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Tin-based halide perovskite nanocrystals: challenges, opportunities, and future directions

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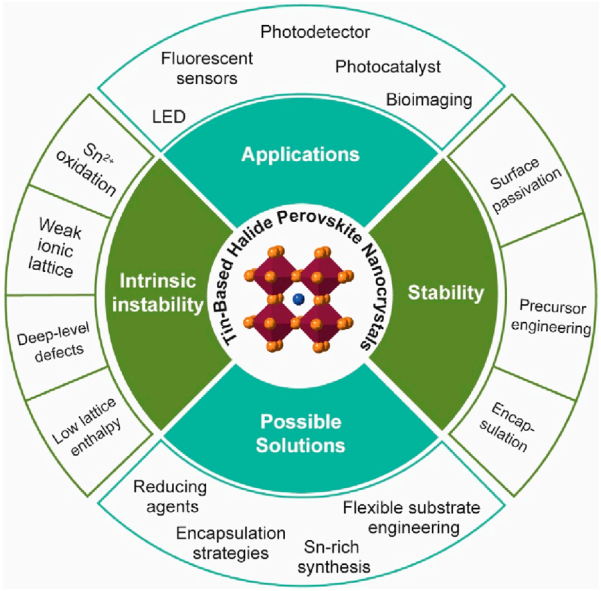
Tin halide perovskite nanocrystals (THP-NCs) provide a pathway to defy the limitations of lead-based equivalents through their lower toxicity and direct bandgaps suitable for near-infrared (NIR) emissions. Thus far, most studies have been limited to stabilizing the material under environmental conditions. This problem can be attributed to the fast oxidation of Sn^{2+} to Sn^{4+}, creating high defect density, particularly in tin vacancies, which act as nonradiative recombination centers, implying a lower photoluminescence quantum yield (PLQY) of around 1%. However, to fully uncover the potential of this material system, explorations of more complex synthesis and their properties, both as single materials and in combination with others in optoelectronic systems, will be essential. The THP-NCs were synthesized using different methodologies, such as hot injection, ligand-assisted reprecipitation, and chemical vapor deposition. These have permitted the adjustment of precursor chemistry, ligand engineering, and doping to reduce this limitation partially. Approaches, like appropriate conditions such as Sn-rich reactions and passivation of surface defects, have shown a potential to enhance stability and optical properties. In this Perspective, we summarize state-of-the-art approaches to synthetize the THP-NCs and highlight existing knowledge gaps and opportunities in their synthesis and characterization. We also propose a roadmap to accelerate the discovery of more stable materials with environmental robustness and predictable properties via the synergistic combination of experimental and computational efforts to achieve defect-tolerant THP-NCs with improved PLQY. Finally, we identify research opportunities and open questions in developing of next-generation Sn-based materials, optoelectronic devices, innovative systems that can bridge the gap between synthesizing and implementing these materials in real-world engineering applications.

KEYWORDS

lead-free perovskite, tin halide, nanocrystals, quantum dots, stability, toxicity



GRAPHICAL ABSTRACT

1 Introduction

In recent years, metal halide perovskites with the general formula ABX_3 (A = Cs^+, methylammonium (MA), or formamidinium (FA); B = Pb^{2+}, Sn^{2+}, or Ge^{2+}; X = Cl^-, Br^-, I^-) have garnered extensive research interest as promising materials for optoelectronic applications (Akkerman and Manna, 2020). Within this family, tin-based halide perovskite nanocrystals (THP-NCs) have emerged as a compelling alternative to lead-based counterparts due to their reduced toxicity and preservation of favorable optoelectronic features. This advantage arises from the comparable ionic radii (1.18 Å for Sn^{2+} vs. 1.19 Å for Pb^{2+}) and similar valence electron configurations (ns^2np^2) of Sn^{2+} and Pb^{2+} (Awais et al., 2021). THP-NCs exhibit tunable band gaps, narrow emission bands, and strong absorption, positioning them as versatile building blocks for next-generation optoelectronic technologies (Chen et al., 2016; Wang et al., 2019).

