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Bridging radiative cooling materials and applications towards alleviating global energy issues

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Received: March 1, 2025; Accepted: April 10, 2025; Published Online: April 12, 2025; https://doi.org/10.59717/j.xinn-energy.2025.100090

Citation: Chen H. and Wang C. (2025). Bridging radiative cooling materials and applications towards alleviating global energy issues. *The Innovation Energy* **2**:100090.

Dear Editor,

The rising demand for cooling is driving a surge in energy consumption, with carbon dioxide emissions from space cooling doubling over the past three decades. This reliance on energy-intensive cooling systems exacerbates global warming, which, in turn, boosts the demand for air conditioning — a self-reinforcing and unsustainable cycle. While renewable energy sources are continually explored to address the growing energy shortage, their implementation often involves significant land use and high costs. Radiative cooling (RC) offers a groundbreaking, fuel-free alternative by leveraging the cold cosmic background (~3 K) for thermal dissipation. Using carefully designed materials with well-tailored spectral-angular reflectivity/emissivity, radiative coolers can reflect over 90% solar irradiation while dissipating redundant heat through the long-wave infrared atmospheric window (8 – 13 μm). As a result, RC enables sub-ambient temperatures without energy consumption, making it a transformative candidate to mitigate energy and environmental challenges on Earth.

Material innovation is pivotal in promoting the capacity of RC technologies. Despite their fast development in the past decade, RC materials still face severe challenges. While nanophotonic structures enable highly efficient passive RC, they are costly and have poor compatibility with existing end-user devices and facilities. Polymer-based photonic alternatives, though affordable, often suffer from inadequate weather resistance and suboptimal solar reflectance. Hence, developing innovative RC materials is the key to boosting RC-based technologies.

Inspired by the hierarchical porous structures of Cyphochilus beetles, Lin et al.[1] developed a hierarchical porous ceramic (Figure 1A) by modifying alumina particles through phase inversion and sintering. This ceramic

