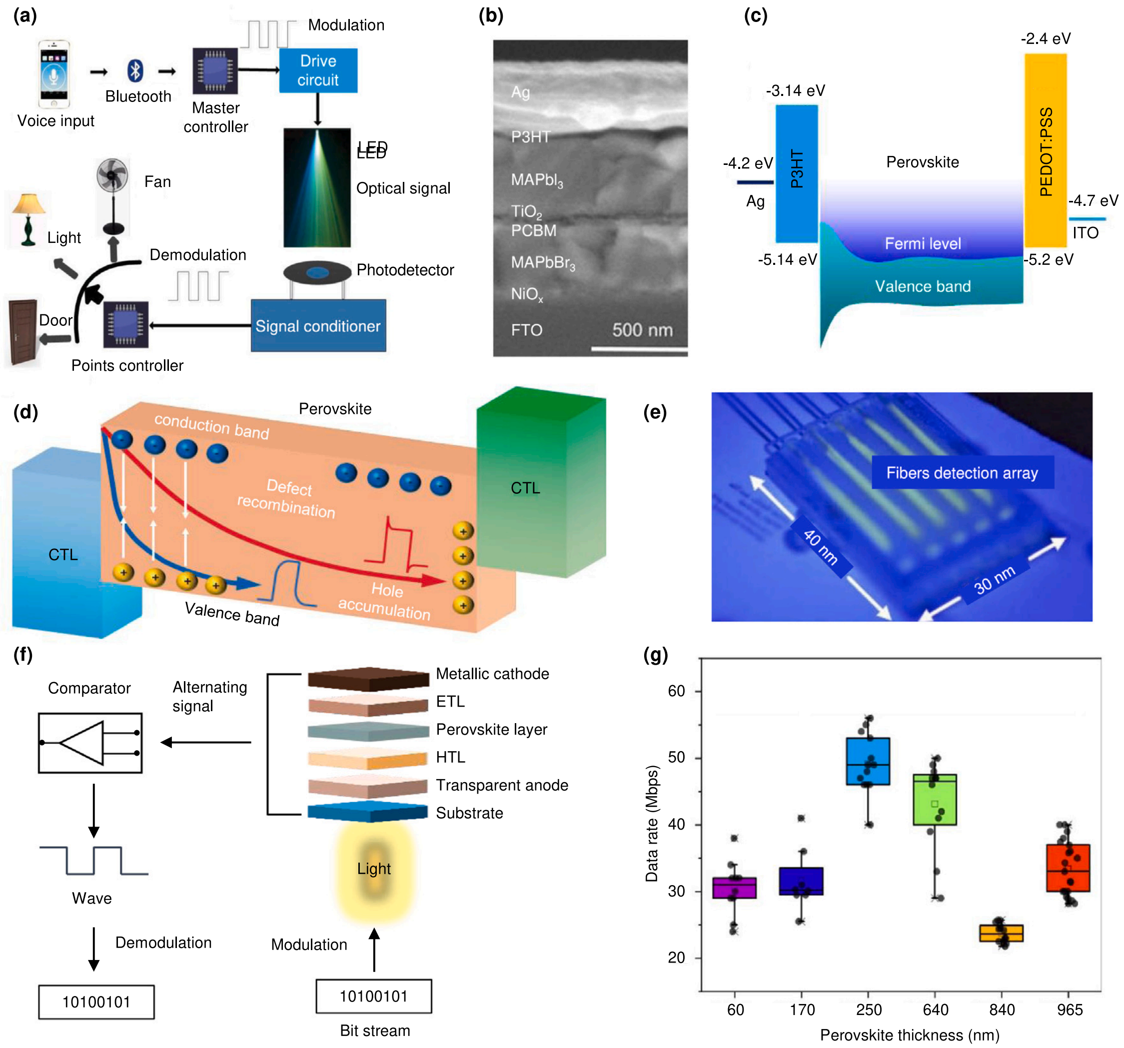

Fig. 7. Integration of perovskite-based photodetectors in VLC systems. (a) System architecture diagram of a $CsPb_2Br_5$-$CsPbBr_3$-based photodetector applied in a voice-controlled VLC system. Reproduced with permission from Ref. [145] © 2018 Wiley-VCH (b) Cross-sectional scanning electron microscope (SEM) image of a dual-band perovskite photodetector based on $MAPbBr_3$ and $MAPbI_3$. Reproduced with permission from Ref. [146] © 2021 American Chemical Society (c) Energy-band diagram of the back-to-back-structured photodetector. Reproduced with permission from Ref. [140] under a Creative Commons licence CC BY 4.0. (d) Device design principle based on adjusting perovskite film thickness to optimize light absorption. Reproduced with permission from Ref. [147] © 2024 Springer Nature (e) Detector array formed by the single perovskite NCs-polymer fiber. Reproduced with permission from Ref. [149] under a Creative Commons licence CC BY 4.0. (f) Potential approach for integrating perovskite-based photodetectors into low-rower VLC receiver. (g) Achieving different data transmission rates by varying the thickness of the triple-cation perovskite layer in the receiver. Reproduced with permission from Ref. [152] under a Creative Commons licence CC BY 4.0.

and spatial dimensions [164]. Leveraging the similar detector array architecture, perovskite-based smart eyeglasses achieve non-contact, high-precision ocular angular tracking across multiple channels [165] (Fig. 8c). The system translates ocular motion into predefined commands, wirelessly interfacing with external devices through Bluetooth, thereby showcasing its transformative potential in augmented reality applications. Through the integration of perovskite with other components into flexible electronic devices, flexible and multi-modal human-machine interactions can be achieved via both contact and non-contact modalities [166]. In this framework, perovskite detects variations in light intensity for ambient light sensing and motion recognition, while polyvinylidene fluoride (PVDF) piezoelectric properties respond to mechanical pressure and deformation to enable multi-modal sensing of motion intensity and bending curvature [167] (Fig. 8d-e). The combination of both enhances the system responsiveness to static and dynamic events. Building on continuous advancements, recent studies have shown that through a comprehensive balance of material surface properties, intrinsic characteristics, and process complexity, perovskite can be successfully integrated into non-contact human-machine interfaces, with its application potential highlighted in wearable devices, automotive displays, and robotic remote control systems [168].

Recent advancements have been made in utilizing perovskite-based optoelectronic devices overcome the limitations of von Neumann architecture, particularly in addressing the inefficient data transfer between memory and processors [169]. Specifically, perovskite devices enable chip-level sensor-computing integration, offering neuromorphic photonic computing with parallel processing capabilities, which reduces data transfer demands while significantly enhancing computational efficiency [170,171] (Fig. 9a). For example, a hybrid integrated lead-free perovskite/graphene array enables in-sensor computing, seamlessly combining photoelectric detection and computation [172] (Fig. 9b). By reducing data transmission between chips, it performs image pre-processing directly at the sensor level. As a result, the 6 × 6 sensor array enhances image recognition accuracy from 69.2% to 89.5% (Fig.