One of the significant challenges in advancing THP-NCs for device integration lies in achieving near-unity PLQY across the visible and near-infrared spectrum while maintaining long-term material stability. Various strategies have been pursued, including tailored synthesis methods, surface passivation, antioxidants, and encapsulation techniques (Zhang B. Bin et al., 2023; Gahlot et al., 2024a; Li et al., 2024). These efforts primarily target the suppression of tin vacancies, which create mid-gap states that act as non-radiative recombination centers, substantially lowering PLQY. Moreover, the strong tendency of Sn^{2+} to oxidize into Sn^{4+} is intrinsically associated with structural destabilization and degradation of optoelectronic performance (Zhang Z. et al., 2023).

Despite progress enabled by synthetic and surface engineering approaches, the realization of stable, highly emissive THP-NCs remains in its infancy. Understanding the complex interplay between surface chemistry, crystal dynamics, and environmental sensitivity is crucial to enhancing material reproducibility and functionality. The enormous interest in THP-NCs has encouraged the synthesis optimization of perovskite in reducing conditions, harnessing confinement, and exploiting coordination chemistry to stabilize the perovskite in the lower oxidation state. In this perspective, we critically assess the current state of THP-NCs development, focusing on recent synthetic advances, surface defect passivation, and encapsulation strategies. Beyond photovoltaics, we explore their potential in emerging applications such as light emission, sensing, and flexible electronics. Finally, we highlight key research directions to overcome intrinsic limitations, paving the way toward integrating THP-NCs into robust, lead-free optoelectronic platforms.

2 Synthetic strategies for tin halide perovskite nanocrystals

The synthesis of THP-NCs has attracted significant attention as a promising approach for developing environmentally friendly optoelectronic materials. Among the various synthetic strategies explored to obtain high-quality THP-NCs with tunable size, morphology, and photophysical properties (Supplementary Table S1), the hot-injection method predominates, as demonstrated by most studies. This approach offers precise control over nucleation and growth, resulting in nanocrystals with relatively narrow size distributions and reproducible properties. In contrast, alternative methods such as the solvothermal route are employed less frequently, typically yielding broader size distributions, and often, their optical performance remains unreported. Other techniques, such as ligand-assisted reprecipitation (LARP) and chemical vapor deposition (CVD), have been described in isolated cases, but their use remains limited. Thus, despite the ongoing development of various methods, the

hot-injection technique stands out as the dominant approach in current THP-NC research.

The hot-injection method is particularly notable for its ability to produce nanocrystals with tunable optical properties. This technique rapidly injects precursors such as cesium halides and tin halides into a hot coordinating solvent containing ligands like oleic acid and oleylamine. The rapid nucleation and growth processes facilitate the formation of THP-NCs with narrow size distributions and high PLQYs (Jellicoe et al., 2016; Wang et al., 2017; 2021; Kang et al., 2021; Zhang B. Bin et al., 2023; Gahlot et al., 2024b).

Ligand-assisted reprecipitation (LARP) is another effective method, which involves dissolving precursors in a polar solvent followed by rapid injection into a non-polar solvent containing surface ligands (Gahlot et al., 2022; Shellaiah et al., 2022). This technique allows for room-temperature synthesis and offers scalability advantages. Researchers have achieved Sn-PQDs with enhanced stability and luminescence properties by carefully selecting ligands and optimizing reaction conditions.

The chemical vapor deposition (CVD) technique has also been explored for THP-NC synthesis, especially for thin-film applications (López-Fraguas et al., 2019). In CVD processes, gaseous precursors react on a substrate surface to form perovskite nanowires (Chen et al., 2019). This method allows precise film thickness and composition control, crucial for device integration. To further improve the quality and stability of THP-NCs, researchers have investigated strategies such as precursor engineering, ligand modification, and compositional tuning. For instance, incorporating excess halide ions during synthesis has been shown to passivate surface defects and suppress non-radiative recombination, thereby improving PLQYs.

Ultimately, the most stable THP-NCs are those with low oxidation states and minimal defects. This condition is most effectively achieved through the hot-injection method, which provides precise control over nucleation kinetics and surface passivation via tailored ligand environments.

3 Challenges and advances in the stability of tin-based perovskite nanocrystals

The stability of THP-NCs has become critical in advancing their practical applications in optoelectronics and photovoltaics. Recent studies have provided insights into the factors influencing the long-term stability of these materials, including surface passivation, crystal structure, and environmental degradation.

