COMMENTARY

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Standardization as the catalyst for radiative cooling technology deployment

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In the context of the ongoing fossil fuel consumption and high greenhouse gas emissions, extreme climate events are increasing [1]. Consequently, the development of zero-energy, passive cooling technologies has become an urgent priority. Radiative cooling technology, which achieves continuous cooling without external energy input by utilizing the high solar reflectivity and high infrared emissivity of material surfaces, has recently demonstrated broad application prospects [2–7]. Despite a well-established theoretical basis [8,9], the practical performance of radiative cooling materials is constrained by the coupling of multiple environmental variables [9], including solar radiation, atmospheric conditions, and convective heat transfer. These factors establish a tight coupling between the material's cooling efficacy and local climatic parameters [9,10], forming complex nonlinear response relationships. Non-standardized measurement procedures may result in erroneous experimental conclusions, such as reporting spectral reflectance exceeding 100% [11] or ambient atmospheric temperatures as high as 40–50 °C [12]. Therefore, the establishment of accurate and repeatable testing protocols is crucial for fostering the healthy development of radiative cooling technology.

To address these challenges, the comprehensive protocol by Wang *et al*. [13,14] provides a critical benchmark for radiative cooling materials, representing a significant advancement for the field. This protocol enables high-precision, repeatable performance assessments through standardized optical/thermal testing, strict boundary condition control, and an open-source predictive model, thereby minimizing systematic errors and performance overestimation. By integrating the entire workflow from experimental design to theoretical modeling and linking spectral data to actual cooling performance, it establishes a systematic framework for rigorous comparison and further advancement. Consequently, this approach significantly enhances research reproducibility and data comparability, facilitating the technology's transition to industrialization. Nevertheless, the protocol faces challenges, including the high cost of specialized instrumentation and the inherent uncontrollability of outdoor environments. The authors acknowledge these limitations and propose potential solutions, such as collaborative equipment-sharing and theoretical com-

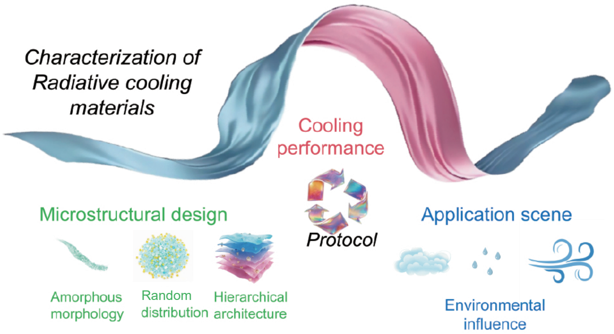

Figure 1 A framework for performance characterization of radiative cooling materials. The ultimate cooling performance of a radiative cooling material is governed by the interplay between its intrinsic microstructure enabled spectral properties and extrinsic environmental factors, such as solar irradiance and ambient temperature. Consequently, establishing a unified and reproducible characterization standard is crucial for the objective assessment of different materials. Wang and colleagues pioneered a comprehensive experimental and theoretical evaluation framework. This framework orchestrates a complete evaluation workflow, which seamlessly links the characterization of key optical properties, controlled indoor thermal testing, real-world outdoor performance validation, and cross-validation with theoretical models. The establishment of this standardized protocol provides a quantifiable and comparable performance benchmark for the field, significantly promoting its scientific rigor and technological advancement.

pensation, demonstrating a commitment to scientific rigor.

However, with the establishment of such standardized evaluation, another concerning trend has emerged: an excessive pursuit of exceptional cooling performance, often at the expense of material durability, aesthetics, and mechanical strength. Given the close integration of radiative cooling materials into daily life, their design must prioritize fundamental functional requirements over cooling performance as the sole objective. For instance, the primary function of a smart window is to ensure adequate lighting and visual comfort, with energy savings being a secondary benefit. Similarly, in applications such as photovoltaic thermal management or personal cooling, an equilibrium must be established between the cooling function and the core requirements of the device or user to ensure practical viability and sustainable adoption.

In summary, the developmental trajectory of radiative cooling technology, from fundamental research to practical application, follows a clear logical progression (Figure 1). To address core challenges such as environmental dependency and measurement inconsistencies, the establishment of standardized evaluation protocols serves as a critical cornerstone for the field's healthy advancement. However, in the pursuit of exceptional performance metrics, the research community must guard against a deviation from practical application requirements. Future breakthroughs will depend not only on innovations in materials science but also on the ability to co-optimize cooling function with engineering constraints like durability, aesthetics, and cost. Therefore, a comprehensive evaluation framework that balances performance standardization with multifaceted practicality will be the ultimate determinant in guiding radiative cooling technology toward successful industrialization and widespread adoption.

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Conflict of interest

The authors declare no conflict of interest.

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