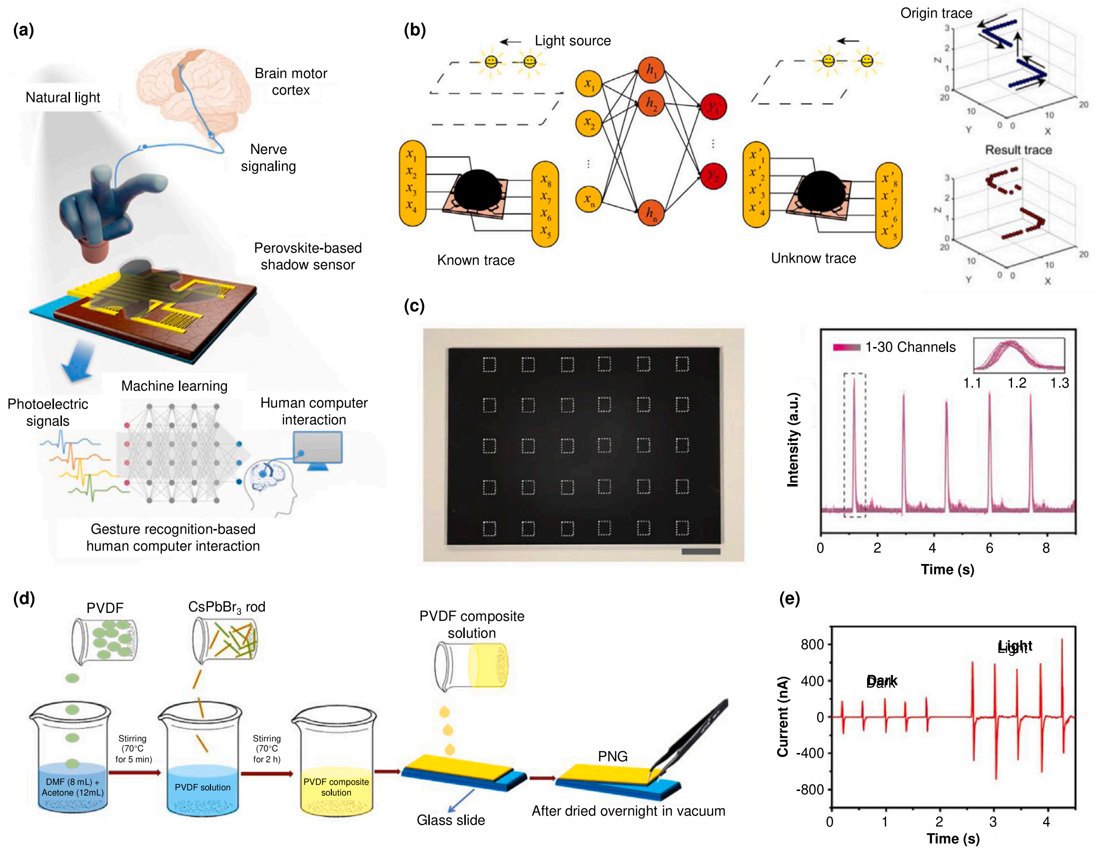

Fig. 8. Human-machine interaction based on perovskite devices. (a) Shadow patterns captured by perovskite PV sensors under ambient light are used to recognize gestures through ML model. Reproduced with permission from Ref. [157] under a Creative Commons licence CC BY 4.0. (b) Differential signals from the perovskite hemispherical detector are fed into a neural network model for training and positional prediction. Reproduced with permission from Ref. [160] under a Creative Commons licence CC BY 4.0. (c) Time-resolved intensity responses across different channels (detectors) in the $MAPbI_3$-based photodetector array. Reproduced with permission from Ref. [165] © 2018 Wiley-VCH (d) Preparation and collection process of the PVDF-$CsPbBr_3$ film. Reproduced with permission from Ref. [167]. © 2020 Elsevier Ltd (e) Current-time spectra of PVDF-$CsPbBr_3$ composites under illumination and dark conditions. Reproduced with permission from Ref. [167]. © 2020 Elsevier Ltd.

9c). Beyond hardware architecture advancements, the intrinsic dynamical properties of perovskite materials can also facilitate backend inference. In particular, the unique transient behavior of V_{OC} in perovskite PV cells can be exploited for in-sensor reservoir computing [173]. This PV reservoir computing system directly modulates the reservoir's physical states through light pulse encoding, enabling the processing of time-varying inputs (Fig. 9d). Further studies demonstrate that perovskite-based photoelectronic synaptic unit exhibits finely tuned responses to visible light absorption and synaptic current modulation under optical pulse stimulation [174] (Fig. 9e). Building on this, vertically aligned Dion–Jacobson (DJ) phase 2D perovskite artificial synapses exhibit excellent stability in linear conductance modulation [175]. Synaptic arrays based on this structure achieved recognition accuracies ranging from 73.83% to 92.29% across various inference tasks on large-scale datasets (Fig. 9f). Data relabeling further fine-tunes synaptic conductance parameters while effectively suppressing label noise artifacts, crucially advancing neuromorphic computing applications [174]. However, the traditional top-down fabrication methods are limited by the degradation issues of perovskites. To address this, a recent study introduces a bottom-up approach for on-site synthesis of PNCs [176]. Under the guidance of a topographical template, the growth and positioning of perovskites in on-chip nanodevices can be precisely controlled (Fig. 9g). The progress enables edge computing and distributed solutions, reducing reliance on cloud-centric processing.

