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Perspective

Breaking the power ceiling of radiative cooling through evaporative-radiative synergy

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PROGRESS AND POTENTIAL Global warming and urbanization have intensified cooling demand across buildings, personal comfort, electronics, and agriculture, making thermal management a major driver of global energy use and greenhouse gas emissions. Traditional vapor-compression cooling exacerbates this crisis, creating a self-reinforcing cooling paradox. Passive daytime radiative cooling offers a sustainable alternative by dissipating heat to outer space through the atmospheric transparency window without electricity input. However, its real-world impact is constrained by a fundamental power ceiling ($\sim$150 W m^{-2}) and high sensitivity to humidity, clouds, and atmospheric conditions, which drastically reduce performance under realistic climates.

Evaporative cooling provides high power in arid regions but suffers from water dependence and efficiency collapse in humid environments. These complementary limitations make their synergistic integration a transformative strategy. This perspective outlines evaporative-assisted radiative cooling, a hybrid platform that breaks the radiative power ceiling via thermodynamic coupling. It unifies synergistic principles, material designs, and broad applications while addressing durability, climate adaptation, and system integration. By establishing scalable frameworks, this work charts a path to next-generation passive cooling, essential for global energy sustainability and mitigating the worldwide thermal management crisis.

SUMMARY

Radiative cooling is a pivotal technology for sustainable thermal management, yet its broad adoption is constrained by a fundamental power ceiling ($\sim$150 W m^{-2}) and strong dependence on atmospheric conditions. This review highlights evaporative-assisted radiative cooling as an emerging strategy that effectively bypasses this constraint. The combined mechanism enables hybrid systems to achieve unprecedented, climate-resilient cooling power. We analyze the thermodynamic principles underlying this synergy, where radiative cooling elevates evaporative performance beyond its standalone limit, and evaporation, in turn, enhances the net cooling flux. We then critically review the material embodiments of this concept, from decoupled tandem and monolithic porous structures to adaptive systems. Their application potential spans from building envelopes and personal thermal management to electronics cooling and agriculture. Finally, we discuss the critical challenges of durability, dynamic climate adaptation, and system integration that must be surmounted for practical deployment. By establishing a unified framework and scalable design principles, this work outlines a pathway toward next-generation high-performance passive cooling technologies essential for global energy sustainability.

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INTRODUCTION

Global warming and rapid urbanization have precipitated a severe thermal management crisis, exemplified by the urban heat island effect and escalating cooling demands worldwide.[1–4] This surge extends across building climate control, personal comfort, and industrial processes, making space cooling a major and growing contributor to global electricity consumption and peak grid loads (Figure 1).[5,6] The prevailing vapor-compression technology, which is heavily dependent on fossil-fuel-based electricity, exacerbates the issue it aims to solve.[7] This is because its operation releases waste heat and greenhouse gases alongside energy consumption, creating a self-reinforcing cycle known as the cooling paradox.[8]

Resolving this paradox necessitates a fundamental shift toward passive cooling solutions that require no energy input.[9] Daytime radiative cooling has emerged as a promising candidate in this regard. This approach exploits the atmospheric transmission window within the 8–13 μm wavelength range to emit thermal radiation directly into outer space.[10,11] By engineering surfaces with high mid-infrared emissivity and high solar reflectance, sub-ambient cooling can be achieved passively.[12,13] Innovative designs such as hierarchical-morphology metafabric and polymer film have led to notable cooling performance.[14,15] However, the practical performance of radiative cooling is intrinsically limited by a low theoretical power ceiling (~150 W m^{-2}) and high climatic sensitivity.[16,17] Its effectiveness is substantially reduced under conditions of high atmospheric humidity, cloud cover, or pollution, which diminish the transparency of the atmospheric window.[18] Under realistic daytime conditions, the net cooling power of such systems is typically restricted to 50–100 W m^{-2}, which is insufficient for numerous high-heat-flux applications. Evaporative cooling, which utilizes the substantial latent heat of water vaporization, can provide higher cooling power, especially in arid environments.[19] Nevertheless, this method faces critical constraints: an essential dependence on water availability, severe performance decline in humid atmospheres, and reduced efficiency due to solar heating of the wetted surface.[20] Significantly, the limitations of these two passive mechanisms are complementary, as the radiative cooling is constrained by its power density and atmospheric conditions, while evaporative cooling is limited by water and humidity. This complementarity suggests that a synergistic integration of the two could form a compelling strategy. The concept of evaporative-assisted radiative cooling is founded on this premise.[21]

This review presents a comprehensive analysis of this transformative hybrid cooling technology. We first elucidate the thermodynamic and mass-transfer principles that underpin the synergy between radiation and evaporation, explaining how it breaks the traditional power ceiling. We then systematically review the advanced materials and system architectures engineered to implement this synergy, from layered to monolithic and adaptive designs. Subsequently, we assess the broad application landscape. Finally, we discuss the pivotal challenges including durability, dynamic climate adaptation, and system integration that must be addressed to transition this innovation from laboratory research to widespread implementation. By consolidating recent advances and clarifying scalable design principles, this review aims to accelerate the development of high-performance, climate-resilient cooling systems. More broadly, it highlights evaporative-assisted radiative cooling not merely as an incremental improvement, but as a versatile and disruptive platform technology. Its potential to provide sustainable thermal management across diverse sectors positions it as a critical enabler for global energy sustainability and a pragmatic pathway to mitigate the growing global cooling challenge.