Research demonstrates that surface engineering, such as the introduction during the synthesis of organic ligands or inorganic passivating agents, and antioxidants significantly improves the stability of THP-NCs, protecting them from moisture, oxygen, and light-induced degradation (Gahlot et al., 2024a; Li et al., 2024). The interplay between the THP-NCs electronic properties and stability is further explored, with findings suggesting that the bandgap and the degree of halide segregation contribute to the resilience of materials under stress conditions, like thermal stress, contact with ambient humidity, and prolonged exposure to light (Dirin et al., 2023; Gahlot et al., 2024b). Furthermore, the development of encapsulation techniques, such as polymer coatings [i.e., PMMA (polymethylmethacrylate), PVP (polyvinylpyrrolidone), PEG (polyethylene glycol)] or multilayer structures, has shown promising results in preventing the degradation of THP-NCs under ambient conditions (Coduri et al., 2020; Dirin et al., 2023). These advancements represent significant strides toward achieving commercially viable, stable THP-NCs for various optoelectronic applications (Zhang B. Bin et al., 2023). Modern encapsulation focuses on hybrid and multifunctional layers, combining polymer flexibility with inorganic imperviousness or using hierarchical shells. These methods have yielded record stability for THP-NCs with engineered lattices, maintaining the desired (often larger) bandgaps without degradation. Each of these approaches has trade-offs. Polymers excel in flexibility and ease of processing but may allow slight gas permeability. Silica/oxides offer maximum impermeability but can increase device resistance if too thick. MOFs provide novel chemical stability but require sophisticated synthesis. The aim is to preserve the oxidation state and bandgap in all cases.

Encapsulation (via polymers, silica, oxides, MOFs, etc.) has proven essential for stabilizing perovskite NCs, especially those with deliberately distorted lattices (Supplementary Table S2). By physically isolating the NCs, these methods maintain the desired octahedral tilt and bandgap, while dramatically improving resistance to moisture, heat, light, and chemical attack (Wang et al., 2023; Kim et al., 2024). Recent research (2021–2025) has advanced these strategies through clever core–shell designs (Das Adhikari et al., 2023), novel polymer composites, and hybrid approaches, yielding NCs systems with tailored bandgaps and practical longevity.

Surface passivation has proven to be a critical strategy for improving the stability of THP-NCs. The surface states of these materials are highly reactive, making them prone to degradation when exposed to environmental factors. Recent studies have demonstrated that using passivating agents, such as organic ligands or inorganic salts, can significantly reduce surface defects, thereby enhancing the resistance of NCs to moisture and oxidative degradation (Gahlot et al., 2024a). For instance, the incorporation of halide ligands or lead-free additives has shown promise in improving the stability of NCs without compromising their optoelectronic properties as PLQY from 4.3% to 18.4% (Zhou et al., 2018). These surface modifications prevent the direct interaction of the perovskite material with environmental agents and enhance the charge carrier dynamics around 2.5–1,000 $cm^2\ V^{-1}\ s^{-1}$ (Shi et al., 2015), improving overall device performance. Indeed, computational strategies primarily focus on suppressing deep traps, engineering surfaces to stabilize Sn^{2+}, and identifying defect-tolerant compositions. Calculations show that Sn vacancies (V_{Sn}) have lower formation energy than Pb vacancies in lead perovskites, making them more abundant. V_{Sn} creates deep levels within the bandgap, leading to severe non-radiative recombination.

DFT studies suggest that growing NCs under iodide-rich or bromide-rich conditions raises the formation energy of V_{Sn}, suppressing defect formation. Excess halides during synthesis reduce deep traps and increase PLQY (Liu Q. et al., 2021; Yan et al., 2022). Moreover, DFT shows that SCN^- binds strongly to undercoordinated Sn, passivating dangling bonds and reducing surface traps (Liu Q. et al., 2021). All these strategies have ample scope for implementation during NC synthesis.