Challenges and solutions of perovskite devices in IIoT applications

Overcoming stability and scalability in perovskite devices

The development of perovskite devices faces two primary challenges: material stability and large-area processability. Intrinsically, perovskites suffer from susceptibility to humidity, oxygen, light, and temperature, which can trigger decomposition or phase transitions. Under continuous illumination, ion migration and defect activation further accelerate efficiency losses. To mitigate these effects, strategies such as incorporating Cs^+, DMA^+, Rb^+, or halide ions (Br^-/Cl^-) have been employed to enhance lattice stability and suppress phase separation [177]. Additional approaches include integrating hydrophobic two-dimensional (2D) perovskite capping layers to block water and oxygen diffusion [178]. These 2D perovskites are typically formed by introducing long-chain hydrophobic organic cations, such as phenethylamine (PEA^+) and butylamine (BA^+), which interact with Pb^{2+} to form quasi-2D coatings [179–182]. This structure passivates uncoordinated Pb^{2+} on the surface, suppresses defects, and reduces non-radiative recombination losses at the interface [178]. Moreover, the hydrophobic spacer cation layers in 2D perovskites effectively hinder external moisture erosion, further improving the long-term stability of the devices. By using atomic layer deposition (ALD) technology to deposit Al_2O_3 or SnO_x on perovskite layers, the thickness and uniformity can be precisely controlled, resulting in a dense protective layer [183,184]. These

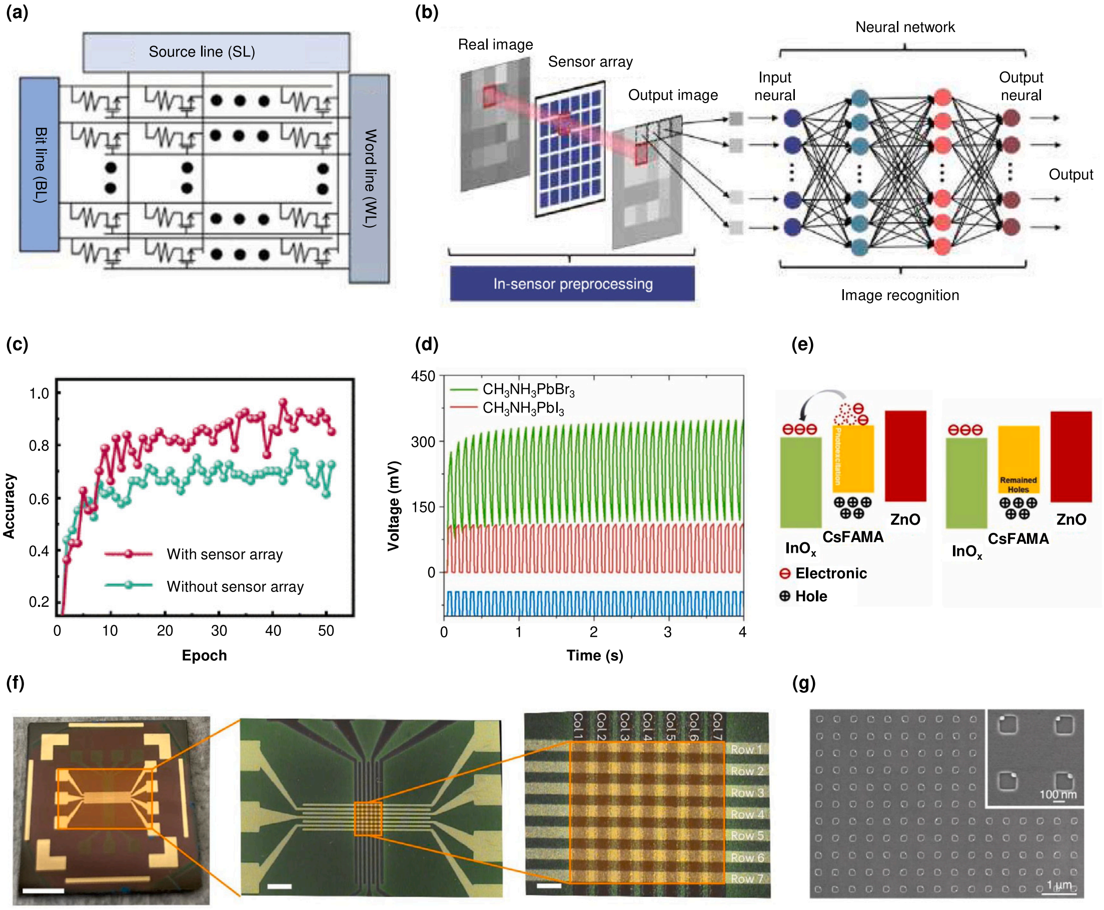

Fig. 9. On-chip computing based on perovskite devices. (a) Schematic diagram of the ANN equivalent circuit realized by $Cs_2AgBiBr_6$-based memory-synaptic hybrid optoelectronic transistors. Reproduced with permission from Ref. [170] © 2022 IEEE (b) Illustration of the neuromorphic vision system based on the perovskite-graphene hybrid array and an artificial neural network (ANN). Reproduced with permission from Ref. [172] © 2024 IEEE (c) Comparison of recognition accuracy with/without perovskite-graphene hybrid array processing at different epochs. Reproduced with permission from Ref. [172] © 2024 IEEE (d) Light pulse train-induced transient V_{OC} characteristics of $CH_3NH_3PbBr_3$ and $CH_3NH_3PbI_3$ PV devices. Reproduced with permission from Ref. [173]. © 2024 Elsevier Ltd (e) Mechanism of excitatory postsynaptic current in perovskite-based synaptic units under light illumination. Reproduced with permission from Ref. [174]. © 2024 Elsevier Ltd (f) Optical images of a 7 × 7 crossbar array with vertically aligned DJ perovskite-based synapses. Reproduced with permission from Ref. [175] © 2024 Springer Nature (g) SEM image shows square wells (150^2 nm^2) containing $CsPbBr_3$ NCs, patterned on a Si substrate. Reproduced with permission from Ref. [176] under a Creative Commons licence CC BY 4.0.

protective layers significantly slow down material degradation, thereby prolonging operational lifetimes under hot and humid conditions.

Beyond intrinsic material strategies, advanced encapsulation techniques are equally essential for ensuring device stability in practical applications. In commercialized photovoltaic technology, multilayer composite encapsulation structures combining polymer-based and glass-based materials have been widely developed and optimized. Encapsulating perovskite photovoltaics with polymer layers such as ethylene-vinyl acetate (EVA), polyvinyl butyral (PVB), polyolefin elastomer (POE), and thermoplastic polyolefin (TPO), in conjunction with glass covers, can significantly enhance stability under damp and hot conditions [185–187]. To prevent moisture and oxygen ingress, the water vapor transmission rate (WVTR) of the encapsulants should be maintained between 10^{-4} and 10^{-6} g m^{-2} day^{-1}, and the oxygen transmission rate (OTR) between 10^{-3} and 10^{-5} g m^{-2} day^{-1}. Additionally, the encapsulation materials must not chemically react with the perovskite absorber or other functional layers during operation. Processing conditions, such as curing or lamination temperatures, must also be carefully optimized to avoid degradation of the perovskite layer caused by thermal stress.

The large-area scalable preparation of perovskite devices is the core issue for its industrialization. Currently, the relatively mature slot-die coating technology, combined with nitrogen air knife or vacuum flash evaporation technology, has led to more than 20% PCE on large-area perovskite devices. Since perovskite photovoltaics can be prepared by the low-temperature solution method, the production cost mainly comes from FTO or ITO substrates and metal electrodes, and the cost proportion of perovskite precursor materials consumed is low [188]. It has obvious cost advantages over traditional photovoltaic technology in large-scale industrial production.