SYNERGISTIC PRINCIPLES: HOW THERMODYNAMIC COUPLING OF RADIATION AND EVAPORATION BREAKS THE POWER CEILING

To gain a clear understanding of the significant performance improvement from evaporative-assisted radiative cooling, it necessitates a quantitative deconstruction of the two independent mechanisms at the level of thermodynamics and mass transfer, revealing the synergistic effects that arise in their coupled state. This analysis shows the strong combined effects that occur when the methods work together. This synergy, in essence, reorganizes the pathways of energy and mass transport through structural design, thereby overcoming the limits of each method individually.

Thermodynamic constraints of radiative cooling and the nature of the power ceiling

Radiative cooling is a long-range energy exchange process mediated by electromagnetic waves.[22] The analysis of its performance limits begins with the energy balance equation at the surface (Figure 2A). The net cooling power of a radiative cooler exposed to the environment results from a complex interplay of multiple energy flows. The cooling power (*Pcooling*) was calculated as follows:[23]

$$P_{cool}(T) = P_{rad}(T) - P_{amb}(T_{amb}) - P_{sun} - P_{cond+conv} \quad \text{(Equation 1)}$$

$P_{rad}(T)$ is the total thermal radiation power of the sky-facing surface of the cooling material with a temperature of T, which can be calculated by the formula $P_{rad} = 2\pi \int_0^{\pi/2} d\theta \cdot \sin\theta \cdot \cos\theta \cdot \int_0^{\infty} d\lambda \cdot I_{BB}(T,\lambda) \cdot \varepsilon_r(\lambda,\theta)$. Among them, $2\pi \int_0^{\pi/2} d\theta \cdot \sin\theta \cdot \cos\theta$ is the angular integral on the hemisphere, $I_{BB}(T_r,\lambda) = \frac{2hc^2}{\lambda^5} \cdot \frac{1}{\exp\ (hc/\lambda K_B T)^{-1}}$ is the thermal radiation of a black body with temperature T from unit surface area and unit solid angle, with unit wavelength as the interval, where h is Planck's constant, c is the speed of light, λ is the wavelength, and K_B is the Stefan-Boltzmann constant. $P_{amb}(T_{amb})$ denotes power from ambient radiation. P_{sun} is the power of absorbed sunlight. $P_{cond+conv}$ is the loss of cooling power due to convection and conduction.

Therefore, the net radiative cooling power is governed by surface emission, atmospheric downwelling radiation, absorbed solar radiation, and non-radiative heat exchange.[26] Surface emission represents the active cooling force, proportional to the emissivity within the atmospheric window and the fourth power of the surface absolute temperature according to the Stefan-Boltzmann law. This self-limiting characteristic means

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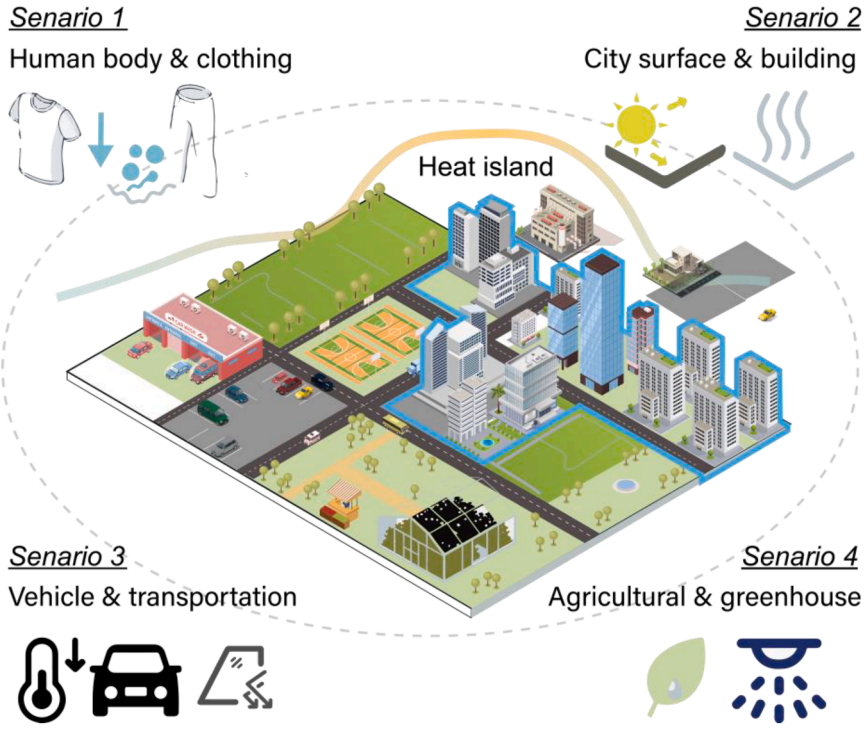

Figure 1. The need for advanced cooling technology for both advanced cities and rural areas to improve comfort and reduce energy consumption

cooling power diminishes as the surface temperature drops.[27] Atmospheric downwelling radiation acts as a major heat load. Its magnitude depends critically on the atmospheric emissivity spectrum, a key environmental variable.[16] Under clear, dry, and clean night skies, atmospheric emissivity can be as low as 0.7 to 0.8, rendering the sky a cold reservoir.[28,29] However, when atmospheric water vapor content increases or clouds and aerosols are present, the emissivity within the atmospheric window rises sharply, even approaching unity, transforming the sky into a warm radiant blanket that severely undermines net cooling.[30] Absorbed solar radiation constitutes the primary challenge for daytime cooling. Therefore, achieving sub-ambient cooling under sunlight is predicated on an extremely low solar absorptance, equivalent to a high solar reflectance, typically exceeding 0.95.[31] Non-radiative heat exchange, primarily convective heat transfer with air, also influences the balance.[32]

For an ideal surface with high infrared emissivity and solar reflectance under typical clear daytime conditions, solving the steady-state energy balance equation yields a maximum net cooling power estimate on the order of 100–150 W m^{-2}, corresponding to a surface temperature depression of approximately 5°C–10°C below ambient.[33,34] However, when ambient relative humidity increases from 30% to 80%, the atmospheric emissivity rises, potentially reducing the net cooling power by more than 50%. Cloudy or polluted conditions cause further drastic performance drops. This difficult-to-surpass power ceiling on the order of 100 W m^{-2} under realistic climatic conditions, combined with extreme sensitivity to atmospheric state, constitutes the power ceiling of radiative cooling technology for widespread application.

