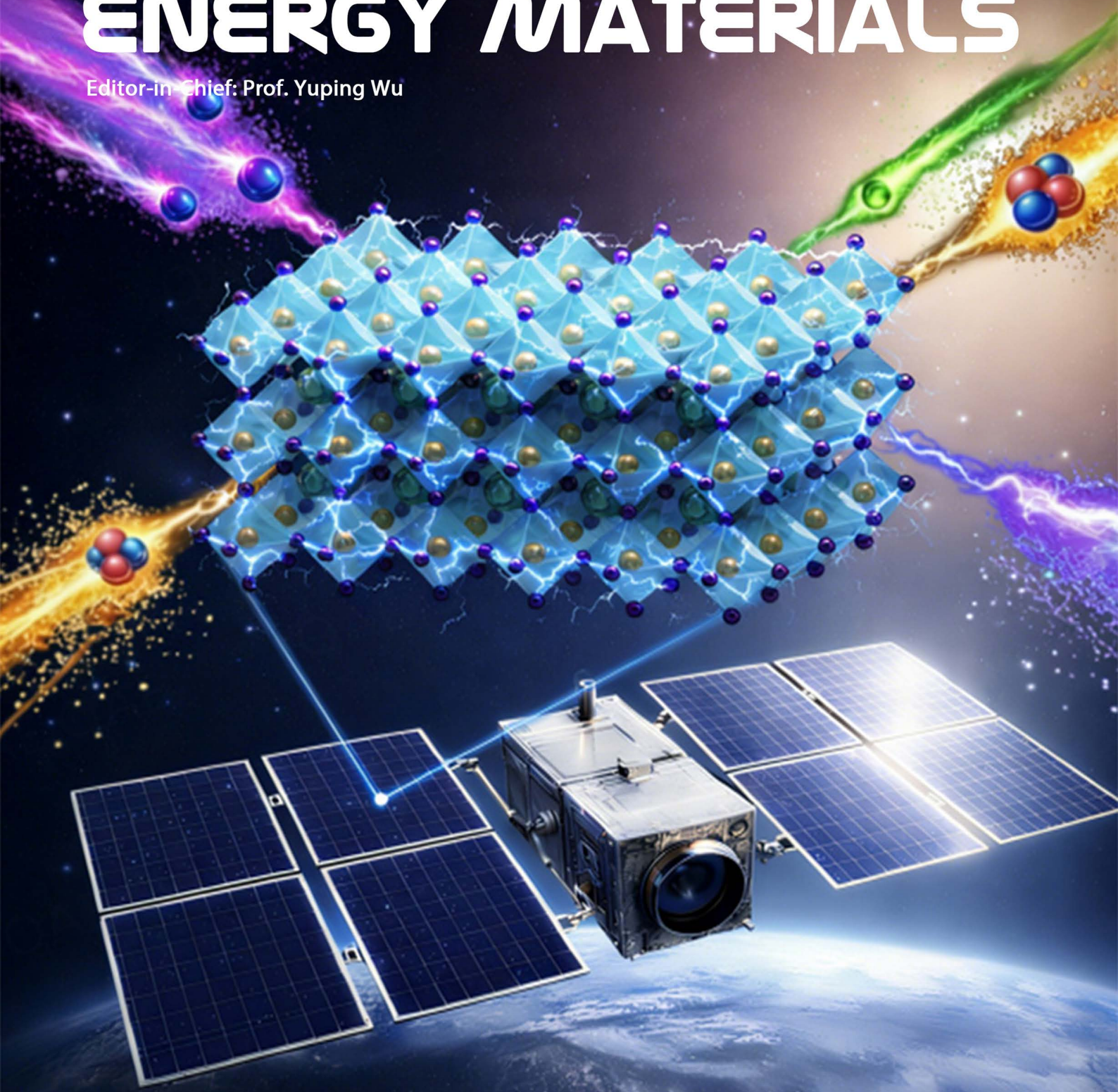


# ENERGY MATERIALS

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**Perovskite solar cells for low earth orbit space applications**

Seyeong Song<sup>#</sup>, Hye Won Cho<sup>#</sup>, Harin Kim, Mihyun Kim, Gi-Hwan Kim<sup>\*</sup>

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Seyeong Song<sup>1,#</sup>, Hye Won Cho<sup>2,#</sup>, Harin Kim<sup>3</sup>, Mihyun Kim<sup>3</sup>, Gi-Hwan Kim<sup>1,2,3,\*</sup> 

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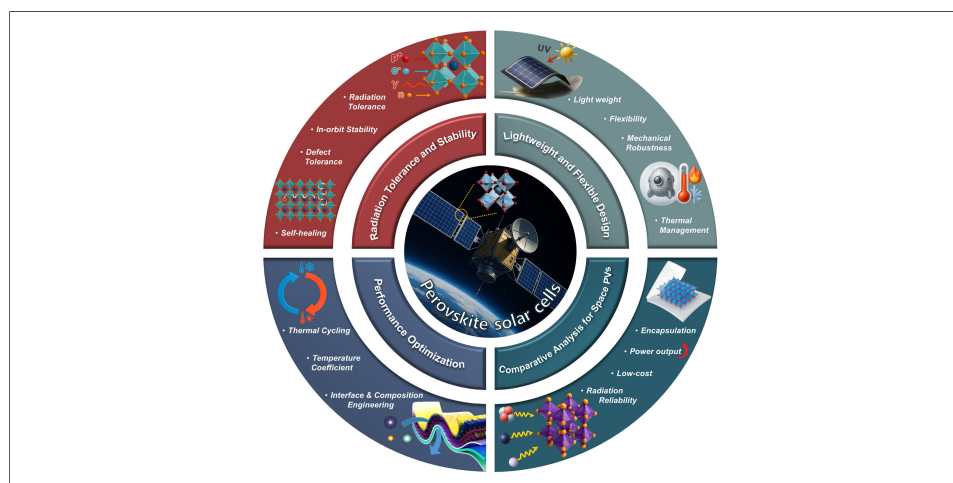
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## Abstract

Perovskite solar cells (PSCs) are a promising next-generation photovoltaic (PV) technology for space applications. Their high power-to-weight ratio, mechanical flexibility, and tunable optoelectronic properties make them particularly attractive for Low Earth Orbit (LEO) applications. PSCs demonstrate favorable behavior under low light and partial shading, as well as a unique self-healing response under certain space conditions. They also achieve specific power densities of 23-30 W g<sup>-1</sup>, representing a 10-15× improvement over conventional silicon arrays (0.5-2 W g<sup>-1</sup>) and 4-6× improvement over III-V multijunction cells (5.5 W g<sup>-1</sup>), while maintaining > 92% efficiency retention under 1 × 10<sup>16</sup> e cm<sup>-2</sup> electron irradiation. The key challenges and opportunities for PSCs in the LEO environment arise from intense ultraviolet radiation, vacuum exposure, thermal cycling, and proton irradiation. In this review, a comprehensive understanding of PSCs in the space environment is presented, including recent strategies to improve efficiency, as well as thermal and mechanical durability, while also addressing performance optimization and space PV analysis. This overview highlights the potential of perovskite photovoltaics for satellite power systems by enabling high-efficiency energy harvesting with minimal mass and processing constraints, positioning PSCs as a promising new PV paradigm for the coming decade.

<sup>1</sup>Research Institute of Molecular Alchemy, Gyeongsang National University, Jinju 52828, Republic of Korea.

<sup>2</sup>College of Space and Aeronautics, Gyeongsang National University, Jinju 52828, Republic of Korea.

<sup>3</sup>Department of Materials Engineering and Convergence Technology, Gyeongsang National University, Jinju 52828, Republic of Korea.

#Authors contributed equally.

\*Correspondence to: Prof. Gi-Hwan Kim, School of Materials Science and Engineering, Gyeongsang National University, 501 Jinju-daero, Jinju 52828, Republic of Korea. E-mail: ghkim@gnu.ac.kr

## INTRODUCTION

Since the Apollo lunar landing in 1969<sup>[1]</sup>, human interest in space exploration and aerospace technology has expanded dramatically. This milestone catalyzed sustained efforts to advance space science and engineering. A key achievement is the establishment of the International Space Station (ISS), symbolizing international collaboration and technological progress in long-term space habitation and experimentation<sup>[2,3]</sup>. In recent decades, governmental space agencies (e.g., National Aeronautics and Space Administration (NASA)<sup>[4,5]</sup>, The European Space Agency (ESA)<sup>[6]</sup>, Japan Aerospace Exploration Agency (JAXA)<sup>[7]</sup>, *etc.*) and private companies (e.g., Space X<sup>[8]</sup>, Blue Origin<sup>[9]</sup>, *etc.*) have invested heavily to accelerate space exploration and to enhance spacecraft technologies [Figure 1A]<sup>[10]</sup>. This global effort has intensified, with remarkable developments for long-duration missions, from orbital platforms to interplanetary travel. To support such missions, an understanding of the space environment, including radiation, thermal cycling, vacuum, and micrometeoroid exposure, is essential. Equally critical is the development of efficient energy systems for spacecraft and satellites, which directly influence mission longevity and functionality. In our solar system, solar energy is the most abundant and accessible power source, with photovoltaics as a key energy-harvesting technology.