Moreover, the stability of THP-NCs is also influenced by their inner crystal structure and composition. The formation of mixed cation and anion perovskite structures has been shown to play a crucial role in stabilizing these materials under various environmental stressors. DFT predicts that formamidinium (FA^+) partially stabilizes Sn^{2+} and reduces trap state density slightly (Liu Q. et al., 2021). By controlling the composition, such as by substituting different halides or introducing dopants, researchers have significantly improved the structural integrity and stability of the NCs (Li et al., 2024). The combination of tin halide with other metals, such as lead or cesium, has been explored to stabilize the perovskite structure, reducing the occurrence of halide segregation and enhancing the resistance of the material to moisture-induced degradation (Gahlot et al., 2024b). This strategy is deeply connected to the Goldschmidt tolerance factor, a concept used to predict the structural stability of perovskite materials.

It is important to note that precise control over the size and morphology of NCs is essential to improving their optical and electronic properties and environmental stability. Studies have shown that optimizing the precursor concentration, reaction temperature, and solvent choice during synthesis can produce NCs with fewer defects and more robust crystal lattices, enhancing stability; this strategy implies better control of the size and morphology of the NCs (Dirin et al., 2023). Additionally, a better understanding of the role of precursor chemistry in determining the NCs' surface chemistry and overall stability has led to the development of more stable tin-halide perovskite nanostructures (Zhang B. Bin et al., 2023). In conclusion, while the stability of THP-NCs presents a significant challenge, ongoing research into surface passivation, compositional optimization, synthesis methods, and encapsulation technologies are making substantial progress in overcoming these obstacles.

4 Tin halide perovskites in action: from photovoltaics to sensing and biomedicine

The increasing interest in lead-free metal halide perovskites, particularly tin-based ones, has driven their exploration across multiple applications, yielding promising results and distinct structural advantages. One of the most established applications is their integration into photovoltaic devices. Tin halide perovskite nanostructures, processed as thin films, quantum rods, or colloidal nanocrystals, have achieved power conversion efficiencies in the 13% range under optimized conditions (Chen et al., 2016). These improvements, combined with advances in phase purity, colloidal stabilization, and encapsulation techniques, have contributed to enhanced environmental stability and reproducibility (Kang et al., 2021; Lyu et al., 2021). Short device lifetimes in real-world environments (air, moisture, light) should be addressed to reduce the device's cost, complexity, and to avoid complicated encapsulation methods. Moreover, limited use in high-temperature or high-intensity light environments (e.g., concentrator photovoltaics) is a real challenge (Aktas et al., 2022).

Their potential in light-emitting technologies is equally noteworthy. High photoluminescence quantum yields, along with tunable emission spectra across the visible and near-infrared regions, have enabled their use in devices such as light-emitting diodes (LEDs), color-conversion layers, and low-threshold lasers—often in fully inorganic, lead-free configurations (Figure 1A (Chen et al., 2018; Mahesh et al., 2020). The formation of ordered emissive films via drop-casting or spin-coating and compatibility with printing processes highlights their viability for future printed and flexible photonic circuits (Wang et al., 2017; Gahlot et al., 2024a). However, competing with lead perovskites in display and