Thermodynamic constraints of evaporative cooling and the dual water-humidity bottleneck

Evaporative cooling removes heat through the latent heat of phase change, driven by a water vapor concentration or partial pressure difference (Figure 2B). The cooling power is directly proportional to the mass flow rate of evaporated water and the latent heat of vaporization.[35] The driving force is the difference between the saturated vapor density at the evaporating surface temperature and the ambient vapor density, the latter being the product of relative humidity and the saturated vapor density at ambient temperature.[36] This reveals two fundamental bottlenecks.[37] The first is the environmental humidity bottleneck. The driving force is directly proportional to the vapor density difference. In dry environments, the difference is large, enabling high cooling power. However, as ambient relative humidity approaches saturation, the driving force tends toward zero, causing the evaporative cooling mechanism to choke. This renders it nearly ineffective in humid climates like tropical rainforests or coastal regions in summer. The second challenge involves a surface temperature paradox coupled with solar heat load. The evaporation rate depends on the saturated vapor density at the surface temperature, which increases exponentially with temperature.[38] This seems to suggest that a higher surface temperature promotes evaporation. However, the goal of cooling is to lower the surface temperature.[39] For traditional wet surfaces exposed to sunlight, strong absorption of solar radiation elevates the surface temperature significantly, potentially above ambient. While this may temporarily increase the evaporation rate, it does so at the expense of sensible heat, resulting in poor cooling performance and inefficient water use. Moreover, the persistent requirement for a water supply introduces practical complexities related to water consumption, distribution systems, and maintenance.[20,40]

Synergistic coupling mechanisms: Nonlinear positive feedback and the collapse of the power ceiling

The transformative potential of evaporative-assisted radiative cooling stems from a fundamental shift in operating principle: moving from independent, self-limited processes to a structurally integrated system where radiative and evaporative cooling engage in mutual reinforcement.[41] This is not a simple juxtaposition of functions, but a strategic coupling that reorganizes energy and mass transport pathways.[42]

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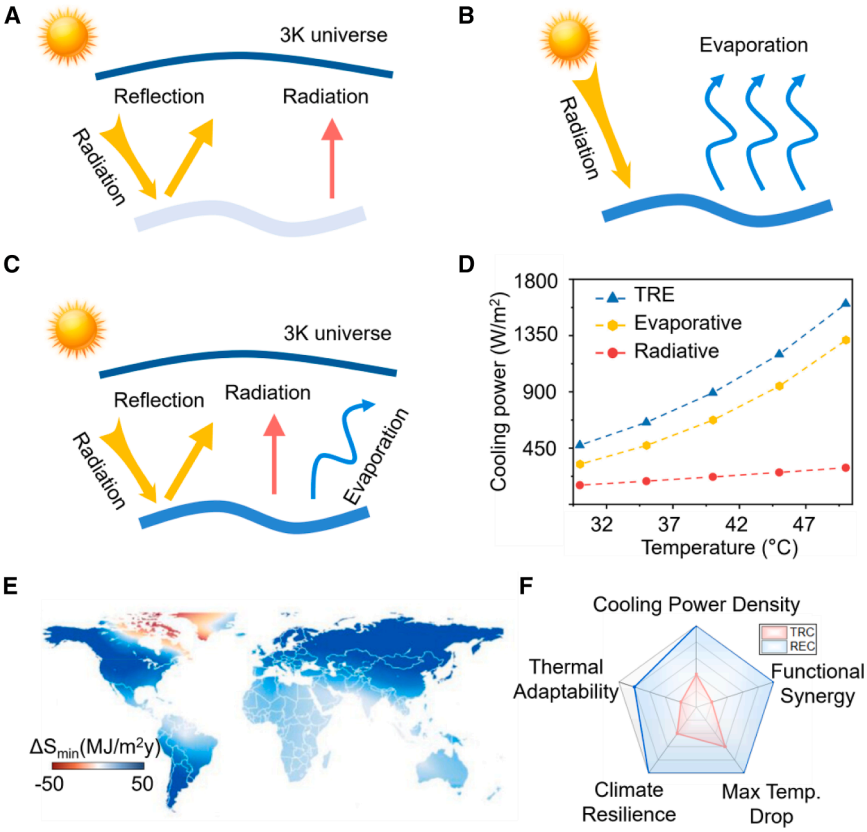

Figure 2. Evaporative-assisted radiative cooling for breaking the power ceiling

(A) Schematic illustration of traditional daytime passive radiative cooling.

(B) Schematic illustration of evaporative cooling.

(C) Synergistic mechanism of evaporative-assisted radiative cooling.

(D) Comparison of cooling power density among pure radiative cooling, pure evaporative cooling, and tandem radiative/evaporative (TRE) cooling. Reprinted with permission from Li et al.[24]

(E) Global distribution map of simulated minimum energy savings.[25]

(F) Radar chart comprehensively comparing the performance of traditional purely radiative cooling (TRC) versus hybrid evaporative-assisted radiative cooling (REC) across five key dimensions: cooling power density, functional synergy, maximum temperature drop, climate resilience, and thermal adaptability.