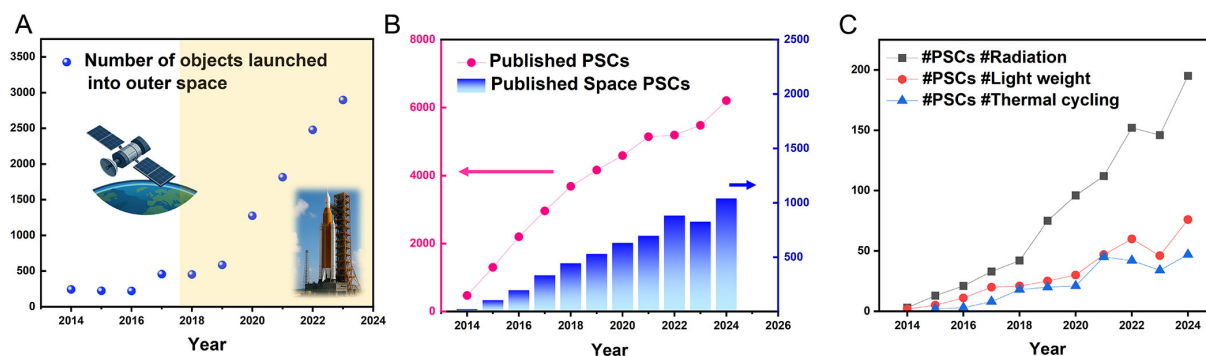
Low Earth Orbit (LEO) missions require photovoltaic (PV) systems that are efficient, lightweight, and durable in harsh space environments. Conventional space PV technologies, primarily crystalline silicon (c-Si) and multi-junction III-V cells (e.g., Gallium arsenide (GaAs)<sup>[11,12]</sup>), provide proven performances but are limited by heavy and rigid panels, high manufacturing costs, and sensitivity to radiation. In contrast, metal-halide perovskite solar cells (PSCs) have emerged as a groundbreaking thin-film PV technology, exceeding 27% power conversion efficiency (PCE) in lab-scale devices<sup>[13,14]</sup>. Since PSCs can be fabricated as ultralight flexible films with remarkable power-to-weight ratios, and their defect-tolerant crystal structure enables remarkable radiation resistance. These features establish perovskites as a next-generation power source in satellites and space systems [Figure 1B]<sup>[15]</sup>, potentially enabling large deployable solar arrays while reducing launch mass and cost.

This review provides a comprehensive overview of PSC technology specifically for LEO applications. As shown in Figure 1C, detailed studies on space PSCs have been actively reported in recent literature. Considering this, we examine key aspects such as the radiation tolerance, material stability, structural design for lightweight and flexible modules, performance under space irradiation, and a comparison with conventional space photovoltaics. Based on a technically grounded perspective, this work aims to support near-term LEO demonstrations and future standardization efforts for PSC-based space power systems.

## RADIATION TOLERANCE AND STABILITY OF PEROVSKITES IN SPACE CONDITIONS

### Intrinsic radiation damage mechanisms and self-healing

Unlike terrestrial environments, solar cells in LEO are exposed to a broad spectrum of high-energy radiations such as protons, electrons, heavy ions, Ultraviolet (UV) and X-rays, and  $\gamma$ -rays<sup>[16]</sup>, which induce severe degradation through lattice-defect formation and increased charge trapping, permanently damaging conventional solar cells [Figure 2A]<sup>[17,18]</sup>. While Si and GaAs accumulate irreversible dislocations under such irradiation<sup>[19-21]</sup>, metal-halide perovskites exhibit inherent defect tolerance and self-healing properties<sup>[22,23]</sup>. Their soft ionic lattice can absorb and dissipate radiation energy via lattice vibrations and ion rearrangements. Radiation-induced Frenkel-type defects such as vacancies or interstitials in perovskite are readily annealed due to low formation energies (0.1-0.5 eV), which is much lower than those in Si (2-5 eV)<sup>[24,25]</sup>. These mobile ionic defects can annihilate or self-heal on millisecond-to-second timescales, assisted by strong electron-phonon coupling that facilitates lattice relaxation after particle impacts [Figure 2B]<sup>[26]</sup>. As a result, perovskites rapidly return to their original crystalline state, although they are temporarily disordered by radiation. This unique radiation resilience has been observed in numerous studies on PSCs, and is absent in conventional covalent semiconductors<sup>[27]</sup>.

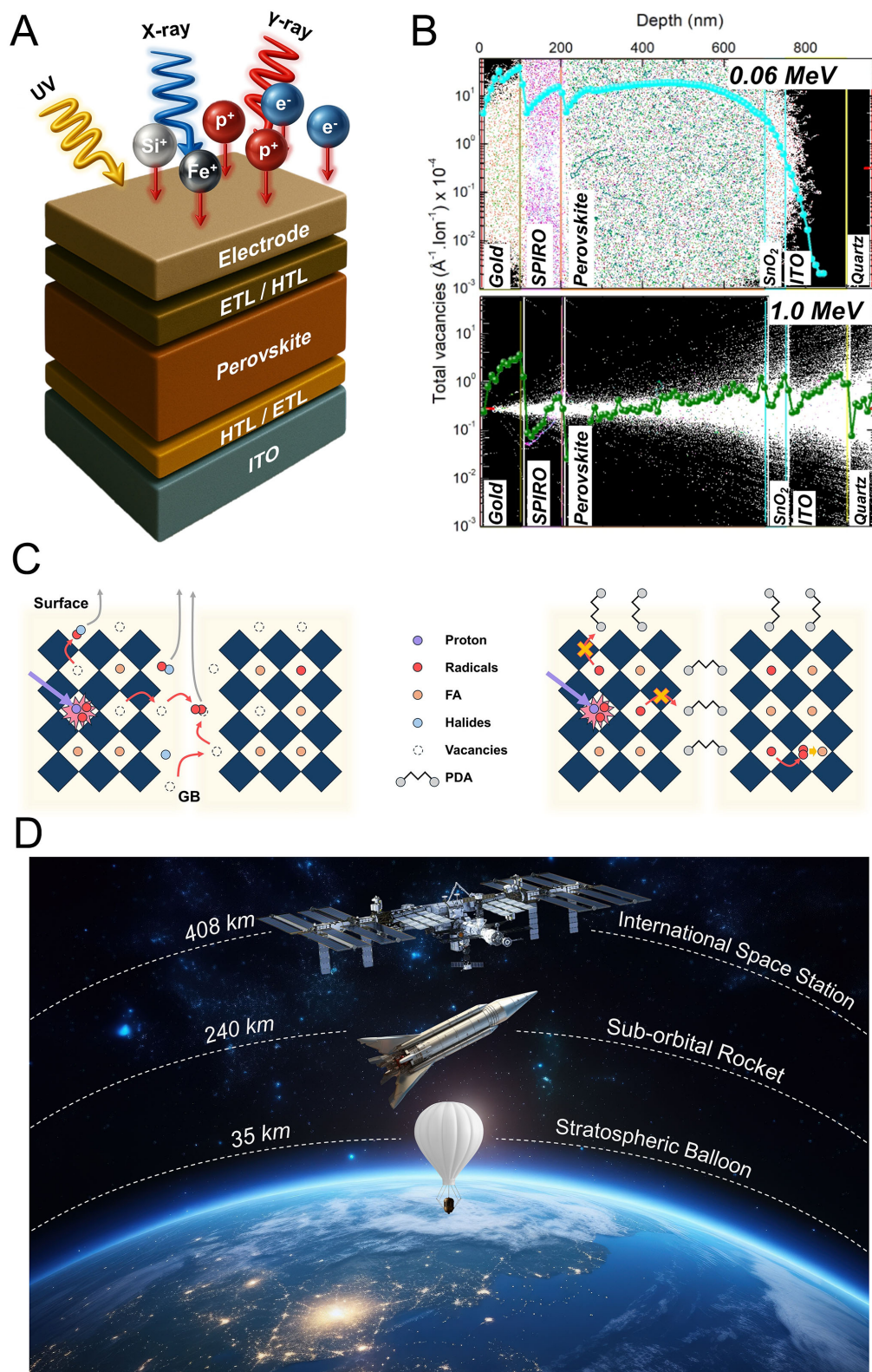


**Figure 1.** (A) Annual number of objects (CubeSat, satellite, etc.) launched into outer space<sup>[10]</sup>, reproduced under a Creative Commons license. (B) Increasing number of journal publications on PSCs and space-related PSCs, retrieved from the Web of Science on 15 September. (C) Number of journal publications for selected keyword combinations retrieved from the Web of Science on 15 September: PSCs + Radiation, PSCs + Light weight, and PSCs + Thermal cycling.