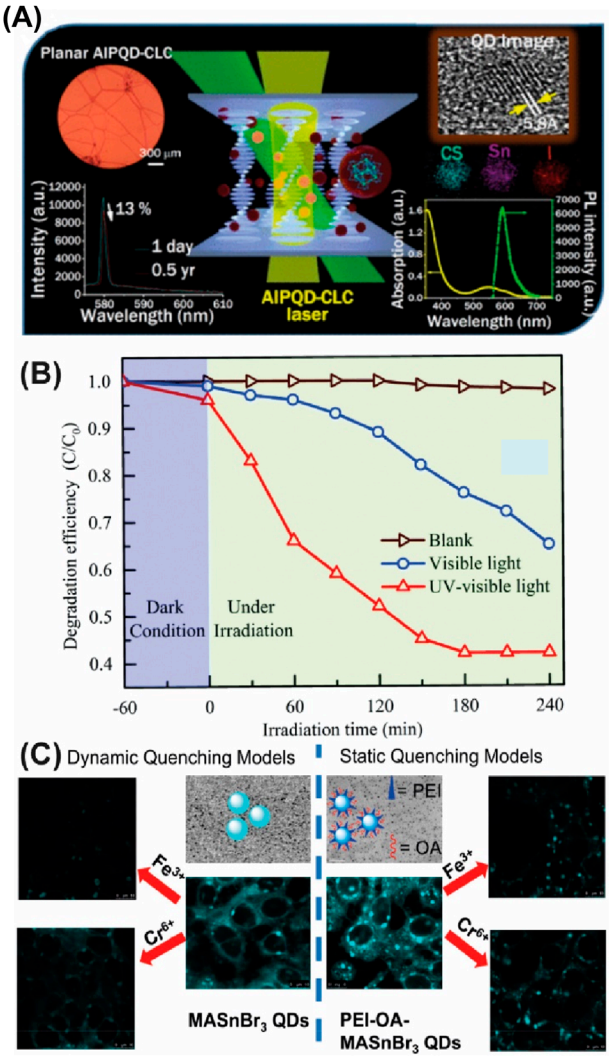


FIGURE 1
Emerging applications and functional behavior of tin quantum dots (SnQDs) in hybrid systems. **(A)** Design of a laser based on cholesteric liquid crystals doped with SnQDs (AIPQD-CLC), showing emission stability after half a year and a TEM image with an atomic spacing of 5.8 Å. Reproduced with permission from American Chemical Society (Chen et al., 2018). **(B)** Dynamic and static quenching mechanisms in $MASnBr_3$ QDs and PEI-OA-$MASnBr_3$ QDs in the presence of metal ions (Fe^{3+} and Cr^{6+}). Adapted with permission from American Chemical Society (Shellaiah et al., 2022). **(C)** Degradation efficiency of rhodamine B (RhB) as a function of irradiation time using $CsSnCl_3$ as a photocatalyst under dark, visible, and UV-visible light conditions. Adapted from Royal Society of Chemistry (Ali et al., 2021).

TABLE 1 Key challenges and mitigation strategies for THP-NCs.

Challenge	Cause	Impact	Implications for application	Possible solutions
Sn^{2+} oxidation	High redox sensitivity of Sn^{2+}	Accelerated degradation, trap formation	Reduced material and device stability	Reducing agents, Sn-rich synthesis, inert atmosphere, and encapsulation strategies
Low PLQY	Deep-level defects (V_{Sn}, surface traps)	Suppressed radiative recombination	Poor performance in LEDs and photodetectors	Surface passivation, ligand engineering, and metal ion doping
Moisture sensitivity	Hygroscopic and polar nature	Structural degradation in humid air	Shortened device lifetime in ambient conditions	Hydrophobic ligand shell, polymer/inorganic encapsulation
Mechanical softness	Weak ionic lattice	Fracture or deformation under stress	Integration challenges in flexible electronics	Composite reinforcement, flexible substrate engineering
Synthesis challenges	High sensitivity to conditions	Poor reproducibility and yield	Hurdles for scale-up and industrial translation	Controlled reaction kinetics, automated/flow synthesis, precursor optimization
Thermal instability	Low lattice enthalpy	Phase transitions at moderate heat	Instability under operating conditions	Elemental alloying, phase engineering, thermal barrier layers
Residual toxicity	Sn^{4+} and byproduct accumulation	Potential environmental and health risks	Regulatory and sustainability limitations	Eco-friendly synthesis, purification, lifecycle assessment

lighting technologies would be difficult due to the low PLQY and brightness (Handa et al., 2019).

Several studies have also demonstrated their effectiveness as fluorescent sensors for the selective detection of heavy metal ions (e.g., Pb^{2+}, Fe^{3+}, and Cr^{6+}) in aqueous and organic media. These materials exhibit strong luminescence and rapid optical responses, making them appealing for environmental monitoring of toxic metals and integration into real-time sensing platforms operable under field conditions (Li et al., 2019; Shellaiah et al., 2022). Their lead-free composition has also conferred notable biocompatibility and stable emission in biological media, positioning them as promising candidates for biomedical imaging—particularly at the cellular level—where perovskite nanocrystals have already been employed successfully as diagnostic probes (Figure 1B (Shellaiah et al., 2022).

In addition, their high optical absorption, charge carrier mobility, and tunable bandgap through halide engineering make them suitable for photodetector applications. In these devices, spectral sensitivity can be precisely tailored. At the same time, long-range ordering in drop-cast films, combined with intrinsic defect tolerance, offers a promising route toward semitransparent, large-area, solution-processable sensors responsive across both visible and near-infrared regions. (Liu F. et al., 2021; Gahlot et al., 2022; Lorusso et al., 2024). On the other hand, challenges in making flexible or large-area devices can be present due to Sn-based perovskite soft structures prone to lattice deformation; however, matching the perovskite bandgap with semitransparent layers could be a promising technological development.