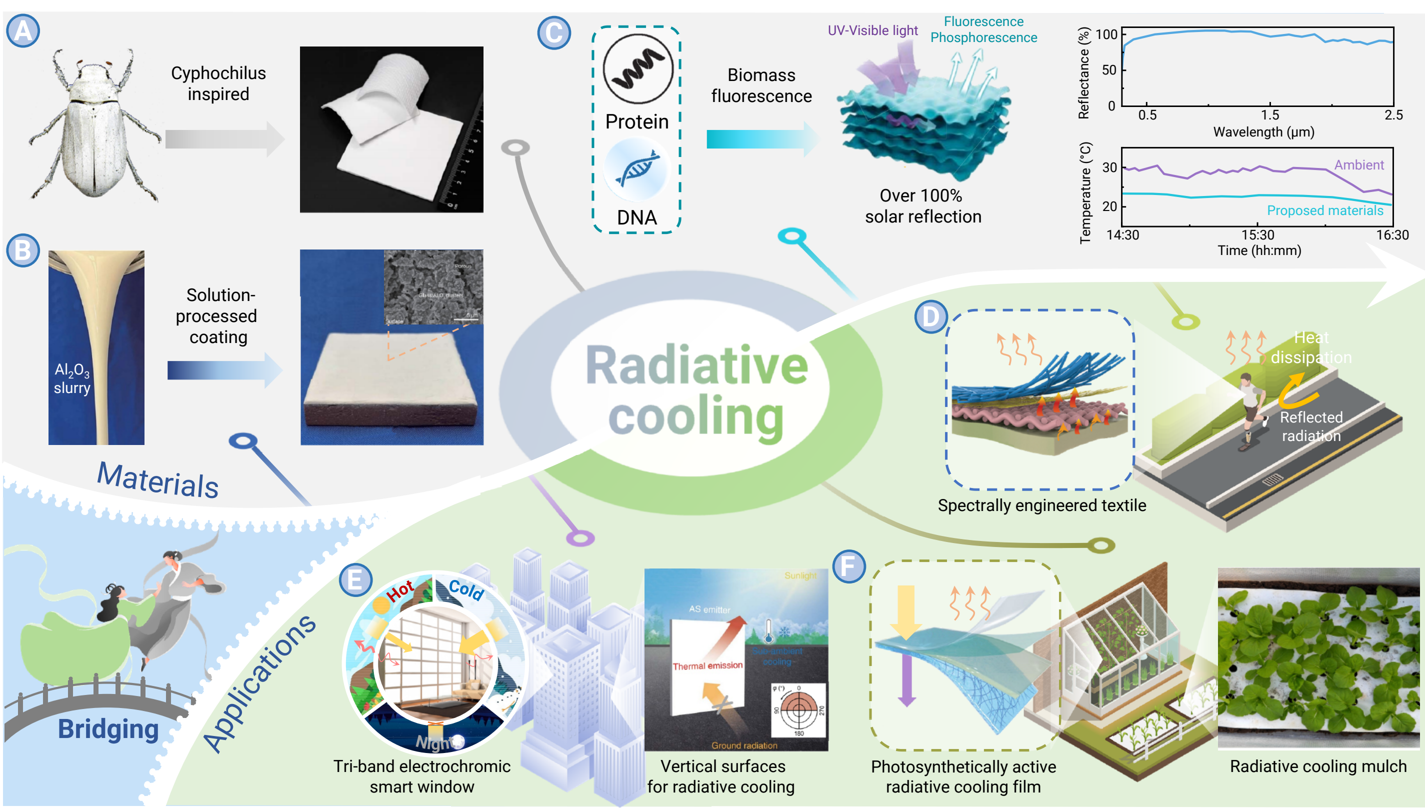

Figure 1. Bridging radiative cooling materials and applications (a–c) Design of radiative cooling materials: Cyphochilus-inspired ceramic[1] with exceptional durability under environmental stresses (a), solution-processed coating glass[2] maintaining high solar reflectance under extreme conditions while being scalable, cost-effective, and construction-compatible (b), biomass fluorescent aerogel[3] achieving a record-high 104.0% solar reflectance, 16.0°C daytime cooling (c). (d–f) Expansion of radiative cooling applications: Mid-infrared-selective textiles[4] designed for passive personal cooling (d), tri-band electrochromic smart window[6] (left) regulating solar transmission and thermal emission for energy-efficient buildings and vertical radiative cooling surface[8] (right) minimizing building heat accumulation (e), photosynthetically active film[9] (left) and radiative cooling mulch[10] (right) for enhanced agricultural productivity (f).

achieved an exceptional solar reflectance of 99.6% and exhibited outstanding durability under environmental stresses, making it suitable for outdoor applications such as rooftops and building facades. In parallel, Zhao et al.[2] introduced a solution-processed RC glass (Figure 1B) to enhance the mechanical strength of nanoscale ceramic components. By mixing glass with Al_2O_3 particles into a slurry and using the glass as a binder during annealing, they developed a mechanically robust material with a porous structure for effective sunlight scattering. This solution-based method enables convenient application via brush or spray coating, with sintering achievable through a hot air gun or heat lamp, providing greater processing flexibility. The glass retains high solar reflectance even under harsh conditions, including water exposure, ultraviolet radiation, pollution, and high temperatures, while being scalable, affordable, and compatible with existing construction materials. Ma et al.[3] leveraged the synergistic interactions between gelatin and DNA to generate phosphorescent and fluorescent features. Through a multilayer design, they integrated an ordered layered aerogel that achieved a solar-weighted reflectance of 104.0% in visible light regions and a 16.0°C temperature drop from the field-test ambient, as shown in Figure 1C. However, it is noted that the reported "ambient temperature" therein,[3] which is more than 40°C might be exaggerated and the cooling performance of the proposed material was argued to be overstated. This concern about nonstandard temperature statements puts forward the request for explicit definition and standardized measurement of temperature data in the following studies on RC technologies. This aerogel exhibits excellent reparability, recyclability, and biodegradability, completing an environmentally friendly lifecycle and providing a pathway for obtaining RC materials from petroleum-based raw sources. The emerging RC materials[1-3] highlight diverse advancements while revealing shared challenges. Cost, durability, and adaptability to various climatic conditions are the primary hindrances to the widespread adoption of RC-integrated technologies. Despite these hindrances, the diversity and complementarity of passive RC materials indicate their capacity to meet specific cooling demands. With growing energy needs and intensifying environmental deteriorations, applications of RC technologies have extended from personal and building thermal management to the agricultural industry, paving an exciting interdisciplinary research frontier for alleviating global issues such as the urban heat island (UHI) effect[4-5], building energy consumption[6-8], and agricultural thermal stress[9,10].

Exacerbated by anthropogenic heat from urbanization and industrialization, urban areas often experience the UHI effect, elevating urban temperatures and compromising human thermal comfort. Therefore, addressing outdoor heatwaves poses a pressing challenge for the coming decades. In recent years, RC textiles[5] have emerged to enhance personal comfort in both indoor and outdoor environments, paving the way for alleviating the UHI effect. Wu et al.[4] developed a mid-infrared-selective layered fabric through molecular design (Figure 1D). This fabric features selective outward emissivity within the atmospheric window to maximize its RC capability. Meanwhile, it exhibits broadband inward emissivity that is helpful to its heat exchange with the covered skin. This material provides an efficient solution for passive personal cooling, potentially reducing air conditioning energy consumption and mitigating heat-related health risks. Liu et al.[5] systemically discussed spectral features required for indoor, outdoor, and all-weather personal cooling, as well as for personal cooling in specific urban environments, paving an on-demand design principle for cooling textiles.