### Tolerance to protons, electrons and gamma radiation

Empirical studies have shown that PSCs maintain high performance under proton, electron, and gamma irradiation. Miyazawa *et al.* reported that Formamidinium Methylammonium Lead Iodide-Bromide (FAMAPb(IBr)<sub>3</sub>) PSCs subjected to 50 keV protons at fluences up to  $1 \times 10^{15} \text{ p cm}^{-2}$  exhibited only modest performance degradation<sup>[28]</sup>, whereas Si<sup>[29]</sup>, Copper Indium Gallium Selenide (CIGS)<sup>[30]</sup>, and GaAs<sup>[31]</sup> solar cells showed significant degradation under comparable conditions. Similarly, they reported that Poly(3-hexylthiophene) (P3HT)- Methylammonium Lead Iodide (MAPbI<sub>3</sub>)PSCs exposed to 1 MeV electron irradiation at fluences of  $1 \times 10^{16} \text{ e cm}^{-2}$  retained 92% of their initial PCE, compared to 60% retention for Si solar cells<sup>[32]</sup>. Even at higher-energy proton irradiation ( $\sim 68 \text{ MeV}$ ), PSCs exhibited minimal external quantum efficiency (EQE) degradation and no observable PbI<sub>2</sub> formation, indicating limited structural damage. Perovskites have also demonstrated robustness under gamma irradiation. Studies have shown that PSCs maintain excellent performance up to 1,000 kilorad (kRad) - equivalent to approximately 20 years of cumulative LEO exposure<sup>[33]</sup>. Boldyreva *et al.* showed negligible MAPbI<sub>3</sub> degradation, attributing most losses to substrate darkening rather than active layer deterioration and reported reversible decomposition related to volatile species release<sup>[33]</sup>. All-inorganic perovskites such as CsPbI<sub>3</sub> and CsPbBr<sub>3</sub> showed no photoluminescence (PL) degradation under gamma radiation doses up to 500 kRad. The lack of PbI<sub>2</sub> formation is attributed to the absence of volatile organic components. These findings confirm the sustainability of PSCs for LEO regions exposed to intense proton and electron flux including the South Atlantic Anomaly and polar orbits<sup>[34]</sup>.

While systematic investigations are still limited, several routes to enhanced radiation tolerance have emerged. Mixed-halide perovskites (FA<sub>0.8</sub>Cs<sub>0.2</sub>Pb<sub>1.02</sub>I<sub>2.4</sub>Br<sub>0.6</sub>Cl<sub>0.02</sub>, where FA = formamidinium) showed defect formation dependent on proton energy, followed by performance recovery via lattice self-healing under dark conditions, with radiative recombination remaining dominant over nonradiative pathways<sup>[35]</sup>. All-inorganic vacancy-ordered double perovskites Cs<sub>2</sub>CrI<sub>6</sub> have also shown remarkable robustness, retaining 90% of initial PCE after 50 keV proton irradiation of  $5 \times 10^{13} \text{ p cm}^{-2}$  and withstanding fluences up to  $10^{16} \text{ p cm}^{-2}$ <sup>[36]</sup>. The absence of hygroscopic and volatile organic cations, combined with the high mobility of Cs<sub>2</sub>CrI<sub>6</sub>, contributed to long-term stability by suppressing charge-carrier recombination at vacancy sites. Surface passivation has emerged as another effective strategy. Moreover, surface passivation has proven effective: propane-1,3-diammonium iodide (PDAI<sub>2</sub>)-treated (Cs<sub>0.22</sub>FA<sub>0.78</sub>)Pb(I<sub>0.79</sub>Br<sub>0.17</sub>Cl<sub>0.04</sub>)<sub>3</sub> devices exhibited reduced ion migration, suppressed volatile species formation, and mitigated  $\delta$ -phase CsPbI<sub>3</sub> and PbI<sub>2</sub> generation after proton irradiation [Figure 2C]<sup>[37-39]</sup>.



**Figure 2.** (A) Schematic illustration of perovskite solar cells (PSCs) exposed to various cosmic radiation sources, including protons, electrons, heavy ions, and UV, X-ray, and  $\gamma$ -ray. (B) Stopping and Range of Ions in Matter (SRIM) simulations of proton penetration of PSCs<sup>[26]</sup>. Copyright © 2024, Springer Nature. (C) Schematic diagram for the degradation mechanism and degradation suppression by passivating the perovskite surface<sup>[37]</sup>. Copyright © 2025, Elsevier. (D) In-orbit demonstrations of PSCs, from stratospheric balloon flights to sub-orbital rockets and extended operation aboard the International Space Station.



### In-orbit tests and long-term stability

Beyond laboratory experiments in controlled environments, several studies have successfully tested the durability of PSCs in real space environments [Figure 2D]<sup>[40]</sup>. The stratosphere, the second-lowest layer of Earth's atmosphere (20–50 km altitude), can be reached by high-altitude balloons<sup>[40]</sup>. Cardinaletti *et al.* launched a balloon incorporating PSCs based on MAPbI<sub>3</sub> to 32 km for over 3 h, where the temperature varied from −53.2 to 16.9 °C<sup>[41]</sup>. The devices retained 64% of initial PCE, showing degradation due to phase transition from the cubic phase to the tetragonal phase at temperatures below 57 °C and increased interfacial recombination at the electron-selecting contact.

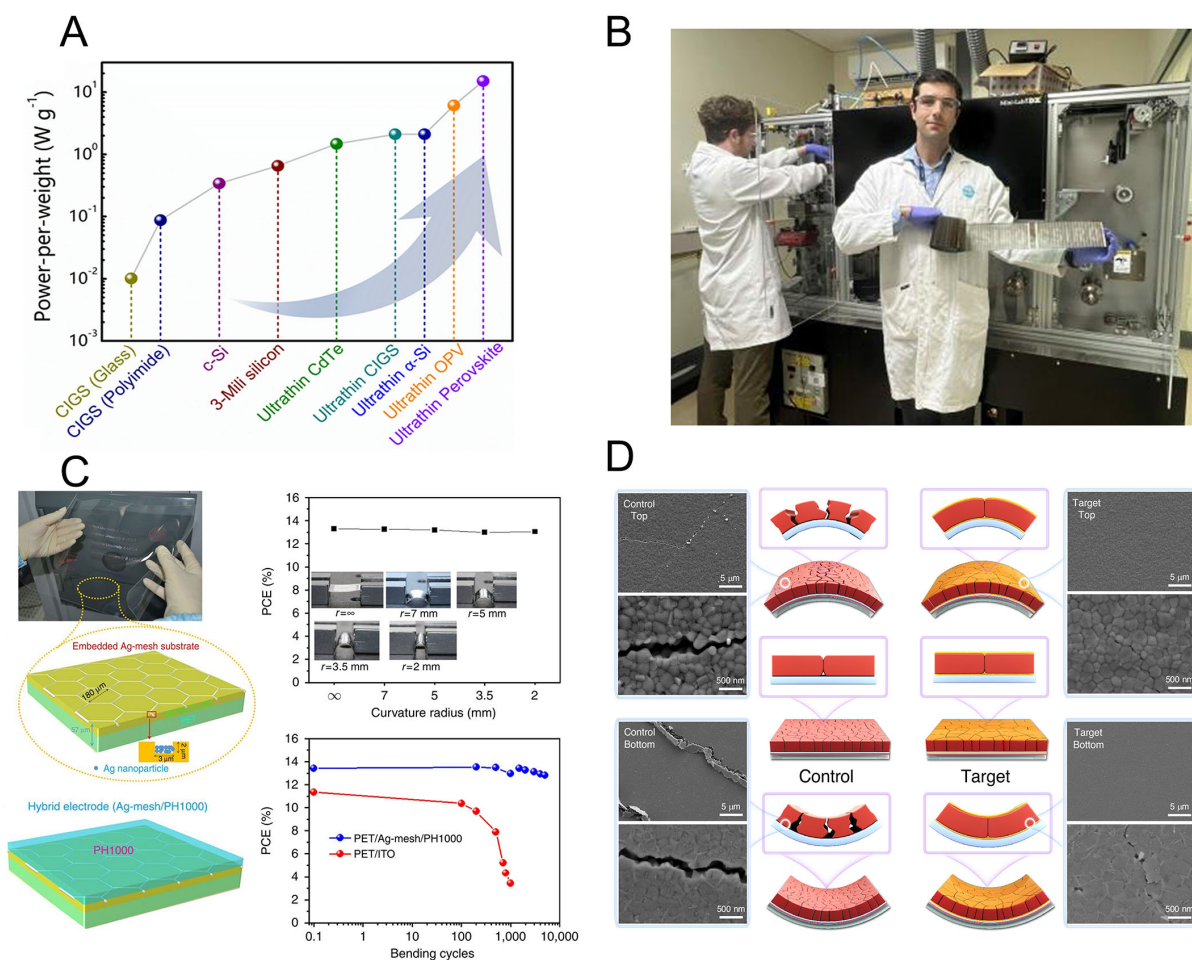
In another experiment, PSCs based on MA<sub>0.17</sub>FA<sub>0.83</sub>Pb(I<sub>0.17</sub>Br<sub>0.83</sub>)<sub>3</sub> (MA = methylammonium, FA = formamidinium) were launched on a sub-orbital rocket with a parabolic trajectory reaching ~240 km altitude, where they experienced microgravity and negligible atmospheric effects<sup>[42]</sup>. During three different illumination phases over 360 s of main measurement, the PSCs showed slight decrease in power density and reduced hysteresis due to reduced charge carrier accumulation and interfacial recombination. This difference was attributed to altered illumination conditions rather than radiation-induced damage.