Evaporative-assisted radiative cooling systems generally leverage the intrinsic synergy between radiative heat dissipation and evaporative cooling, regardless of specific architectural configurations (Figure 2C). The radiative component functions as an efficient optical and thermal regulator: it reflects incident solar radiation to minimize heat gain and emits thermal energy through the atmospheric transparency window to achieve sub-ambient cooling. This sub-ambient state, in turn, serves as the critical thermal foundation for the evaporative component, which is typically composed of hydrophilic and porous materials that facilitate water transport and evaporation. This thermodynamic coupling establishes a positive feedback loop between heat and mass transfer: radiative cooling lowers the surface temperature, thereby suppressing the local vapor pressure at the interface and sustaining a driving force for evaporation, while the latent heat extracted through evaporation further reduces the surface temperature, in turn enhancing net radiative heat loss by increasing the temperature gradient relative to the ambient environment. The result is a dynamically stabilized, sub-ambient interface where both cooling pathways operate cooperatively rather than competitively, effectively overcoming the intrinsic limitations of each individual mechanism (Figure 2D). In arid or semi-arid climates, this leads to a dramatic amplification of peak cooling power. Experimental demonstrations have reported cooling powers exceeding 700 W m^{-2} under dry conditions, a value that is multiple times higher than that achievable by radiative cooling alone.[24] In hot and humid climates, where evaporative driving force is naturally low, the sub-ambient temperature of the coupled system's surface preserves a finite vapor pressure gradient, allowing evaporative cooling to contribute meaningfully. Concurrently, the radiative component, though attenuated, continues to provide a baseline cooling effect. The combined output remains substantially higher than the marginal cooling power of a pure radiative cooler under identical humid conditions, conferring upon the hybrid system a critical attribute: climate resilience. This complementary dynamic allows the system to self-adjust its dominant heat rejection pathway across diurnal and seasonal cycles, ensuring robust year-round thermal management.

Advanced implementations of this paradigm incorporate atmospheric water harvesting to address the evaporative water consumption. The sub-ambient temperature of the radiative cooling components is leveraged as a condensation site or enhances the moisture capture capacity of integrated hygroscopic materials. This enables a "capture-and-reuse" cycle: atmospheric moisture is adsorbed or condensed during cooler, more humid periods, stored within the material matrix, and subsequently utilized for daytime evaporative cooling. More sophisticated designs may employ low-grade thermal energy to drive the release of captured water, further intensifying the evaporation process.[43] This integration of moisture sorption/desorption dynamics with the cooling cycle creates a synergistic loop that intelligently couples latent heat flows with radiant heat rejection. It significantly reduces dependency on external liquid water supplies, charting a path toward fully autonomous, self-sustaining passive cooling systems.

Energy exchange logic and quantitative demonstration of synergy

The radiative cooling power is strictly determined by the surface temperature via the Stefan-Boltzmann law, and the evaporative cooling power is coupled to the surface temperature through

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Table 1. Representative cooling technologies differ in their typical cooling power, estimated cost, unit cost, and input requirements

Cooling technology	Typical power (W m^{-2})	Estimated cost (USD m^{-2})	Cost (USD W^{-1})	Input
Evaporative-assisted radiative[24,44]	200–650	40–80	0.06–0.40	–
Radiative[14,31]	80–120	20–70	0.17–1.00	–
Regenerative evaporative[45]	~70–220	30–80	0.14–1.14	water

its influence on saturation vapor pressure and thus the mass flow rate. The lower temperature of the radiative layer and components directly serve as a boundary condition for the evaporation layer. Within a reasonable humidity range, the negative impact of a lower surface or interface temperature on the evaporation drive is far outweighed by the positive benefit of eliminating solar heat gain. The net result is a synergistic enhancement of both evaporation rate and cooling power. The cooling power of such a hybrid system can be theoretically calculated as follows[24]:

$$P_{cool}(T) = P_{rad}(T) - P_{amb}(T_{amb}) - P_{sun} - P_{cond+conv} + H_{ev}\dot{m} \quad \text{(Equation 2)}$$

where H_{ev} is the enthalpy of water evaporation, and $\dot{m}$ denotes the evaporation rate of water. It is evident that the cooling power of the radiative cooling component can exhibit a synergistic effect with that of the evaporative cooling component. Given that the enthalpy of water evaporation is as high as 2,257 J g^{-1}, the synergistic enhancement of the cooling power of the hybrid systems can be substantial.

Experimental data strongly support this analysis. For instance, under an ambient temperature of 30°C, researchers measured a cooling power of approximately 470 W m^{-2} for a hydrogel-based tandem system. Source analysis attributed about 150 W m^{-2} to the radiative component and about 320 W m^{-2} to the evaporative component.[24] This total power far exceeds the theoretical limit for pure radiative cooling under the same conditions and also surpasses the evaporative cooling power of an identical hydrogel exposed directly to the same environment. The fact that over 60% of the total power originates from the evaporation process empowered by radiative cooling irrefutably proves the existence and potency of the synergistic effect.

Preliminary economic analysis: Cost and energy advantage following performance leap

Alongside breaking the performance ceiling, economic feasibility must be considered. A preliminary cost analysis based on literature data reveals encouraging prospects. The following table compares the estimated unit cost of cooling power for several technologies.