Besides photovoltaic performance, the environmental safety of perovskite PV cells has also drawn significant attention. The lead leakage from perovskite devices has raised concerns. For the environmental risk of lead leakage, researchers have tried to prepare Sn-based perovskite PV cells using Sn^{2+} instead of Pb^{2+}, but the susceptibility of Sn^{2+} to oxidation leads to a decrease in PCE. Yang et al. used an antioxidant (catechin) to inhibit the oxidation of Sn^{2+} to Sn^{4+} to prepare a Sn-based mixed halide perovskite ($FA_{0.75}MA_{0.25}SnBrI_2$) with a PCE of 12.81% under 1000 Lux LED indoor light [43]. Lead-free double perovskites were designed, but with a large bandgap ($\sim$2 eV) and low carrier mobility ($<$10 cm^2/V s). Krishnaiah et al. reduced defect density by introducing N, N-methylene bisacrylamide (MBA) into $Cs_2AgBi_2I_9$ as a multifunctional crosslinking agent to regulate nucleation and growth dynamics, thereby achieving approximately 8% PCE under 1000 Lux white LED illumination [46]. The introduction of lead chelating agents to convert free lead ions into stable complexes is also a method to improve the stability of perovskite PV cells and prevent lead leakage [189]. Considering the environmental impact of lead leakage and sustainable development, developing sustainable lead recycling technology can not only solve the problem of environmental pollution, but also further reduce the cost of raw materials by recycling the lead compounds [190]. It mainly includes methods such as chemical dissolution and precipitation, physical adsorption, and electrochemical reduction. Among them, developing lead recovery methods based on green solvents can further reduce the harm to the environment [191].

Optimization strategies for perovskite PV-powered nodes

In general, perovskite-powered IIoT nodes necessitate predictable operational stability for practical implementation. Two fundamental constraints currently hinder progress: the reliance on conventional trial-and-error approaches for performance optimization and the enduring challenge of precisely quantifying operational lifetime [192,193]. To overcome these challenges, researchers must co-optimize system architectures and algorithms that simultaneously ensure energy efficiency and operational stability. The developments will position perovskite PV-supported nodes as a vital research priority.

In this context, machine learning (ML)-driven optimization has emerged as a highly promising approach, operating across multiple dimensions. First, data-driven global optimization frameworks enable efficient and robust exploration of high-dimensional parameter spaces [194]. By leveraging ensemble learning techniques such as eXtreme Gradient Boosting (XGBoost) and random forests, researchers can construct precise structure–property relationships for perovskite devices, facilitating simultaneous optimization of key performance metrics, including short-circuit current density (J_{SC}) and open-circuit voltage (V_{OC}), with unprecedented efficiency [195]. Furthermore, when integrated with high-throughput experimental platforms such as microfluidic systems, ML enables rapid screening of material parameters and precise control over crystal structure, morphology, and purity, thereby enhancing device stability and adaptability under complex environmental conditions [196]. In addition, ML algorithms surpass traditional Equilibrium Optimizer (EO) methods in extracting and predicting dynamic equivalent circuit parameters under varying conditions (e.g., fluctuations in light intensity and temperature) [197]. Finally, the entire optimization process can be framed as a multidimensional search problem, where Bayesian optimization and related algorithms significantly reduce experimental and computational costs, expediting the discovery and performance enhancement of high-efficiency photovoltaic materials [198].

Beyond material-level advancements, the overall efficiency of perovskite PV systems critically depends on the integration of meticulously designed energy management algorithms. Recent breakthroughs demonstrate the successful integration of perovskite PV cells with MPPT-based energy management systems [199]. This architecture achieves robust operational stability with merely 6% power degradation over 200 h, fulfilling a key requirement for real-world deployment. A study analyzing 2245 MPPT aging curves found that high-efficiency perovskite PV cells exhibit superior stability, with a negative correlation between maximum PCE and relative PCE loss after 150 h [200]. Additionally, the tracking accuracy of the MPPT has been enhanced to 99.25% using a customized fractional V_{OC} algorithm [201]. When integrated with flexible perovskite PV modules (PCE of 18.71%), the system maintains 98.3% accuracy even under bending conditions. Self-organizing maps (SOM) clustering of degradation curves further confirmed that high-efficiency perovskite devices are more likely to display stable patterns, such as 'initial gain'. The energy yield model, developed through optical modeling and indoor characterization, can be employed to assess the impact of various light management technologies and device configurations [202]. Insights from these evaluations enhance energy scheduling precision, optimizing system-wide efficiency.

Elucidating perovskite device behavior requires consideration of multifield coupling effects, where multiphysics simulations provide critical mechanistic insights [203–205]. This is exemplified through finite-difference time-domain (FDTD) simulations of optical field distributions, enabling thickness optimization for enhanced light absorption [147]. Such progress ultimately enabled accurate recognition of both wavelength and intensity of monochromatic light through photocurrent waveform analysis. Recent studies employed comprehensive modeling approaches, integrating optical transfer matrix methods (TMM) with electrical simulations such as Poisson's and carrier continuity equations, to analyze the interactions between material properties, layer thickness, and device architecture. This approach led to significant improvements, achieving a PCE of 15.15% while maintaining an average visible transmittance (AVT) of 27.37% through optimized designs [206]. With a focus on thermal stability, Zandi et al. [207] computationally demonstrated the effectiveness of multiphysics simulations to investigate heat distribution in perovskite PV cells with reduced graphene oxide (RGO) contacts. Their work highlighted the importance of coupled optical-electrical-thermal models in understanding heat dissipation mechanisms and improving device stability, showcasing the potential of RGO as a superior electrode material for thermal management in perovskite PV cells, replacing traditional metals. Multiphysics simulations theoretically constitute a sophisticated paradigm for elucidating complex coupled physical–chemical phenomena. Nonetheless, their practical utility is often impeded by formidable computational exigencies and the extant lacunae in mechanistic understanding, thereby potentially compromising their predictive fidelity and broader applicability [208]. Recent study on perovskite-based optical architecture demonstrate that ML can enhance high-throughput simulation predictions through optimization of critical structural parameters [209].

The integration of ML into perovskite PV optimization enables significant improvements in material selection, structural tuning, and performance prediction. ML-empowered circuit modeling enhances real-time device monitoring under fluctuating conditions. Compared to rule-based design, these data-driven strategies support rapid iteration and deeper insights, particularly when combined with high-throughput systems. Their application is especially valuable for accelerating the development of stable, high-efficiency PIPV modules.