Most impressively, perovskite films were subjected to continuous LEO conditions at an altitude of 408 km for 10 months on the ISS in 2020–2021<sup>[15]</sup>. The samples, fabricated with the structure of borosilicate/encapsulant/SiO<sub>2</sub>/MAPbI<sub>3</sub>/borosilicate, exhibited partial degradation: borosilicate turned yellow under electron radiation, while bubbles trapped in the encapsulant induced perovskite decomposition into PbI<sub>2</sub>. In addition, extreme thermal cycling (> 200 °C swings per orbit) induced strain in the perovskite lattice. But intriguingly, upon re-illumination on Earth, the accumulated stress gradually relaxed under sunlight, leading to effective recovery of the initial structure, reduced defects, and increased charge carrier lifetime. Overall, these in-orbit demonstrations confirm that, with proper encapsulation, perovskites can remain stable for extended durations in LEO, supporting their feasibility for multi-year satellite missions. The next steps will be multi-year orbital tests of fully operational perovskite solar arrays.

## LIGHTWEIGHT AND FLEXIBLE DESIGN CONSIDERATIONS FOR LEO APPLICATIONS

### Ultra-high specific power and power-to-weight ratio

PSCs can be fabricated with an extremely thin active layer of a few hundred nanometers<sup>[43]</sup>, and devices can be built on ultralight substrates such as plastic films, thin metal foils, or 10–50 µm glass<sup>[44–47]</sup>. Consequently, the power output per unit weight of PSC devices is higher than that of today's space solar panels. State-of-the-art flexible PSCs have demonstrated specific powers on the order of 20–30 W g<sup>−1</sup><sup>[48–50]</sup>. Kaltenbrunner *et al.* reported that a 300 nm thick PSC on a plastic foil achieved a specific power of 23 W g<sup>−1</sup> using a lightweight encapsulant, with a Cr<sub>2</sub>O<sub>3</sub>/Cr interlayer enabling air-stable operation by protecting metal contacts<sup>[48]</sup>. Zhang *et al.* also reported polyethylene terephthalate (PET) substrate-based flexible PSCs using a pyridine-promoted growth method to obtain high-quality perovskite films, achieving a PCE of 14.19% and a specific power of 23.26 W g<sup>−1</sup><sup>[51]</sup>. Thus, recent analyses indicate that fully optimized designs can achieve PSC specific powers close to ~30 W g<sup>−1</sup><sup>[52]</sup>, approaching the theoretical limits for any PV technology. This is over an order of magnitude higher than the specific power of conventional space solar technologies based on rigid silicon PV panels (0.5–2 W g<sup>−1</sup>)<sup>[53,54]</sup> and III–V multi-junction GaAs-based solar cells on lightweight substrates (~5.5 W g<sup>−1</sup>)<sup>[55–57]</sup>. Figure 3A shows the power-to-weight ratios of various PV technologies<sup>[58]</sup>. The implications for space are significant, as reducing the mass of solar arrays increases payload capacity or reduces launch costs. A perovskite PV array is lighter than a silicon PV array for the same power output. This high specific power enables large-area or rollable solar panels that were previously infeasible with heavier, rigid photovoltaics. In short, perovskite photovoltaics allows highly efficient power generation without the mass penalty of traditional PV panels, making it highly attractive for both LEO satellite constellations and deep-space probes.



**Figure 3.** (A) Comparison of the power-to-weight ratios of various photovoltaics<sup>[58]</sup> Copyright © 2023, Springer Nature. (B) Photograph of a researcher holding a roll of printed PSCs on a plastic substrate (CSIRO, Australia)<sup>[71]</sup>. (C) PSC based on PET/Ag mesh/PH1000 and its bending test, reported by Li *et al.*<sup>[76]</sup> Copyright © 2016, Springer Nature. (D) Scanning electron microscope (SEM) images of the top and bottom surfaces of a control perovskite film and a bifacial 2D-capping-layered perovskite film after 10,000 convex and concave bending cycles, reported by Jin *et al.*<sup>[80]</sup> Copyright © 2025, Springer Nature.

### Flexible substrates and mechanical robustness

Another advantage of perovskites is that they can be fabricated on flexible substrates using low-temperature processes. Unlike III-V multi-junction solar cells, which are grown on rigid wafers, PSCs can be fabricated at temperatures below  $\sim 150$  °C<sup>[48,59]</sup>, using polymer films, metal foils, or thin glass as substrates. Polyimide (Kapton) substrates tolerate space temperatures up to  $\sim 400$  °C and have excellent mechanical strength<sup>[60–62]</sup>, as well as PET<sup>[63–65]</sup>/polyethylene naphthalate (PEN) films<sup>[66,67]</sup> for low-cost roll-to-roll manufacturing. Ultrathin ( $< 1$  mm) flexible glass is another attractive substrate, offering flexibility along with superior barrier properties against moisture and oxygen ingress. Metal foils, such as titanium or aluminum, can serve as both substrate and encapsulant, providing mechanical robustness and thermal management<sup>[68–70]</sup>. The integration of flexible substrate-based solar cells indicates that the entire solar arrays can be designed for folding, rolling and stowing compactly during launch and then deploying to large areas in orbit. This is ideal for small satellites or deployable structures such as roll-out solar blankets. Figure 3B shows a flexible perovskite PV module<sup>[71]</sup>. Thus, the mechanical durability of PSCs under bending and vibration has recently attracted attention and shown promising results. Typically, flexible PSCs maintain high performance under tight bending radius and repeated flexing<sup>[72–75]</sup>. Li *et al.* reported that the PSCs on PET/Ag-mesh/poly(3,4-ethylenedioxythiophene):poly(styrenesulfonate) (PEDOT:PSS, PH1000) substrates

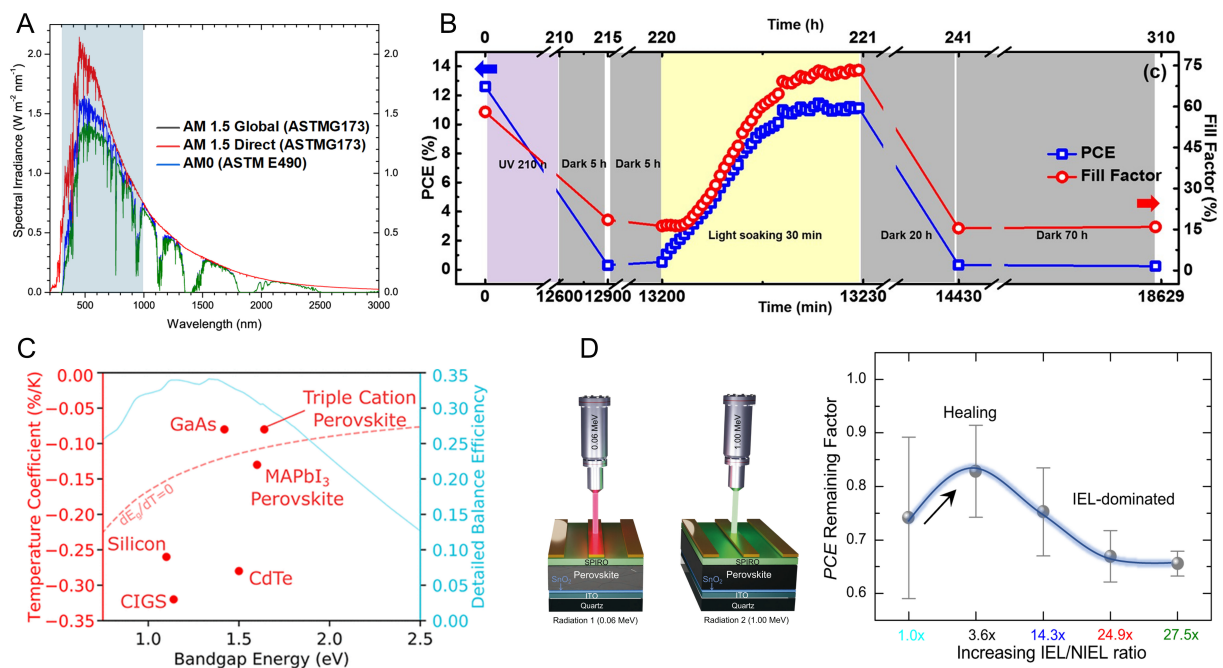
retained over 95.4% of their original efficiency after 5,000 bending cycles of 5 mm radius. Additionally, PSCs endured with a few mm curvature ( $r = \infty, 7, 5, 3.5$  and 2 mm), retaining 98.1% of the original PCE value [Figure 3C]<sup>[76]</sup>. One strategy to improve the flexibility of PSCs is to incorporate 2D/3D perovskite interfaces or strain-relieving additive microstructures, which act as micro-shock absorbers in the film<sup>[77-79]</sup>. Accordingly, introducing a bifacial 2D capping layer that cushions grain boundaries has recently been reported to achieve ~80% PCE retention after 10,000 bending cycles at a 3 mm radius [Figure 3D]<sup>[80]</sup>. The thin device is capable of being bent or rolled while continuing to generate power. The ability of PSCs to endure high vibration during launch and flexural stress during deployment without cracking is a critical prerequisite for space solar panels.