The analysis indicates that while the material cost per square meter for hybrid evaporative-assisted radiative cooling materials may be higher than for simple radiative cooling and regenerative evaporative cooling films, their significantly higher cooling power results in a notably lower cost per Watt of cooling power (Table 1). This unit cost is competitive with or even superior to completely passive radiative cooling and regenerative evaporative cooling films. This analysis suggests that evaporative-assisted radiative cooling possesses not only the potential to disrupt traditional technologies in physical performance but also the foundational economic potential for large-scale commercial adoption. However, due to the lack of unified lifetime evaluation standards and comparable long-term degradation data across different cooling technologies, the comparison mainly focuses on the initial cost-to-cooling capability relationship. Besides, global energy saving simulation maps demonstrate that while traditional radiative coolers have limited potential in humid regions, adaptive hybrid materials maintain significant performance nearly globally, unlocking immense energy-saving and emission-reduction potential (Figure 2E).[25] A comprehensive performance radar chart comparison shows that hybrid evaporative-assisted radiative cooling systems outperform traditional pure radiative cooling across all core dimensions: cooling power density, maximum temperature depression, climate adaptability, thermal regulation intelligence, and functional synergy (Figure 2F). This marks the transition of passive cooling technology from a static, clumsy, weather-dependent tool to a dynamic, intelligent, environmentally interactive, and economically friendly thermal management system.

ADVANCED HYBRID COOLING MATERIALS AND STRUCTURES

Translating the theoretical concept of synergistic cooling into practical, high-performance systems demands innovative material embodiments capable of co-managing the transport of photons, phonons, and water molecules across multiple scales.[46] This challenge has inspired a progression of material architectures, evolving from functionally decoupled designs to fully integrated and, ultimately, intelligent adaptive systems. Each paradigm embodies a distinct design philosophy to master the interplay between optical, thermal, and hydraulic properties.

Tandem architecture

The most straightforward approach to integration is the tandem architecture, which employs a vertical, stratified design to physically separate the optical and hydraulic functions (Figure 3A). This strategy enables the independent optimization of each layer. The top layer acts as a spectral management engine, designed for extreme selectivity and reflectivity. Strategies include photonic crystals and multilayer dielectric films, which offer near-ideal performance through precise periodic structures but face scalability challenges. Highly porous electrospun nanofiber membranes and random scattering particle composites balance high solar reflectance via Mie scattering with intrinsic infrared emissivity for cost-effective, large-area fabrication, and metal reflector/selective emitter stacks.[13,47,48] The bottom layer functions as the hydraulic engine. Porous hydrogels, with their immense water-holding capacity and capillary-driven transport, are prime candidates. For enhanced autonomy, hygroscopic salt (e.g., LiCl and $CaCl_2$) composites can be integrated to enable atmospheric water harvesting, creating a capture-and-release cycle.

A prominent example of this architecture is a bilayer polymer tandem cooler, comprising a top cellulose acetate (CA) fibrous

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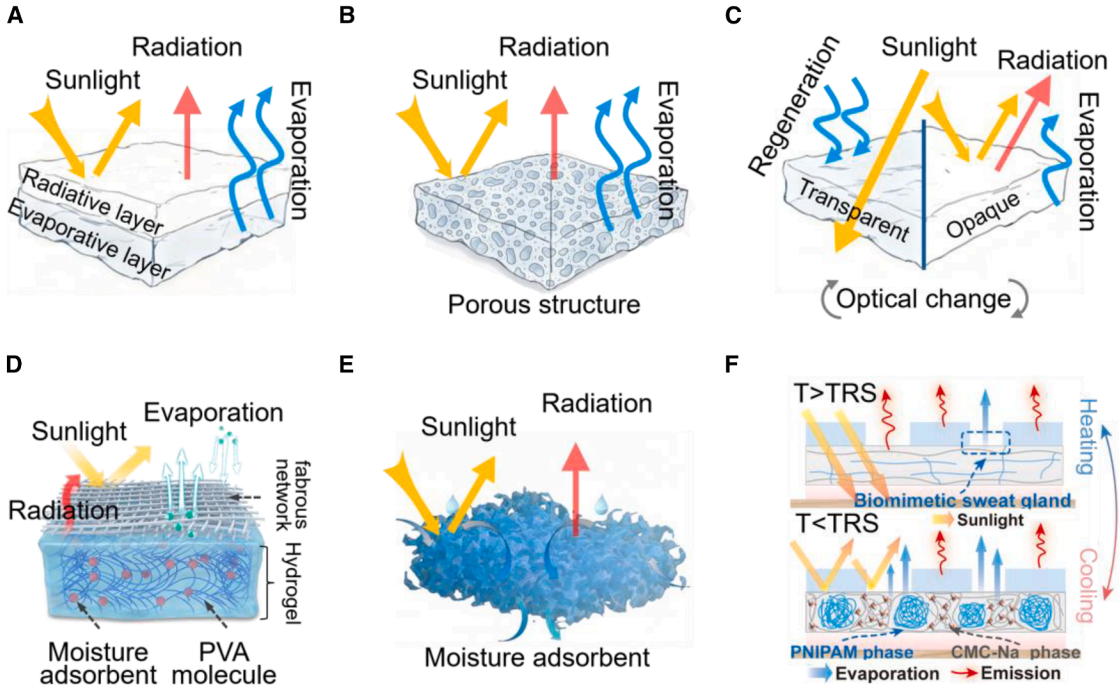

Figure 3. Structures and advantages of evaporative-assisted radiative cooling materials

(A) Tandem architecture consisting of a radiative cooling layer and an evaporative cooling layer.

(B) A porous network integrating spectral selectivity and capillary moisture transport.

(C) A stimuli-responsive adaptive structure capable of dynamic state switching.