Multifunctional trade-off optimization in self-sustaining nodes

For multifunctional nodes performing communication or sensing tasks, low-power operation is paramount. Energy-efficient components and communication protocols enhance the reliability and adaptability of self-sustaining systems [210]. Emerging wireless technologies like passive Wi-Fi and backscatter LoRa, with power consumption as low as microwatt levels, are ideally suited for operation with power generated by PIPVs [211,212]. Balancing the demands of energy harvesting, sensing, and communication in perovskite-based multifunctional nodes can be achieved through hierarchical energy scheduling, which prioritizes critical sensing tasks based on predicted energy availability, while adaptive duty-cycling adjusts sampling rates, communication intervals, and storage utilization to align energy allocation with task urgency. An optimized system architecture and flexible energy management further coordinate energy harvesting with sensing and communication operations. The integration of perovskite photovoltaics with energy storage modules (e.g., supercapacitors) establishes a harvest-store-use (HSU) architecture [213]. This end-to-end energy management strategy significantly enhances the fault tolerance of perovskite-based nodes in task execution [19,214,215].

Owing to its exceptional performance under low-light conditions, perovskite device emerges as an ideal candidate for efficient EH in non-directive SLIPT systems within multi-user environments [216]. However, the intrinsic transient time of PV cells may engender nonlinear effects, posing significant challenges to communication performance [217]. The integrated architecture enables transmitter-side predistortion to address these constraints [218]. This approach simultaneously enhances bandwidth while resolving the fundamental trade-off between EH and information transmission. System-level optimization can be achieved while maintaining compactness and lightweight design. For instance, shared-electrode configurations (two-electrode or three-electrode) minimize redundant electrical connections, thereby optimizing structural architecture and enhancing energy efficiency [219–221].

Optimizing system adaptability in dynamic indoor environments is critical for ensuring stable performance and energy efficiency, particularly in scenarios with fluctuating lighting conditions and variable user demands. Light-induced ion migration in perovskites dynamically reconfigures their internal potential distribution. This inherent mechanism enables tunable photoresponsivity, facilitating adaptive sensing and enhanced imaging functionalities [222]. More importantly, the tunable photovoltaic properties of perovskites enhance both the fabrication flexibility and system-level efficiency of PV arrays. The series-parallel configured perovskite module integrated with supercapacitors in the HSU system optimizes the EH-storage pathway while enabling demand-oriented power delivery [215]. The perovskite-based HSU systems support nodal configuration and 3D deployment. The coordinated execution of wireless communication and environmental sensing enables the establishment of high-density perception-feedback networks [223]. Notably, in HSU systems, self-powered photodetection based on p–n junctions often faces a trade-off between response speed and power output. A viable solution is to enable rapid switching of the perovskite module between photoconductive and PV modes, achieving a balance between EH and information transmission [224]. In this process, the energy storage module can serve as an intermediary for mode regulation [81]. At the algorithmic level, adaptive scheduling of communication and sensing processes exhibits potential for reducing energy demands in perovskite-powered node [225]. Analyzed data throughput and delay minimization scheduling policies have been investigated for energy harvesting systems, including greedy and stable throughput scheduling optimization methods [226]. A two-layer energy management framework, demonstrating a similar approach, predicts energy harvesting rates and dynamically schedules node tasks to enable the long-term, self-sustained operation of sensor nodes [227]. Recent advancements in research have introduced automated frameworks leveraging deep reinforcement learning (DRL) for the dynamic optimization of energy allocation strategies [228]. Extending this approach to perovskite-based HSU systems could reduce operational costs while facilitating the establishment of a technological chain from sensing to autonomous decision-making.

Overall, multifunctional nodes must balance low-power communication, resilient HSU architectures, and adaptive scheduling. Efficient communication schemes need to align with diverse data and range requirements while minimizing energy consumption. HSU systems with perovskite PV and supercapacitors buffer lighting intermittency but add design complexity. Adaptive scheduling, from heuristics to DRL, improves stability under variable energy while controlling computational overhead. These factors collectively determine how perovskite-powered nodes sustain reliable sensing and communication in dynamic IIoT settings.

The prospects of PIPVs in IIoT applications

Smart healthcare for a sustainable future

The development of smart healthcare is characterized by trends such as precision, remote accessibility, and intelligence, with the indoor applications of perovskite technology providing significant support for its advancement.

Precision medicine heavily relies on the accurate detection of biological markers, providing the foundation for early disease diagnosis and the development of personalized treatment plans. Perovskite-based photodetectors achieve sensing by utilizing the interaction between the target analyte and photogenerated charge carriers, which alters the charge transport dynamics, such as the mobility or density of charge carriers [229]. This alteration leads to measurable changes in the current between electrodes, enabling the detection of the analyte. Even when trace amounts of tumor markers or other substances are present in the blood, with concentrations as low as ng/mL, these sensors demonstrate exceptional accuracy and sensitivity in detection [230]. For instance, in the early diagnosis of cancer, perovskite-based photodetectors can sensitively detect metabolic changes in biomarkers such as alpha-fetoprotein (AFP) [230], neuron specific enolase (NSE) [231] and 5-hydroxymethylcytosine (5-hmC) [232], providing critical insights for the precise identification of diseases. On the other hand, in contrast to conventional biosensing techniques that often necessitate direct sample contact, perovskite materials, with their optical, non-contact detection capabilities, enable non-invasive and expedited early diagnostics, offering a more sophisticated and efficient paradigm for precision medicine [233].

With the rapid expansion of telemedicine, the development of compact, high-performance diagnostic devices and the seamless, rapid transmission of data have become critical. The integration of perovskite materials has unlocked new frontiers in the miniaturization and efficiency of home-based diagnosis. Perovskite-based optoelectronics empower robust biomarker monitoring (including glucose, blood pressure, and cholesterol) and medical data interoperability in demanding environments [234–236]. By integrating optical sensing with VLC, perovskite-based photodetectors enable real-time physiological signal acquisition and transmission, facilitating applications like remote heart rate monitoring and telemedicine [237]. With remarkable stability and ultrafast response times, including rise and fall times on the order of tens of nanoseconds, these devices empower patients to conduct routine diagnostics from home and promptly send their data to clinicians. This allows for real-time health assessments, overcoming geographical barriers and significantly advancing the accessibility and effectiveness of remote healthcare services.