### Space-grade encapsulation and thermal management

Operating in LEO exposes solar cells not only to radiation but also to vacuum, extreme temperatures, and atomic oxygen. Notably, the exposure of perovskite photoactive layer to oxygen with light results in superoxide ( $O_2^-$ ) species, enabling deprotonate the cation of photo-excited perovskite, leading to the formation of  $PbI_2$ , water, methylamine and iodine<sup>[81]</sup>. Furthermore, atomic oxygen can cause corrosion, surface texturing, or the formation of metal oxides in the metal electrode contacts, all of which contribute to the degradation of PSCs in LEO<sup>[82]</sup>. Therefore, an effective encapsulating technology is vital to protect perovskite devices and ensure long-term stability. Space PV encapsulation must have multiple roles, including sealing the cell from vacuum and oxygen, maintaining transparency to radiation, withstanding thermal cycling, and blocking UV and atomic oxygen<sup>[83-85]</sup>. Traditional space solar cells use rigid cover glasses fused silica with anti-reflective coating for bonding over the cell, which results in significantly increased mass. Although the traditional encapsulated glasses have high transparency, UV radiation absorption and high durability, they are not suitable enough for space perovskite photovoltaics. From these reasons, more innovative lightweight encapsulations are being developed for PSCs<sup>[82,86-88]</sup>. A common approach is to use ultra-thin barrier films composed of multilayer inorganic/polymer coatings, often deposited by atomic layer deposition (ALD). For example, an ALD-grown  $Al_2O_3$  layer of a few nanometers in thickness on a polymer sheet can dramatically reduce moisture and oxygen permeation, with negligible added weight<sup>[89]</sup>. Edge sealing with low-outgassing epoxies or thermoplastics is used to prevent vacuum ultraviolet penetration and isolate the cell's edges<sup>[83,90]</sup>. Flexible glass or polyimide/fluoropolymer sheets can act as the outer layers, offering both mechanical protection and atomic oxygen resistance<sup>[91-94]</sup>. The PV encapsulation must also minimize optical loss. Therefore, the encapsulation materials are required to be transparent across the solar spectrum to avoid attenuating the incoming sunlight.

A corresponding challenge for fully flexible perovskite photovoltaics is managing thermal stress. Perovskite cells in orbit cycle through temperatures from roughly -150 °C (night side) to +150 °C (sun side). Such thermal cycling can induce expansion mismatch between the different layers of the cell, causing mechanical issues. To address this, researchers are incorporating stress-relief elements into the module stack. A practical strategy is to match the coefficients of thermal expansion (CTE) of the substrate and transport layers with that of the perovskite layer, thereby reducing differential strain<sup>[95-97]</sup>. Alternatively, introducing an elastic buffer layer or adhesive within the encapsulation can absorb some of the expansion and contraction, such as a silicon-based encapsulant that remains pliable at low temperatures<sup>[93]</sup>. Careful optimization of material selection and device engineering allows perovskite panels to tolerate repeated thermal cycling without cracking or delamination. Notably, in ISS experiments, employing a specialized encapsulation architecture comprising a thin glass superstrate and edge sealant enabled the devices to endure nearly one year of orbital cycling without degradation<sup>[98]</sup>.





**Figure 4.** (A) Solar irradiation spectra under different air mass conditions (AM0, AM1.5 direct, AM1.5 G). (B) Light-IV characteristics of PSCs showing PCE and FF under the indicated illumination conditions<sup>[103]</sup>. Copyright © 2016, Springer Nature. (C) Temperature coefficients of major photovoltaic technologies overlaid on the detailed balance limit of photovoltaic efficiency at 290 K; dashed lines indicate  $T_{PCE}$  at AM 1.5 under 1 sun and for the case without bandgap shift with temperature<sup>[117]</sup>. Copyright © 2021, American Chemical Society. (D) Irradiation of PSCs with elastic non-ionizing energy loss (NIEL)-dominated 0.06 MeV proton beam (red) and 1.0 MeV proton beam (green), and remaining PCE for PSCs irradiated at various inelastic ionizing energy loss (IEL)/NIEL ratios<sup>[26]</sup>. Copyright © 2024, Springer Nature.

## PERFORMANCE OPTIMIZATION UNDER SPACE IRRADIATION CONDITIONS

### Adapting to the AM0 space solar spectrum

In space, solar cells are exposed to unfiltered sunlight characterized by the Air Mass 0 (AM0) spectrum, which has higher light intensity and a distinctly different spectral shape compared to the standard AM1.5G spectrum commonly used on Earth. Key differences include: (i) Higher UV flux: The UV photon flux is significantly higher under the AM0 spectrum, representing approximately 8% of the total photon power compared to about 4% under AM1.5G, since there is no atmospheric filtering to absorb a large portion of incoming UV radiation; (ii) No atmospheric absorption bands: The spectrum is continuous from 250 to 2,500 nm; (iii) Over 36% higher intensity: Sunlight intensity is up to 1,366 W m<sup>-2</sup> in space compared to around 1,000 W m<sup>-2</sup> at Earth's surface<sup>[99]</sup>. These differences indicate that solar cells in LEO must withstand high UV conditions while also utilizing a broader irradiance range in the UV-Blue region [Figure 4A].

Effective utilization of UV-Blue photons is one of the critical issues for PSCs in LEO<sup>[100–102]</sup>. PSCs that absorb the UV-Blue region can be optimized through compositional tuning of perovskite materials and device architecture engineering. Promising approaches include employing slightly wide-bandgap perovskites (1.8–2.0 eV) and fabricating tandem device architectures to more effectively harvest UV-Blue photons. CH<sub>3</sub>NH<sub>3</sub>PbI<sub>3</sub>-based PSCs have recently been reported to demonstrate improved UV stability and effective absorption of high-energy UV photons without rapid device degradation [Figure 4B]<sup>[103]</sup>. Tandem solar cells based on perovskite/silicon<sup>[104,105]</sup> or all-perovskite<sup>[106,107]</sup> have also been explored as potential candidates for LEO applications. These devices are generally configured with a top perovskite sub-cell featuring a wide bandgap of 1.7–1.8 eV to harvest high-energy photons, and a bottom Si or narrow-bandgap perovskite sub-cell (1.1–1.2 eV) to absorb longer-wavelength photons extending into the infrared region. Such tandem

solar cells could maximize performance under the AM0 environment in space, potentially achieving efficiencies beyond the single-junction limit of 30%-35%<sup>[108]</sup>. In addition, another important strategy in device engineering is the introduction of integrated UV filters or UV-tolerant charge transport layers, since photo-induced degradation of perovskite thin films occurs at short wavelengths, including the UV range<sup>[109]</sup>. For example, metal-oxide electron transport layers, such as TiO<sub>2</sub> or SnO<sub>2</sub>, were widely used to filter out the most damaging UV wavelengths and protect the chemical bonds in the perovskite film from direct exposure to high-energy UV light due to their wide bandgap and cutting UV region<sup>[110]</sup>. In addition, recent studies have raised concerns that oxygen-vacancy-related Ti ions of TiO<sub>2</sub> under UV illumination can lead to photocarrier losses<sup>[100]</sup>, and SnO<sub>2</sub> often exhibits more severe charge recombination due to its lower conduction band<sup>[111]</sup>, along with degradation during high-temperature processes<sup>[112]</sup>. Accordingly, emerging research efforts are underway to develop innovative charge transport materials with improved UV durability<sup>[113,114]</sup>. Thus, compositional engineering of perovskites allows their absorption to be tuned for the space solar spectrum, while PSCs can selectively absorb a broad range of wavelengths with high device stability through appropriate choice of materials and device architecture.