(D) Implementation of the tandem/hybrid concept utilizing atmospheric water harvesting networks to sustain high-power daytime evaporation. Reprinted with permission from Li et al.[24]

(E) Mechanism of continuous moisture absorption and vapor diffusion within a highly porous hydrogel composite matrix.[49]

(F) A skin-inspired biomimetic layered gel featuring thermo-responsive components. Reprinted with permission from Guo et al.[50]

network and a bottom poly(vinyl alcohol)-$CaCl_2$ (PVA-$CaCl_2$) hydrogel layer (Figure 3D).[24] The electrospun CA network acts as the radiative cooling layer, exhibiting high solar reflectivity (~0.95) and strong mid-infrared emissivity (~0.94 in the 8–13 μm window). The PVA-$CaCl_2$ hydrogel serves as the hydraulic layer, capable of adsorbing substantial atmospheric moisture during nighttime, which is subsequently utilized for daytime evaporative cooling. A key design feature is the engineering of the top CA layer to be hydrophobic and highly vapor-permeable. This critical attribute allows water vapor to diffuse through while preventing liquid water from wetting the top surface, thereby confining water within the bottom hydrogel and averting the severe degradation of solar reflectance that would occur if the radiative surface itself became wet. This design effectively tackles the water-sunlight absorption conflict inherent in tandem systems. Consequently, this cooler demonstrated a sub-ambient cooling temperature of ~10°C on a clear day, significantly outperforming a pure radiative cooler, and maintained a ~2.7°C sub-ambient temperature even on a cloudy day where the radiative cooler failed. Its cooling power reached 200–240 W m^{-2}, nearly double that of its standalone radiative cooling component. While this architecture facilitates top-tier, independently optimized performance and eases maintenance, it introduces challenges such as interfacial thermal resistance, potentially long vapor diffusion paths, and structural complexity.

Integrated network architecture

In contrast to the layered approach, the integrated network architecture pursues functional unity within a single, homogeneous matrix (Figure 3B).[51] Such architectures generally require an intrinsically multifunctional framework capable of simultaneously integrating optical regulation, water management, vapor transport, and mechanical stability within one continuous material system.[52] A representative example of this strategy is the utilization of atmospheric moisture to convert low-cost sodium polyacrylate (PAAS) powder into a continuous and flexible hydrogel film (Figure 3E).[49] This approach yields a monolithic material system that intrinsically integrates the optical and hydraulic functionalities required for hybrid cooling. The resulting PAAS photonic film combines radiative and evaporative cooling functions within a porous hydrogel network (Figure 3E). In this system, the hydrophilic PAAS polymer framework serves not only as a water-transport matrix but also as an efficient infrared emitter with a high emissivity of approximately 0.99 across the atmospheric window. Meanwhile, the spontaneously generated hierarchical porous structure, spanning from tens of nanometers to tens of micrometers, simultaneously fulfills several critical functions: efficient backscattering of solar radiation with a solar reflectance of approximately 0.93, storage and capillary-driven transport of absorbed atmospheric moisture, and provision of interconnected diffusion pathways for vapor evaporation.

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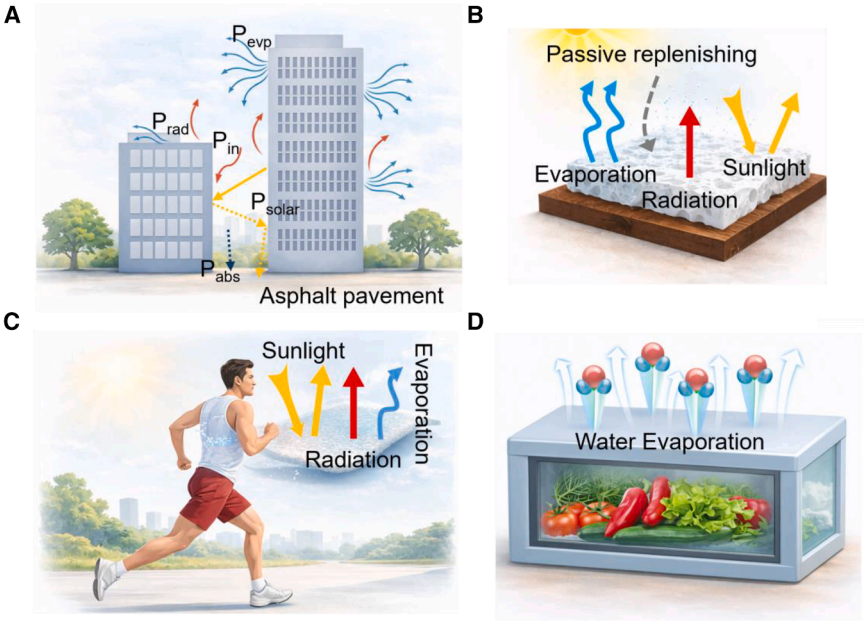

Figure 4. Applications of evaporative-assisted radiative cooling technology

(A) Mechanism for the cement-based cooling paint applied to urban building facades. Reprinted with permission from Fei et al.[59]

(B) Evaporative-assisted radiative cooling paint for buildings.

(C) Hierarchically designed metafabric for personal cooling.

(D) Illustration of food preservation.

Furthermore, regulation of the fabrication conditions, which determine the porosity and pore hierarchy, enables tunable optimization of the balance among mechanical strength, water retention capacity, and evaporation kinetics.

Compared with layered configurations, this monolithic architecture effectively eliminates interfacial incompatibility and delamination issues while improving structural robustness and mechanical flexibility, as demonstrated by its self-healing behavior and recovery after deformation.[53] These characteristics make integrated network systems particularly attractive for scalable and low-cost applications requiring conformability and large-area deployment, such as wearable cooling platforms and surface coatings.