Buildings consume ~40% of global energy, and windows, as a primary part of energy and light management, account for up to 20% of thermal loss from space heating and cooling. To overcome the low energy efficiency of windows, Shao et al.[6] proposed a tri-band electrochromic window (Figure 1E, left) that makes full use of mid-infrared RC and visible and near-infrared light. The proposed smart window could dynamically adjust solar transmission and thermal emission to optimize energy efficiency, offering an energy-saving window design for pushing the goal of carbon peaking and neutrality.

In addition to improving the energy efficiency of windows, another strategy for reducing building energy consumption involves lowering the surface temperatures of building exteriors during summer days. But the vertical walls are hard to cool via RC as they are not facing the sky, but in contrast, they are partially facing hot ground. Cheng et al.[7] proposed a zigzag wall-supported structure with asymmetric emission to address the overheating of vertical walls. Their field experiments indicated the proposed asymmetric emissive wall could achieve an additional 2.3°C temperature drop compared to the isotropic high emissive RC material-coated wall[7]. Recently, Xie et al.[8] reported sub-ambient daytime RC of vertical walls enabled by a hierarchical, angularly asymmetric, and spectrally selective radiative cooler (Figure 1E, right). The designed radiative cooler features a sawtooth grating with a periodicity that exceeds the thermal wavelength. It is coated with a nanoporous polyethylene film that reflects solar radiation while transparent to infrared-thermal radiation. Under peak solar irradiance of ~920 W/m^2, the reported radiative cooler achieved a 2.5°C temperature drop from ambient, addressing the unique challenge of sub-ambient daytime RC of building facades. This innovation broadens RC applicability to diverse architectures, offering a promising strategy for zero-carbon buildings.

In addition to addressing the energy issues in individuals and buildings, RC technologies have also found great success in agriculture, particularly in hot and dry regions.[9-10] Li et al.[9] proposed a photosynthetically active RC film (Figure 1F, left) composed of an outermost PDMS layer, a middle nine-layered photonic crystal on a substrate, and an innermost PAM hydrogel layer. The proposed film could simultaneously decrease the environment temperature, restrain water evaporation, and increase photosynthesis of the plants in the greenhouse, resulting in a significant increase (20 – 370%) of biomass yields. Wang et al.[10] investigated RC mulches that could effectively lower soil temperatures and conserve water resources (Figure 1F, right). The mulch therein is made of a thermal emitting and a solar reflection layer, sandwiched in two protection layers, making it more affordable for large-scale applications. Field tests indicated that applying the RC mulch to the bare soil could provide a 12.5°C temperature reduction of the root zone and a 127.4% enhancement of the yield of Chinese cabbage. Collectively, the integration of RC with greenhouses and mulches paves a guide for addressing the food-energy-water nexus in hot climates.

In summary, bridging RC materials and applications paves an eco-friendly way to alleviate global energy issues associated with individuals, buildings, agriculture industries, and beyond. Developing multifunctional RC materials and pushing their real-world applications via interdisciplinary collaboration would be the next thing to be included on the to-do list.

Designing RC materials with desired versatility is the first thing on the list. For personal thermal management, RC materials are expected to have flexibility, human compatibility, breathability, and a colorful appearance. For building envelope applications, durability, fire resistance, mild color, compatibility with various construction materials, and dynamic tunability are essential for long-term, all-season energy savings and safety. When used for agriculture and food industries, degradability and biosecurity are vital in addition to low-cost scalability. Fortunately, the developments of AI-driven design algorithms pave an alternative solution for designing new RC materials that meet the versatility needs.

Secondly, developing RC-driven and RC-integrated technologies also requires continuing efforts from both scientists and engineers. The combination of RC materials with existing devices such as electronics, photovoltaic cells, and vehicles for temperature reduction needs further research in system designs and performance tests. Besides, integrating RC with thermoelectric generators and triboelectric nanogenerators is promising for electricity generation, highlighting the development of next-generation technologies for microelectronic systems. The sub-ambient cooling capability has also shown potential for ice protection and desalination, but the technology of reaching deep sub-freezing temperatures via RC is still challenging.

Finally, expanding the applications is expected based on the bridged material-technology-application nexus of RC. Due to the various climate features around the world, assessing the practical performance of RC-based technologies via field experiments—other than theory predictions via spectral properties of the RC materials—is important as the RC power is intrinsically volatile to local environments. In addition, when serving as alternatives to previously used materials, RC materials are still relatively expensive, which hinders their wide applications. At the current stage, various financial incentives and market-driven strategies could help accelerate the adoption of RC technologies, facilitating their transition from material developments to global implementations.

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FUNDING AND ACKNOWLEDGMENTS

This work was supported by the Beijing Natural Science Foundation (F252071). The funders had no role in study design, data collection and analysis, decision to publish, or preparation of the manuscript.

AUTHOR CONTRIBUTIONS

All authors contributed to the manuscript and approved the final version

DECLARATION OF INTERESTS

The authors declare no competing interests.