### Temperature coefficients and thermal cycling performance

Due to unpredictable solar phenomena, such as solar flares and coronal mass ejections, as well as the orbital motion of spacecraft alternating between light and dark environments, thermal fluctuations become more intense. The space temperature range of -185 to -150 °C, as specified by the American Institute of Aeronautics and Astronautics in AIAA S-111A-2014, “Qualification and Quality Requirements for Space-Qualified Solar Cells”<sup>[115]</sup>, requires that solar cells possess high thermal tolerance across a broad operational range (-150 to +120 °C) to maintain stable and reliable performance in orbit. The temperature coefficient ( $T_{PCE}$ ) is an important parameter for evaluating and improving the thermal cycling performance of PSCs. It is defined as the change in efficiency or voltage with temperature. For example, c-Si solar cells have a relatively low  $T_{PCE}$  of about -0.4 to -0.25%°C<sup>-1</sup>, indicating a significant efficiency drop with increasing temperature due to their high sensitivity to thermal effects. GaAs-based solar cells, commonly used in current space applications, have a  $T_{PCE}$  of approximately 0.1 ~ -0.05%°C<sup>-1</sup> [Figure 4C]. PSCs generally exhibit a less negative  $T_{PCE}$  of around -0.2%°C<sup>-1</sup><sup>[116]</sup>. Notably, Moot *et al.* reported a significantly improved  $T_{PCE}$  of -0.08%°C<sup>-1</sup> for PSCs, achieved through compositional engineering of the perovskite and optimization of the charge transport layers<sup>[117]</sup>. This interesting result can be attributed to the unique properties of perovskites, as discussed below. (1) The bandgap of lead-halide perovskites typically increases with temperature, resulting in an improvement in the open-circuit voltage ( $V_{oc}$ ) of PSCs or a smaller  $V_{oc}$  drop compared to other solar cells. Consequently, PSCs exhibit reduced thermal voltage losses upon heating, partially offsetting the performance degradation commonly observed in any commercial solar cells; (2) Although the carrier density in perovskites varies depending on film engineering, device architecture<sup>[118,119]</sup>, and application, high-quality MAPbI<sub>3</sub> perovskites have a lower carrier density<sup>[120]</sup> compared to Sn-based narrow-bandgap, highly doped perovskites<sup>[121]</sup>. This lower carrier density contributes to suppressed charge recombination and reduced performance loss with increasing temperature. From a practical view, PSCs have high potential for thermal tolerance with increased environmental temperatures<sup>[122,123]</sup>, such as prolonged sunlight exposure up to ~85 °C and repeated thermal cycling, compared with conventional solar cells<sup>[124-126]</sup>. Reportedly, the PCE of PSCs decreased by only 5%-10% at 65 °C conditions, whereas silicon solar cells showed a PCE reduction of approximately 20% relative to their initial room-temperature performance<sup>[117]</sup>.

Basically, the perovskite PV materials undergo phase transitions in response to temperature variations, leading to changes in crystal structure, structural disorder, and charge-carrier dynamics. For example, MAPbI<sub>3</sub> undergoes well-known phase transitions from the orthorhombic ( $\gamma$ ) phase below ~-115 °C, to the tetragonal ( $\beta$ ) phase between -115 and ~60 °C, and finally to the cubic ( $\alpha$ ) phase above ~60 °C<sup>[127,128]</sup>. As temperature increases, lattice symmetry increases, leading to enhanced dynamic disorder and stronger

electron-phonon coupling<sup>[129]</sup>. This enhances ionic mobility and can lead to increased non-radiative recombination. At low temperatures (below  $-100\text{ }^{\circ}\text{C}$ ), carrier mobility is reduced due to localized states and suppressed lattice motion<sup>[130]</sup>, while at high temperatures ( $> 80\text{ }^{\circ}\text{C}$ ), thermal degradation and  $\text{MA}^+$  instability become dominant concerns.  $\text{FAPbI}_3$  tends to undergo phase transitions from tetragonal ( $\beta$  phase, below  $\sim -140\text{ }^{\circ}\text{C}$ ), to hexagonal ( $-140$  to  $\sim 30\text{ }^{\circ}\text{C}$ ), and then to cubic ( $\alpha$  phase, above  $\sim 30\text{ }^{\circ}\text{C}$ )<sup>[127]</sup>. Under high-temperature conditions below  $\sim 150\text{ }^{\circ}\text{C}$  and in the presence of moisture,  $\text{FAPbI}_3$  exhibits instability, with structural distortion involving transformation from the  $\alpha$  phase to the non-perovskite  $\delta$  phase, because the  $\text{FA}^+$  cation size leads to dynamic fluctuations at intermediate temperatures<sup>[131,132]</sup>. At temperatures above  $100\text{ }^{\circ}\text{C}$ , phase decomposition and trap-assisted recombination further increase.

Consequently, the thermal cycling endurance of PSCs can be enhanced through interface engineering between 2D and 3D perovskite layers, the introduction of self-healing compositions, and suppression of phase transitions via compositional engineering of perovskite materials<sup>[133,134]</sup>. In addition, it has been reported that the use of 2D capping layers and strain-relieving buffer layers prevents light-induced phase segregation in mixed-halide perovskites under high-temperature conditions. These studies suggest promising strategies for enhancing the thermal endurance of PSCs in space environments. On the other hand, to prevent device degradation caused by extremely high and low temperatures, it is also essential to develop thermally robust materials and to consider additional thermal management strategies, such as reflective coatings, thermal straps, and heat-insulating films.

### Low-light and partial illumination performance

In dark space environments encountered during deep-space exploration, eclipses, and on planetary surfaces beyond direct sunlight, solar cells are required to operate under low-light conditions. Notably, PSCs can perform efficiently at low irradiance while maintaining relatively high  $V_{oc}$  and efficiency, owing to their superior electronic properties, such as low non-radiative recombination rates and high charge-carrier mobility<sup>[135–137]</sup>. Corresponding to the characteristics of PSCs, Glowienka *et al.* investigated a light-intensity-dependent analysis of current density-voltage ( $J$ - $V$ ) parameters to identify the mechanisms in PSCs, such as bulk or interfacial recombination and series or shunt resistance<sup>[138]</sup>. Glowienka and Raifuku *et al.* reported that PSCs exhibited superior performance by maintaining higher  $V_{oc}$  value under  $0.1\text{ mW cm}^{-2}$  illumination, compared to more severe  $V_{oc}$  drop observed in c-Si solar cells, which exhibit a higher ideality factor under low-light conditions<sup>[138,139]</sup>. Additionally, Guo *et al.* reported that narrower-bandgap perovskites can efficiently harvest light at low irradiance<sup>[140]</sup>. These reports indicate that PSCs can perform well in space environments with weak sunlight, even under shadowed conditions or partial illumination of PV panels. Moreover, PSC modules may mitigate non-uniform power generation in PV arrays through bypass diode integration and segmentation of the system into smaller cells<sup>[141,142]</sup>.

### Radiation-induced performance enhancements

The response of perovskites to space radiation, including protons, electrons,  $\gamma$ -rays, and neutrons, demonstrates their promising tolerance and unique self-healing characteristics. The intriguing and unique recovery phenomenon about perovskite is that device performance can be temporarily improved under certain radiation exposure. This has been attributed to radiation-induced defects passivating pre-existing trap sites in the material. For example, some studies reported that PSCs exhibited a slight increase in fill factor (FF) and efficiency immediately after exposure to a low, followed by a higher fluence of proton irradiation ( $0.9 \times 10^{13}$ – $3.8 \times 10^{13}\text{ cm}^{-2}$ ) [Figure 4D]<sup>[26]</sup>. The proposed hypothesis is that ionizing radiation can displace halide ions into vacancy sites and relieve lattice strain, effectively “healing” certain defects. In particular, Lang *et al.* demonstrated the proton robustness of  $\text{MAPbI}_3$  by investigating the positive-intrinsic-negative (p-i-n) solar cells, resulting in stable  $V_{oc}$  and FF at high proton energy of ( $\sim 10^{13}$  protons  $\text{cm}^{-2}$ ) and slightly decreased short-circuit current density ( $J_{sc}$ )<sup>[23]</sup> with optical degradation of



glass<sup>[143,144]</sup>. They also demonstrated that some irradiated PSCs enhanced  $J_{sc}$  and efficiency post-irradiation, attributed to a self-healing mechanism. Proton irradiation may dissociate C-H and N-H bonds, releasing  $H^+$  ions, which subsequently passivate defect sites once irradiation, restoring or even improving device performance. According to a report by Lang *et al.*, exposure to a 20 MeV proton beam contributes to passivation of deep traps at the perovskite/ $TiO_2$  interface, resulting in improved charge collection with slightly increased FF and  $V_{oc}$ <sup>[145]</sup>.