The integration of PIPV technology with intelligent systems is poised to transform medical devices from mere diagnostic tools into comprehensive health management platforms. In the near future, such devices are expected to achieve full automation across data acquisition, transmission, intelligent analysis, and feedback, significantly advancing personalized healthcare and precision medicine. In the realm of wearable technology, the miniaturization, flexibility, and power-generation potential of perovskite materials significantly broaden their range of applications [238]. From a specific perspective, perovskite-based flexible photoelectronic sensors, harnessing the inherent PV properties for autonomous power generation, can be seamlessly integrated into wearable devices such as skin patches or wristbands [115,239]. This integration enables continuous, real-time monitoring of physical activity and health parameters without reliance on external power sources. Data transmission occurs via BLE or light fidelity (Li-Fi), and when combined with advanced network infrastructures, a home healthcare ecosystem can be established, allowing secure upload of health data to the cloud for ongoing medical analysis [84,240]. The incorporation of AI algorithms enables these devices to detect abnormal signals collected during monitoring, providing valuable insights to support early assessment and disease management [235,241].

Smart home for a enhanced future

Smart homes are poised to revolutionize the way we interact with our living environments by incorporating advanced technologies that enhance comfort, energy efficiency, and health. The integration of PIPV technology could be the key innovation driving this transformation, providing sustainable energy support while enabling novel solutions for air quality monitoring and thermal management in modern buildings.

The flexibility and lightweight properties of perovskite materials enable versatile integration into home environments [242]. For instance, semi-transparent perovskite films can be seamlessly embedded into walls or curved surfaces, efficiently harvesting light energy while preserving spatial aesthetics. By combining PIPVs with IIoT communication modules, self-powered smart sensing nodes achieve remote data transmission and intelligent feedback control [223]. This framework allows interconnected networks of smart locks, surveillance cameras, and environmental control devices to operate autonomously, eliminating reliance on traditional batteries or power wiring. Reduced dependence on disposable batteries optimizes energy sustainability and lowers maintenance costs. Furthermore, PIPVs demonstrate inherent compatibility for integration into comprehensive smart home ecosystems.

Air quality monitoring plays a pivotal role in ensuring both environmental safety and user health. Halide perovskite PV devices provide sustainable energy support, not only powering the entire system but also seamlessly integrating with perovskite-based gas sensors. These sensors, leveraging photocatalytic modules, initiate redox reactions through photogenerated electron–hole pairs to efficiently degrade airborne pollutants systems [243]. It is undeniable that the degradation toxicity of lead-based variants is a critical concern, driving the pursuit of safer and more environmentally friendly formulations. Substitutes such as $Cs_2AgBiBr_6$ aim to minimize toxicity while preserving the functional properties for effective detection [244]. This enables the development of a highly effective air quality monitoring and purification framework. Through the automated linkage of the smart control platform, the system can promptly activate air purifiers or ventilation devices upon detecting pollutant thresholds, creating an eco-friendly and intelligent living environment.

Windows, as a major conduit for energy loss in buildings, necessitate the optimization of light and thermal management systems to substantially reduce energy consumption for heating, cooling, and lighting [245]. Perovskite-based smart windows, leveraging their exceptional optoelectronic properties and cost-effective manufacturing processes, offer the dual functionality of light modulation and power generation, thereby effectively meeting both the energy-saving requirements and indoor comfort needs of modern buildings [246]. In light of the substantial fluctuations in solar intensity and its profound influence on the indoor environment, research on perovskite smart windows has predominantly centered on the sophisticated regulation and optimized harnessing of solar energy, with particular emphasis on advanced domains such as light modulation [247], thermal management [248], and PV energy conversion [249]. Additionally, perovskite smart windows can also adapt to other light sources and environmental factors. For example, a self-powered electrochromic smart window, leveraging the light-detection and energy-harvesting capabilities of perovskite, can autonomously switch the electrochromic device (ECD) between bleached and colored states in real-time based on ambient light intensity variations, thereby enhancing indoor comfort and energy efficiency [250]. Recently, electronics manufacturer Panasonic showcased perovskite windows made using inkjet coating technology, demonstrating significant commercial potential in the smart home sector [251]. However, large-scale deployment of such products may still incur non-negligible switching load. [252]. Targeting this problem, a synergistic approach integrating adaptive priority scheduling and temporal pattern recognition holds promise for suppressing redundant switching events [253].

Smart cities for a connected future

PIPVs, serving as a foundational technology for powering IIoT nodes, have the potential to distributed energy networks, enabling energy optimization and data interaction in smart cities. From smart buildings and traffic management to environmental monitoring and smart homes, PIPVs are poised to drive efficient operations and sustainable development across various urban applications.

Capitalizing on its formidable energy-saving potential, real-world deployments in public environments substantiate PIPV technology's transformative capabilities. In 2022, Japanese company Enecoat Technologies integrated its self-developed perovskite solar cells into an IoT air quality sensor. Deployed in offices at the Tokyo Metropolitan Government Building, the device transmits environmental data such as CO_2 levels, temperature, and humidity in real-time using BLE technology. From the perspective of market growth and risk mitigation, electronic shelf labels could be the next key area for PIPV technology [254]. Saule Technologies addresses energy-intensive label operations in volatile pricing environments with its IoT-enabled perovskite electronic shelf labels (PESLs) deployed in retail stores. These devices support 15 daily remote content updates while delivering near-maintenance-free operation, backed by a 10-year lifespan. At the recent Mobile World Congress (MWC) in Barcelona, the world's first smartphone equipped with BOE's perovskite PV technology, capable of indoor and outdoor charging, was unveiled. This integration of PVs with consumer electronics significantly advances the application of PIPV technology in mobile devices.

Next-generation PIPV architectures show potential to revolutionize spatial resource allocation in high-density occupancy facilities through spatiotemporal analytics, particularly within commercial complexes and transportation hubs. Leveraging optical integrated sensing and communication (O-ISAC) systems, IPVs can achieve exceptional precision in localization and behavior recognition, driving the development of advanced and highly efficient applications [255–257]. Supported by light-shadow analysis and sophisticated encoding techniques, centimeter-level precision in positioning, activity recognition, and three-dimensional skeletal reconstruction can be achieved within indoor environments [258–260]. Additionally, the integration of PV devices presents promising potential to deliver sustainable energy solutions, facilitating the system's long-term autonomous operation within indoor environments.

Recent advancements suggest integrating optical and radio signals as dual modalities to develop hybrid optical-radio ISAC networks, optimized for ubiquitous connectivity and sensing [261,262]. This approach eliminates the need for wearable devices and image capture, reducing energy consumption while enabling real-time behavior analysis and inference through edge devices [263]. By leveraging the complementary strengths of line-of-sight and non-line-of-sight links, these networks enable more reliable communication and sensing capabilities. The optical-radio ISAC model eliminates the need for users to wear additional devices or capture images, resulting in lower communication and sensing energy consumption. This methodology enables real-time behavioral state inference through edge computing architectures. In mission-critical infrastructure such as subterranean cable networks, this system establishes an autonomous operational ecosystem through spatially distributed perovskite-radio nodes. Precise optical positioning combined with RF penetration enhances ISAC network coverage. By integrating multimodal data fusion with edge computing architectures, this technology enables optimized energy allocation, accelerated data throughput, and enhanced system interoperability, while supporting real-time pipeline diagnostics and personnel tracking [264, 265].