Furthermore, certain perovskite compositions—such as $CsSnCl_3$—have exhibited photocatalytic activity in dye degradation (Figure 1C and hydrogen evolution, pointing to their potential use in solar-driven catalytic systems and water-splitting platforms (Ali et al., 2021).

Moreover, their ability to form nanostructures with diverse morphologies (e.g., nanocages, nanocubes, and 2D/3D frameworks), together with surface adaptability and encapsulation strategies, has opened new avenues for the development of portable and mechanically adaptive optoelectronic devices. Their suitability as printable inks, compatibility with low-temperature processing, and integration into flexible substrates further reinforce their potential in flexible electronics. However, practical demonstrations are still in the early stages (Wang et al., 2017; Gahlot et al., 2024b; 2024a).

These advances position lead-free tin halide perovskites as highly versatile semiconductors with broad multifunctional potential. However, practical deployment still requires significant material engineering (e.g., encapsulation, doping, surface passivation) to meet commercial-grade durability and efficiency standards. In this regard, developing novel device architecture and optical management strategies presents a promising path forward. For instance, the use of dielectric/metal/dielectric (DMD) electrode configurations has been shown to enhance angular efficiency and optical transmittance in semitransparent solar cells, enabling better integration into real-world applications such as windows and agrivoltaics (Lorusso et al., 2024). Likewise, advances in electromagnetic mode management in transparent OLEDs provide a valuable design framework for achieving stable color output and directional light control. These features could be adapted to future tin halide perovskite-based optoelectronic technologies (Triolo et al., 2025).

Although these approaches have been primarily demonstrated in lead-based or alternative systems, they offer a compelling foundation for the rational design of more stable, efficient, and adaptable devices using lead-free perovskite materials (Pareja-Rivera et al., 2021). As control over their dimensionality, crystal phase, and surface chemistry advances, their integration into stable, scalable, and environmentally sustainable technologies becomes feasible and exceptionally compelling.

5 Conclusion

Thanks to their favorable optoelectronic properties, THP-NCs are emerging as promising lead-free semiconductors for next-generation optoelectronic technologies. However, challenges remain, particularly the chemical instability of Sn^{2+} and the high density of defects—especially vacancies—which promote nonradiative recombination. Addressing these issues is essential for developing stable materials suitable for practical applications. Recent advances under Sn-rich synthesis conditions, such as the use of halide excess, post-synthetic treatments, and encapsulation strategies using polymers or inorganic coatings, have significantly improved environmental stability. A deeper understanding of the interplay between structure, surface chemistry, and degradation mechanisms will be key to further enhancing the long-term performance of both materials and devices. A summary of the main challenges associated with THP-NCs, along with their causes, implications, and possible mitigation strategies, is provided in Table 1. Future efforts should prioritize the development of defect-tolerant, self-passivating compositions, scalable synthesis protocols, and customized encapsulation techniques. Notably, controlling oxidation pathways has already shown promise in stabilizing Sn^{2+}, reinforcing the effectiveness of the strategies discussed in this Perspective. Continued research is expected to drive substantial progress, especially in the stabilization and integration of THP-NCs into high-performance photovoltaic and optoelectronic systems. Moreover, expanding their application beyond photovoltaics—to semitransparent and flexible electronics, neuromorphic computing, and bioimaging—could unlock new functionalities derived from their unique structural and optoelectronic features. With sustained interdisciplinary efforts, THP-NCs hold strong potential to enable stable, efficient, and environmentally sustainable lead-free optoelectronic devices.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary Material, further inquiries can be directed to the corresponding authors.

Author contributions

CP-R: Writing – original draft, Writing – review and editing. FP: Writing – original draft. KG-J: Writing – original draft. IM-S: Writing – review and editing. SM: Writing – original draft, Writing – review and editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Generative AI statement

The author(s) declare that no Generative AI was used in the creation of this manuscript.

Publisher's note

Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fmats.2025.1627480/full#supplementary-material

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