In the case of  $\gamma$ -rays, which are highly penetrating and difficult to shield<sup>[146]</sup>,  $Cs_{0.15}MA_{0.10}FA_{0.75}Pb(Br_{0.17}I_{0.83})$  exhibits PL enhancement and red-shift under up to 5,000 gray (Gy), with Hoke effect indicating halide segregation and bandgap formation under illumination. Boldyreva *et al.*<sup>[147]</sup> also reported a reversible mechanism in perovskites: upon irradiation,  $MAPbI_3$  decomposes into methylammonium iodide (MAI) and  $PbI_2$ , with MAI further breaking down into  $NH_3$  and  $CH_3I$ .  $\gamma$ -rays cleave the C-I bond, producing  $CH_3^+$  and  $I^-$ , which may passivate iodine vacancies or reform MAI via reactions with  $NH_3I^+$ , ultimately restoring the perovskite phase<sup>[147-149]</sup>.

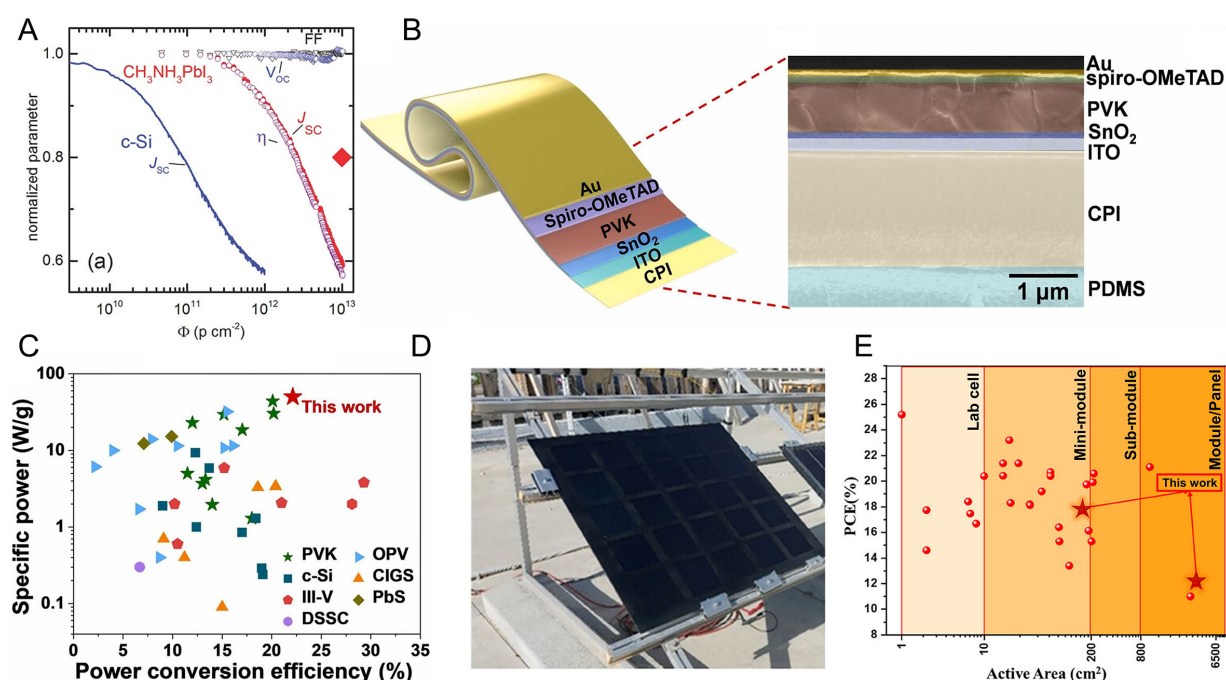
Fast neutrons with energy  $> 10$  MeV are generated through collisions between incoming plasma or cosmic rays and the atmosphere's constituents or materials comprising the spacecraft<sup>[150,151]</sup>. Paternò *et al.* demonstrated  $MAPb(I_{3-x}Cl_x)$ -based p-i-n PSCs using a spallation neutron source at the ISIS Neutron and Muon Source facility (Rutherford Appleton Laboratory, UK), simulating  $\sim 80$  years of fast neutron exposure equivalent to levels experienced on the ISS ( $1.5 \times 10^9$  particles  $cm^{-2}s^{-1}$ )<sup>[152]</sup>. The PSCs exhibited more stable PV performance under neutron irradiation than under illumination, due to neutron bombardment<sup>[152]</sup>.

This counterintuitive self-healing under radiation does not occur in conventional semiconductors, which typically suffer cumulative damage under such conditions. Although applying radiation to enhance PSC performance is impractical, this phenomenon highlights the unique radiation response of perovskites, including a radiation-annealing threshold beyond which degradation begins. Identifying the optimal radiation dose window that triggers beneficial defect healing without causing additional damage is currently under investigation. By exploiting these unique properties, PSCs can be refreshed during service via natural background radiation or controlled radiation. Overall, the self-healing of perovskites under radiation provides potential for their long-term performance in space.

## COMPARATIVE ANALYSIS WITH CONVENTIONAL SPACE PHOTOVOLTAIC TECHNOLOGIES

### Radiation hardness and reliability

To withstand prolonged radiation exposure in space, solar cells require physical protection such as cerium-doped glass<sup>[153]</sup> or fused silica<sup>[154]</sup>. Even with such shielding, ionization and lattice displacement gradually degrade device performance and shorten PV lifetimes. PSCs exhibit exceptional intrinsic radiation hardness compared with conventional silicon or III-V based photovoltaics [Figure 5A]. For instance, Si solar cells typically lose 50%-80% of their output under proton irradiation at doses as low as  $\sim 1 \times 10^{10}$  p  $cm^{-2}$ , due to defect formation<sup>[23]</sup>. GaAs solar cells show similar vulnerability, with maximum power reduced by 50%-60% under fluences of  $\sim 1 \times 10^{16}$  e  $cm^{-2}$  or  $1 \times 10^{12}$  p  $cm^{-2}$ <sup>[17]</sup>, and pronounced degradation of electroluminescence and  $V_{oc}$  arising from nonradiative recombination centers induced by electron irradiation, even at fluence as low as  $3 \times 10^{13}$  e  $cm^{-2}$ <sup>[155]</sup>. By comparison, PSCs have maintained their initial performance even under higher proton fluences reaching  $1 \times 10^{15}$  p  $cm^{-2}$ . This inherent radiation hardness suggests that PSCs could potentially operate in orbits or mission durations without the need for heavy shielding, enabling lighter and simpler arrays with improved specific power. However, it is important to note that the long-term reliability of PSCs remains unproven over multi-year timescales, especially compared with the extensive flight heritage accumulated over decades for Si and III-V solar cells<sup>[156,157]</sup>. Therefore, extensive qualification testing for PSCs is essential to validate that no unexpected failure modes arise, including



**Figure 5.** (A) Proton radiation tolerance of  $\text{CH}_3\text{NH}_3\text{PbI}_3$ -based PSCs compared to a c-Si photodiode as a function of the proton dose,  $\Phi$ .<sup>[23]</sup> Copyright © 2016, Wiley. (B) Device architecture and cross-sectional SEM images of an ultra-thin flexible PSC achieving a specific power of  $50 \text{ W g}^{-1}$ .<sup>[159]</sup> Copyright © 2024, Elsevier. (C) Summary and comparison of PCE and weight-specific power density of ultra-thin solar cells.<sup>[159]</sup> Copyright 2024, Elsevier. (D) Photograph of a realized perovskite panel installed for outdoor characterization.<sup>[171]</sup> Copyright © 2025, Wiley. (E) Summary of PCEs for perovskite-based photovoltaics across various device sizes.<sup>[171]</sup> Copyright © 2025, Wiley.

extended thermal cycling or micrometeoroid impacts on thin films. Nevertheless, the remarkable radiation tolerance of perovskites highlights their promise as candidates for more robust spacecraft power systems.

### Specific power and deployability

In terms of specific power, PSCs already surpass conventional solar cells. State-of-the-art multi-junction panels based on gallium indium phosphide/gallium indium arsenide/germanium ( $\text{GaInP/Ga(In)As/Ge}$ ) triple junctions<sup>[57]</sup> can achieve a specific power of  $1.3 \text{ W g}^{-1}$  by reducing the cell thickness from 150 to 50  $\mu\text{m}$ . By comparison, silicon arrays typically provide less than  $0.1 \text{ W g}^{-1}$ .<sup>[158]</sup> In contrast, ultra-thin PSCs on 1–3  $\mu\text{m}$  colorless polyimide have achieved  $50 \text{ W g}^{-1}$  at the laboratory scale without encapsulation [Figure 5B]<sup>[159–161]</sup>. Even when accounting for the mass of deployment structures and wiring, perovskite-based systems can deliver specific power an order of magnitude higher than traditional arrays, potentially enabling up to tenfold reductions in cost for equivalent power generation [Figure 5C]. This exceptionally high specific power is particularly advantageous for mass-constrained missions, including small CubeSats or ambitious concepts such as solar sails<sup>[162,163]</sup>. Additionally, the flexible or rollable form factor of perovskite modules allows much more compact stowage compared to rigid silicon or GaAs panels<sup>[164]</sup>. With lighter, larger deployable arrays, substantially higher on-orbit power generation becomes feasible. Although research on flexible conventional solar cells, such as thin GaAs on Kapton<sup>[165]</sup>, is ongoing, these approaches remain costly and relatively heavy. In contrast, perovskites offer the potential to reduce launch costs while increasing available power in orbit.