Adaptive architecture

Another promising design is to transition from static structures to dynamically intelligent surfaces that autonomously optimize performance in response to environmental fluxes.[54] Adaptive architectures integrate stimulus-responsive components to modulate their cooling behavior (Figure 3C). The most common trigger is temperature, using thermo-responsive polymers like poly(N-isopropylacrylamide). Below its lower critical solution temperature, the polymer is hydrophilic and swollen, permitting high water transport and evaporation; above it, a hydrophilic-to-hydrophobic transition collapses the network, suppressing evaporation and conserving water (Figure 3F).[50] Humidity-responsive components adjust the material's swelling ratio to modulate the evaporation area. Furthermore, light/heat dual-response systems can be created by incorporating photothermal agents, using sunlight itself to locally trigger the opening of cooling channels.[55] Inspired by biological tissues like skin, more sophisticated designs implement hierarchical, multi-layer structures that separate optical, regulatory, and reservoir functions, enabling precise, on-demand management of the water supply and evaporation front.[56]

A representative embodiment of this architecture is a hydrogel-elastomer hybrid for passive, temperature-adaptive regulation.[57] The system features a clear functional stratification: a top polyacrylamide (PAM) hydrogel layer acts as the evaporative cooling engine, utilizing its porous structure to hold and release water. A middle thermochromic PVA-Borax-Poly(N-isopropylacrylamide) (PBN) hydrogel layer serves a dual purpose. It primarily functions as a dynamic spectral management layer, undergoing a reversible transparent-to-opaque transition upon heating above its lower critical solution temperature. This switch modulates solar transmittance by ~85% and reflectance by ~42%, providing adaptive solar reflection. Concurrently, the PBN hydrogel and the materials maintain high mid-infrared emissivity, contributing to radiative cooling. The bottom layer consists of a boric acid-polydimethylsiloxane (B-PDMS) elastomer. This layer acts as a protective, waterproof barrier that encapsulates the PBN hydrogel, ensuring its thermochromic stability by inhibiting moisture loss, and provides structural integrity to the hybrid film. These microstructural innovations confer revolutionary macroscopic benefits, transforming passive cooling from a static, climate-vulnerable technology into a dynamic, resilient, and highly efficient thermal management system adaptable to a wide range of environments and applications.

APPLICATION PROSPECTS: FROM URBAN-SCALE TO PERSONAL THERMAL MANAGEMENT

Evaporative-assisted radiative cooling technology, with its disruptive characteristics of zero energy consumption, high power, and strong adaptability, is poised to trigger cascading changes across numerous sectors with pressing thermal management needs, serving as a key technological pillar for building a sustainable society.

Building envelopes and urban-scale cooling

The building sector, a major energy consumer and carbon emitter, represents the most scalable application for this technology (Figures 4A and 4B). Roof and facade coatings or cladding made from hybrid cooling materials can significantly reduce surface temperatures and cooling loads for various buildings, especially large industrial facilities and data centers.[58] Energy-efficient

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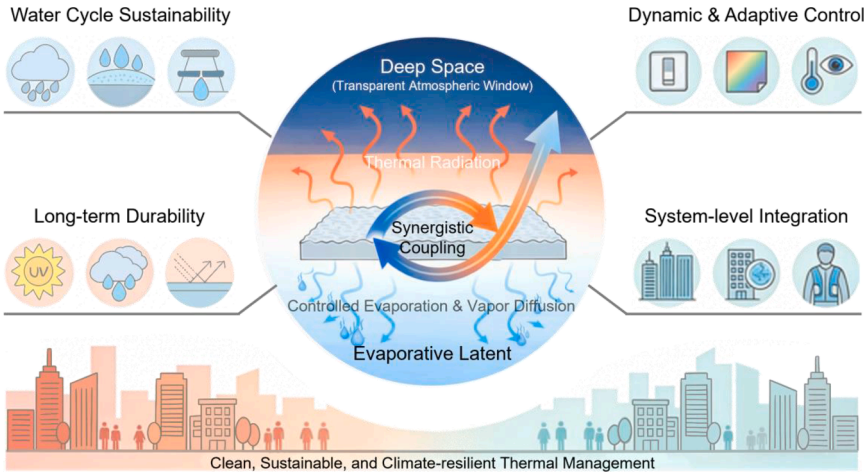

Figure 5. Summary and future perspectives

smart windows and glazing incorporating transparent or translucent hybrid cooling interlayers or films can dissipate absorbed solar and indoor heat through evaporation and radiation, addressing the overheating problem in glazed buildings.[59] Passive cooling towers or radiative-evaporative condensers can be designed as modular add-ons for building HVAC systems or small data centers, reducing or eliminating water and fan energy use in dry climates and enhancing efficiency in humid ones compared to pure radiative units.[60] Applying the technology to urban surfaces like square pavers, bus shelter roofs, and park structures can directly lower local ambient temperatures, mitigate the urban heat island effect, and improve outdoor thermal comfort.

Personal thermal management and wearable devices

Extreme heat threatens outdoor workers and impacts public well-being, creating a vast market for personal cooling.[61] Next-generation cooling textiles and smart garments integrating flexible hybrid cooling materials can be used in workwear, sportswear, and especially protective gear for firefighters and industrial workers (Figure 4C).[62] Utilizing sweat or stored water, they create a cooling microclimate, reducing heat stress and enhancing safety and performance. Integration with flexible sensors enables real-time monitoring and closed-loop regulation.[63] Portable personal cooling devices like cooling neck wraps, vests, helmet liners, and seat pads based on this technology provide immediate, electricity-free cooling for outdoor workers, athletes, commuters, and in off-grid scenarios like disaster relief or camping.

Electronics thermal management and industrial process cooling

The performance and lifespan of electronics are critically temperature-dependent, driving demand for efficient passive cooling.[64] Photovoltaic panel cooling by attaching hybrid cooling films to panel backs can lower cell operating temperature, boosting electricity generation efficiency and extending module lifespan, particularly beneficial for large solar farms in hot, arid regions. Thermal management for outdoor communication and power equipment like 5G base stations and transformers can be enhanced with passive cooling modules, ensuring stable operation in extreme weather and reducing reliance on air conditioning.[65] High-performance electronics cooling may explore integrated heat sinks combining microchannel evaporation with surface radiative cooling to handle very high heat fluxes.