Towards an efficient industrial IoT

Industrial IoT has become a pivotal driver of intelligent manufacturing and automation, relying on the synergy between edge computing and sensor networks to enable real-time data processing and decision-making. The integration of the perovskite-based devices with industrial-grade edge computing platforms transforms real-time data processing and analytics, particularly in indoor settings [266].

Memristors, with their in-memory computation capabilities and ultra-low power requirements, enable efficient, low-latency data analysis at the edge [267]. In the context of edge computing, perovskite memristors, distinguished by their capability to facilitate self-supervised learning, demonstrate exceptional potential for advancing real-time processing of complex multimodal datasets [268]. Additionally, by modulating resistance in response to environmental stimulation, perovskite memristors can be expanded to incorporate sensing functionalities, enabling integrated detection and in-memory computation [269, 270]. This dual functionality integrates sensing and storage, enabling real-time local data analysis and reducing data transmission for efficient edge computing. The high-fidelity insights seamlessly integrate into cloud infrastructures or IoT platforms, driving systemic optimization and enabling predictive, data-driven decision-making to enhance resilience, efficiency, and sustainability.

On the other hand, direct EH from indoor light sources serves as a key solution for maintenance-free powering low-power industrial IoT nodes, including microcontrollers and edge devices. Currently, while there are reports of dye-sensitized solar cells [271] and algae-based fuel cells [272] powering microcontrollers, performing tasks ranging from floating-point calculations to complex ANNs, research on perovskite-based energy storage devices remains exceedingly rare. This may be due to a focus on applications of perovskite in areas such as PVs and memristors, where their high efficiency and unique properties are more closely aligned with current research priorities. Nonetheless, a series of recent studies have shed light on the potential of perovskite-based devices for low-power electronics, offering a promising direction for expanding their applications beyond traditional domains. A hardware platform, Riotee, integrates an advanced solar panel-based EH and management system, complemented by a highly efficient energy storage architecture [273]. The system enables battery-free operation under illuminance as low as 500 lux, maintaining ultralow power states (4.8 μA idle, 72 nA deep sleep) to support intermittent computing and low-power wireless communication. In a similar effort, the battery-free microrobot MilliMobile integrates an advanced solar-based EH and power management system, enabling intermittent autonomous mobility and long-range wireless communication under indoor lighting conditions as low as 20 W/m^2 [274]. This design renders MilliMobile highly suitable for industrial IoT applications, including intelligent warehouse management, hazardous environment data collection, and dynamic sensor network deployment. Notably, before using perovskite-powered Network-on-Chips (NoCs), strategies like fixed-point quantization, weight sharing, and dynamic voltage frequency scaling can be applied to save energy budget [275,276].

Given the exceptional performance of perovskite PV cells in EV under indoor low-light conditions, it is well-founded to suggest that adopting perovskite as an alternative harvester holds significant potential to optimize energy efficiency and bolster the operational reliability of the system. Advancements in integrated technologies such as VLC and edge computing enable PIPVs to target factory automation applications, where conveyors and robots require robust real-time positioning in dynamic operating conditions [277]. Nonetheless, stability concerns associated with perovskite materials remain a critical limitation. To address this, the development of specialized perovskite PV panels optimized for durability and reliability could be pursued [278]. Furthermore, leveraging a distributed, multi-panel design strategy could mitigate the impact of potential degradation, with the controlled production costs of perovskite materials enabling scalability and cost-effective implementation in industrial IoT scenarios [273].

Overall, IPV is emerging as the key energy self-sufficiency solution for IIoT devices, with perovskite photovoltaics demonstrating the greatest commercial potential as the fastest-growing and most compatible PV technology for IPV applications. Its application market is expected to experience explosive growth in the future. In the short term, PIPV will mainly be popularized in the consumer electronics first, including the energy supply of smart home devices, wearable devices and smart medical devices, and will replace part of the market share of button batteries. In the long term, it will gradually become the main energy supply force for industrial IoT and intelligent urban buildings, and play a key role in fields such as visible light communication, computer integration technology, and artificial intelligence automation. The industrialization process of PIPVs is confronted with two core challenges: stability and scale-up of the preparation process. In terms of stability, researchers have achieved relatively good stability through technologies such as 2D perovskite passivation, ALD technology packaging, and multi-layer composite material packaging. However, compared with traditional silicon-based solar cells, there is still a certain gap. Industrialization still needs further enhanced stability in damp and hot environments. In terms of large-scale production, the currently mature slot-die coating and roll-to-roll printing processes can achieve large-scale preparation by low-temperature solution methods. However, close attention should be paid to relatively poor device performance caused by the uneven quality of large-area films.

Conclusion and outlook

Global IIoT market expansion and decarbonization policy imperatives jointly propel PIPV technology into a strategic inflection point (Fig. 10). According to industry-proven scaling models, perovskite PV modules exhibit substantial economies of scale. Projections indicate that as production scales up from 0.3 MW/year to 1 GW/year, the cost of flexible perovskite modules will decrease from \$3.30/W to \$0.53/W [279]. Nonetheless, penetrating the mainstream solar market, where crystalline silicon modules currently maintain a \$0.40/W price point, remains economically challenging. For indoor IIoT applications, perovskite materials offer a unique value proposition that partially resolves this cost paradox. The core rationale stems from the inherent synergy between the ubiquitous expansion needs of IIoT and the exceptional indoor spectral adaptability of perovskite materials. The realization of this vision requires resolving perovskite's critical stability challenge in practical engineering applications. For instance, industry-standard hydrogenated amorphous silicon (a-Si:H) modules have demonstrated field operational lifespans exceeding a decade since the last century, whereas perovskite materials typically exhibit significant performance degradation within 1000 h [182,280]. Complementing material-level optimizations (e.g., interface engineering, defect passivation), strategic prioritization of perovskite-Si tandem architectures offers a scalable pathway to address PV manufacturing bottlenecks through industry-driven collaborations [280,281]. This innovation transcends the physical limitations of single-junction cells, integrating exceptional weak-light responsiveness, structural flexibility, and temperature-resistant stability in a unified architecture. Extended outdoor operational testing confirms that well-encapsulated perovskite-silicon tandem modules retain stable performance over six months, with V_{OC} sustained above 1.6 V and no measurable efficiency loss [282].