### Efficiency and power output

Single-junction perovskite cells have achieved record efficiencies of 27.0%<sup>[14,166]</sup> at the lab scale, comparable to silicon ( $\sim 27\%$ )<sup>[15,167]</sup> and approaching those of state-of-the-art triple-junction GaAs cells ( $\sim 39\%$  under 1 sun,

AM1.5G<sup>[168]</sup>). Although GaAs multi-junctions still maintain extremely high efficiencies of ~34% under the AM0 space spectrum<sup>[168]</sup>, the performance gap can narrow - or even reverse - after radiation exposure and thermal cycling, as GaAs cells are expected to degrade by nearly 25% over several years in orbit<sup>[169]</sup>. Beyond single-junction devices, tandem PSCs have shown remarkable progress, with efficiencies of 29.1% for two-terminal perovskite-perovskite<sup>[106]</sup> and 34.85% for perovskite-silicon tandem devices<sup>[14]</sup>. The latter is comparable to III-V solar cells, while offering the potential for much higher specific power due to the lightweight nature of perovskites. However, scaling PSCs from laboratory-scale devices to large-area modules (> 100 cm<sup>2</sup>) without significant efficiency loss remains a challenge<sup>[170]</sup>. Recently, perovskite panels with an aperture area of 0.73 m<sup>2</sup> and 12.0% efficiency were demonstrated by interconnecting 156 cm<sup>2</sup> modules with individual efficiencies of 16.3% [Figure 5D and E]<sup>[171]</sup>. These advances highlight the rapid progress toward large-area PSCs, although they still lag behind III-V multijunction panels with proven meter-scale fabrication<sup>[172]</sup>. Continued improvements in perovskite efficiency, combined with their inherent radiation tolerance, could substantially reduce the cost of space-grade solar power.

### Cost and manufacturing

One of the most compelling advantages of PSCs for space applications is their potential for dramatic cost reduction. Conventional space-grade III-V multi-junction solar cells remain extremely expensive - typically several hundred to over one thousand USD W<sup>-1</sup> - due to epitaxial growth on costly substrates and limited mass production<sup>[173]</sup>. c-Si modules are cheaper at terrestrial module levels (0.2–0.4 USD W<sup>-1</sup>), but radiation-hardened silicon architectures adapted for space also incur elevated costs because of specialized processing<sup>[174]</sup>. PSCs, in principle, can be fabricated using scalable solution-based or roll-to-roll techniques<sup>[175]</sup>, with preliminary estimates suggesting module manufacturing costs below 0.1 USD W<sup>-1</sup> once stabilized high-efficiency modules are realized<sup>[176–178]</sup>. More recent technoeconomic modeling studies indicate that, under favorable stability and scale-up scenarios, the levelized cost of electricity (LCOE) for PSCs could fall in the range of 0.04–0.25 USD kWh<sup>-1</sup>, making them competitive with c-Si and III-V PVs in applications such as satellite mega-constellations, where deploying large quantities of solar panels renders traditional PV economically unfeasible<sup>[179]</sup>. Lower PV costs could also expand mission design options, enabling concepts such as expendable solar arrays or increased on-board power availability for electric propulsion systems<sup>[180]</sup>. However, these projections remain theoretical in the space context. The transition from laboratory-scale devices to qualified space-grade modules will require extensive testing for encapsulation, radiation hardening, and long-duration operation. Initial deployments are therefore likely to be expensive, mirroring the early trajectory of other PV technologies. Nonetheless, the ability to leverage terrestrial thin-film manufacturing infrastructure, combined with the intrinsic advantages of PSCs in mass per watt, presents a credible pathway toward cost breakthroughs in space photovoltaics.

### Challenges and considerations

Sections "Adapting to the AM0 space solar spectrum" - "Radiation-induced performance enhancements" have highlighted the performance characteristics of PSCs relevant to space applications. As summarized in Table 1, PSCs demonstrate competitive efficiency, specific power, and radiation tolerance compared with GaAs- and Si-based photovoltaics, while remaining at an earlier stage of technological maturity. Despite these attractive properties, PSCs face several challenges before they can be adopted as mainstream space technologies. The foremost challenge is long-term operational stability. Although radiation-induced degradation in PSCs is often less pronounced than in conventional solar cells, the combined influences of multiple space stressors - including high vacuum, ultraviolet irradiation, and repeated thermal cycling - over multi-year missions remain insufficiently characterized. Robust encapsulation will be essential, as even minor breaches can accelerate degradation pathways, for example, through residual outgassing or UV-induced chemical reactions<sup>[181]</sup>. By contrast, GaAs solar cells have demonstrated decades of in-orbit flight heritage with well-understood failure modes, which underpins space agencies' confidence in their use<sup>[182,183]</sup>.



**Table 1. Quantitative comparison of photovoltaic (PV) technologies for space applications**

PV technology	Initial efficiency (%)	Specific power (W g <sup>-1</sup> )	Radiation tolerance	10-year performance retention <sup>1</sup>	Manufacturing cost (USD W <sup>-1</sup> )	TRL <sup>(186)</sup> 2
c-Si	22-27 <sup>(167)</sup>	0.1-0.4 <sup>(158)</sup>	Low (severe degradation > 10 <sup>12</sup> p cm <sup>-2</sup> ) <sup>(23)</sup>	70%-85% <sup>(157)</sup>	0.2-0.4 <sup>(174)</sup>	9
III-V (GaAs, multi-junction)	30-39 <sup>(168)</sup>	0.3-1.5 <sup>(57)</sup>	Medium (significant degradation > 10 <sup>13</sup> p cm <sup>-2</sup> ) <sup>(155)</sup>	80%-90% <sup>(157)</sup>	150-1,000 <sup>(173)</sup>	9
Perovskite	25-27 <sup>(166)</sup> , 34.8 <sup>(14)</sup> (tandem)	2-50 <sup>(159)</sup>	High (tolerant up to -10 <sup>16</sup> p cm <sup>-2</sup> ) <sup>(28)</sup>	Unvalidated	< 0.1 (target) <sup>(176)</sup>	4, 5

<sup>1</sup>Representative in-orbit performance retention values from satellite telemetry; <sup>2</sup>Technology Readiness Level (4: component or breadboard validation in laboratory environment, 5: component or breadboard validation in relevant environment, 9: actual system “flight prove” through successful mission operations).

Consequently, PSCs are likely to be deployed initially in less critical roles or as supplemental power sources until their reliability is firmly established.

Thermal tolerance represents another limitation. PSC materials and device architectures have yet to demonstrate stability under sustained high-temperature operation (> 150 °C), where phase transitions or decomposition are likely to occur. In contrast, Si and GaAs solar cells can endure higher temperatures, albeit with some efficiency loss<sup>[184]</sup>. Effective thermal management - through optical reflectors or sun-tracking to avoid overheating - will be indispensable in PSC array design. Integration and scalability also remain unresolved. The reliable interconnection of many thin-film cells into deployable arrays is an engineering challenge. Furthermore, fabricating large-area modules (> 100 cm<sup>2</sup>) without performance loss remains a work in progress and must be addressed before operational deployment can be realized<sup>[185]</sup>.

## CONCLUSION AND OUTLOOK

Overall, PSCs combine high efficiency, exceptional specific power, and intrinsic radiation tolerance, positioning them as strong alternatives to conventional Si- and GaAs-based solar cells for space PV applications, particularly in LEO. Experimental studies consistently indicate that PSCs experience less severe radiation-induced degradation than traditional photovoltaics, with partial performance recovery enabled by defect-tolerant lattice dynamics. However, the lack of comprehensive device-level validation under fully representative LEO conditions highlights the early stage of technological maturity. Progress toward space deployment will therefore depend on coordinated efforts to establish robust encapsulation, thermal management, and space-qualification pathways through targeted demonstration missions.

## DECLARATIONS

### Authors' contributions

Made substantial contributions to the conception of this mini-review and proposed its topic: Kim, G. H.

Conducted the literature survey and prepared the manuscript: Song, S.; Cho, H. W.

Collected literature and summarized the reports: Kim, H.; Kim, M.

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## Conflicts of interest

All authors declared that there are no conflicts of interest.

## Ethical approval and consent to participate

Not applicable.

## Consent for publication

Not applicable.

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