Food preservation and agriculture

An estimated one-third of global food production is lost due to a lack of effective refrigeration in the supply chain. Passive cooling offers a low-cost solution for the last mile and remote areas. Passive cold chain transport boxes and mobile cold rooms with hybrid cooling functionality can extend the shelf life of fresh produce and vaccines during short-haul transport or temporary storage, ideal for rural cooperatives or emergency response (Figure 4D).[57] Post-harvest produce precooling and energy-efficient cold storage can utilize passive cooling sheds for rapid field heat removal or as part of cold storage building envelopes to reduce mechanical cooling load. The most forward-looking applications integrate the technology into macroscopic resource circulation systems. Atmospheric water-harvesting-coupled cooling and water production systems can provide cooling by day and collect water by night, addressing both needs in arid regions. Collected water can be used for drinking, irrigation, or to replenish evaporation. Solar photovoltaic-thermal-cooling synergistic systems combine with PV panels for cooling, while potentially using PV waste heat to drive adsorption-desorption cycles, enhancing system performance. Smart agricultural greenhouse climate control can use hybrid materials to reflect excess sun and provide evaporative cooling in summer, reducing ventilation needs, and potentially utilize radiative cooling at night for specialized crops.[66]

CHALLENGES AND OUTLOOK: TOWARD PRACTICAL APPLICATION AND INTELLIGENT FUTURES

Despite impressive laboratory achievements, evaporative-assisted radiative cooling technology must confront and overcome a series of severe scientific, engineering, and system integration challenges toward large-scale commercial application (Figure 5).

Operational water, energy, and life cycles

Beyond static durability, the true potential of evaporative-assisted radiative cooling technology lies in its ability to intelligently manage dynamic resource cycles during operation. A core challenge and opportunity is the establishment of a stable, climate-resilient water autonomy cycle. The atmospheric moisture "adsorption-storage-evaporation" loop must be engineered for reliable long-term function. This involves optimizing materials and structures to balance adsorption kinetics with evaporation rates across diverse climates, managing the potential accumulation of airborne pollutants within the porous matrix, and preventing performance decay. Achieving this demands adaptive, predictive system control. Besides, a full life cycle sustainability

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assessment must rigorously evaluate the technology from cradle to grave, ensuring net positive environmental impact and promoting designs for recyclability or biodegradability.

Dynamic climate adaptability and intelligent control

Materials need to evolve from static, set-and-forget states to dynamic sense-decide-respond entities. Multi-stimuli responsive coordination and optimization are needed for future smart materials to respond smoothly and reversibly to combined signals like temperature, humidity, and light, requiring careful design of response thresholds and kinetics to avoid instability. Predictive control for system energy efficiency maximization involves integrating low-cost sensors and microcontrollers with weather forecasts and machine learning algorithms for preemptive adaptation, optimizing operation for cooling demand, water use, and material life.

Long-term durability and environmental reliability

The long-term retention of material performance under harsh outdoor conditions is the primary hurdle. Irreversible degradation of optical performance can occur due to UV-induced polymer degradation, soiling, abrasion, and microbial growth, reducing solar reflectance.[67] Solutions include developing inorganic binders, self-cleaning surfaces, and UV stabilizers. Functional degradation of hydrogel or porous structures may involve mechanical fatigue from wet-dry or freeze-thaw cycles, leakage of deliquescent salts, and microbial fouling. Research focuses on anti-freezing, anti-shrinkage, antimicrobial, and salt-stabilizing composite systems via interpenetrating networks or hybridization. Long-term stability of self-sustaining water cycles requires field validation to understand the balance between adsorption, storage, and evaporation under real, varying climates, and the impact of airborne pollutants on material properties over time.[68]

System-level integration and scalable manufacturing

A significant engineering gap exists between lab samples and industrial products. Seamless integration with buildings and infrastructure requires developing modular, standardized product forms and compatible installation details, waterproofing, drainage, and interfaces with building rainwater systems, all while meeting building code safety standards.[18,69] Low-cost, scalable manufacturing processes such as roll-to-roll coating, large-area spraying, and three-dimensional (3D) printing must be developed. Balancing performance and cost through techno-economic analysis is crucial, favoring industrial-grade materials.

CONCLUSION

Evaporative-assisted radiative cooling represents a paradigm shift in passive thermal management, transcending the optimization of individual physical mechanisms. This review has elucidated the core principles that enable the breakthrough of the traditional cooling power ceiling and has outlined viable implementation pathways. Despite persistent challenges in durability, dynamic response, system integration, and cost-effectiveness, the technology's transformative potential is clear. Its significance stems from broad applicability and extensibility across critical sectors, while a competitive projected cost per unit of cooling power underscores its strong potential for market adoption and scalability. Realizing this potential requires concerted cross-disciplinary collaboration, involving materials scientists, chemical and mechanical engineers, architects, urban planners, industry, and policymakers to advance materials, system integration, sustainable design, manufacturing, and supportive market frameworks.

In summary, evaporative-assisted radiative cooling represents a critical advance toward a new paradigm in thermal management, one in which effective cooling is fundamentally decoupled from high energy consumption and adverse environmental impacts. By integrating natural thermodynamic principles with advanced materials science, this technology is positioned to transition from a promising research concept into a foundational element of sustainable infrastructure. It thereby offers a viable and impactful pathway to mitigate global warming and contribute to a sustainable, low-carbon future.

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DECLARATION OF INTERESTS

The authors declare no competing interests.

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