The industrial-scale deployment hinges on robust process standardization — a prerequisite for viable commercialization of advanced PV architectures [21]. The international standard IEC 60904-1, which specifies current–voltage (I-V) characterization procedures, explicitly excludes applicability to perovskite thin-film cells and other devices prone to sweep rate effects during testing. While the technical report IEC TR 63228 offers supplementary insights into the metrological challenges of perovskite PV devices, its limitations in methodological rigor and technical granularity preclude its adoption as definitive guidelines for indoor applications and commercial deployment. The International Electrotechnical Commission (IEC) has recently defined the indoor standard testing conditions for IPV devices under 50-1000 Lux lighting in IEC TS 62607-7-2:2023, signifying notable strides in the standardization process [22]. China's NEA has introduced the NB/T 11736-2024 specification to resolve perovskite tandem PV I-V measurement inconsistencies. This binding standard, effective June 2025, creates a harmonized benchmarking framework for PV research and development institutions. Given the distinct degradation mechanisms between perovskite and c-Si PVs, existing IEC standards inadequately assess perovskite module longevity. This discrepancy underscores the

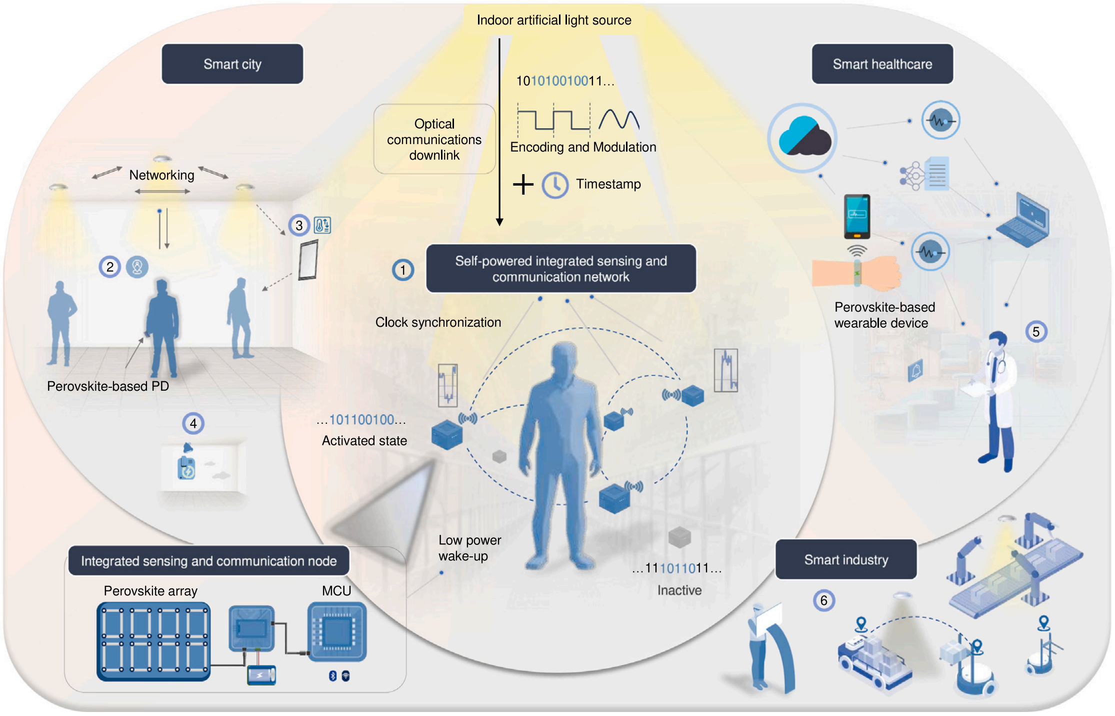

Fig. 10. Future scenarios for PIPVs: (1) the construction of a self-powered integrated sensing and communication network; (2) indoor visible light positioning using perovskite-based PD; (3) perovskite-based smart windows for indoor temperature control; (4) self-powered perovskite sensors for real-time detection of gases (e.g., CO_2, NO_2); (5) healthcare professionals receive timely data collected by perovskite-based wearable devices (e.g., blood glucose, blood pressure); (6) factory automation based on perovskite PVs and VLC technology.

critical need to develop indoor-specific energy efficiency ratings and aging test protocols to establish a robust certification framework for PIPV systems. To bridge the standardization gap for PIPVs, establishing rigorous testing protocols is imperative. These must encompass traceable light source calibration, standardized spectral and angular response characterization, and well-defined I-V measurement procedures [283, 284]. Equally critical are dedicated durability assessment methods and unified performance reporting guidelines to enable reliable device benchmarking and accelerate commercialization. Incorporating accelerated aging tests and standardized low-light efficiency rating schemes will be essential to ensure consistency across products and support market adoption.

Energy policies and multi-level incentives will accelerate the integration of PIPV and IIoT infrastructure. The U.S. Department of Energy Solar Energy Technologies Office (SETO) has explicitly outlined a strategy leveraging non-dilutive funding support and defined technology readiness level targets to achieve commercial viability competitive with incumbent technologies such as silicon-based PVs [285]. In 2024, the revised Energy Performance of Buildings Directive (EPBD) (EU/2024/1275) entered into force, establishing a legislative framework that mandates European Union (EU) member states to enhance building energy performance [286]. This policy mandates 100% renewable energy consumption in buildings, creating an optimal opportunity for the intelligent application of PIPV. Furthermore, the Chinese government aims to peak carbon emissions by 2030, further underscoring its commitment to sustainable energy practices. This policy has the potential to drive systemic innovations and market penetration of PIPV and green IoT technologies. Given the accelerated strategic moves by industry leaders such as Oxford PV, Dazheng Micro-Nano Technologies, and Halocell Energy in the IPV sector, PIPVs are projected to witness explosive growth globally commencing in 2025. We believe perovskites with high PV conversion efficiency will play a pivotal role in iPVs, driving the proliferation of ubiquitous smart technologies.

CRediT authorship contribution statement

Yongyun Li: Writing – review & editing, Writing – original draft, Formal analysis, Data curation, Conceptualization. **Juncheng Wang:** Writing – review & editing, Writing – original draft, Formal analysis, Data curation, Conceptualization. **Zhongren Jiang:** Formal analysis, Data curation. **Yimao Sun:** Formal analysis, Data curation. **Die Wu:** Formal analysis, Data curation. **Ayi Bahtiar:** Formal analysis, Writing – review & editing. **Yanbing Yang:** Writing – review & editing, Supervision, Project administration, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Dewei Zhao:** Writing – review & editing, Supervision, Project administration, Funding acquisition, Formal analysis, Data curation.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

This work was financially supported by the National Natural Science Foundation of China (Grant Nos. 62272329 and 52461160298) and the Engineering Featured Team Fund of Sichuan University (2020SCUNG102).

Data availability

Data will be made available on request.

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