© APR 2026 | IRE Journals | Volume 9 Issue 10 | ISSN: 2456-8880
DOI: https://doi.org/10.64388/IREV9I10-1716793

Hydrogel-Based Passive Cooling for Photovoltaic Systems: Mechanisms, Materials Design, and Performance Benchmarking

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Abstract- The power conversion efficiency of photovoltaic (PV) solar cells deteriorates markedly as operating temperatures rise above ambient, with silicon-based modules losing roughly 0.45% of efficiency per degree Celsius of excess heat. Conventional active cooling— water spraying, forced-air circulation— restores performance but consumes electricity and complicates installation. Passive evaporative cooling by hydrogels presents a zero-energy alternative that exploits the large latent heat of water vaporization (approximately 2450 J g^{-1}). This seminar paper synthesizes three recent studies that collectively advance the design, characterization, and deployment of hydrogel-based cooling systems for photovoltaics. Li et al. (Small, 2026) engineered a spectrally tailored, Janus-structured, LiCl- embedded two-layer membrane capable of simultaneous evaporative and radiative cooling from the front surface of both rigid silicon and flexible polymer solar cells, achieving a maximum efficiency improvement of 21.3% under outdoor conditions. Tadano et al. (Journal of Applied Polymer Science, 2024) demonstrated that macroporous polyacrylamide hydrogels fabricated by slow-rate freeze casting sustain stable, capillary-fed evaporative cooling even under airflow, reducing target temperatures by up to 72°C relative to the uncooled baseline. Lapsirivatkul et al. (Advanced Materials Technologies, 2025) showed that semi-interpenetrating polymer networks of poly(N-isopropylacrylamide) and polyacrylamide combine a swelling ratio of 30 with a rapid water release rate and a specific cooling power of 1.86 W g^{-1}, cooling silicon PV cells by 23°C while requiring only 5.1 kg m^{-2} of material— approximately 90% less than conventional phase-change materials. Together, these works reveal how hydrogel architecture, porosity, hygroscopic salt loading, optical properties, and thermoresponsive phase transitions can be co-engineered to maximize photovoltaic performance under realistic operating conditions.

Keywords: hydrogel cooling; photovoltaics; evaporative cooling; radiative cooling; PNIPAM; polyacrylamide; freeze casting; Janus membrane; hygroscopic composites.

I. INTRODUCTION

Solar photovoltaic technology now represents the fastest-growing segment of global renewable energy capacity, and its continued expansion is constrained not only by materials cost but also by thermally induced efficiency losses and accelerated degradation. Under standard test conditions, a crystalline silicon (c-Si) module operating at 50°C above ambient loses approximately 22.5% of its rated efficiency, equivalent to the output forgone every time clouds part on a hot summer afternoon. At the system level, this represents billions of kilowatt-hours of unrealized generation annually across the installed global fleet, and the problem will intensify as average surface temperatures rise and solar installations expand into hotter climates.

Active cooling solutions—water spray systems, forced-convection fans, thermoelectric coolers—are thermodynamically effective but parasitic: they consume electrical power and mechanical infrastructure whose lifecycle costs and maintenance requirements offset a portion of the efficiency gains. Passive cooling, by contrast, operates without external power input by harnessing physical phenomena such as evaporation, thermal radiation, or conductive heat spreading. Among passive approaches, hydrogel-based evaporative cooling has attracted considerable recent attention because hydrogels can store and release large quantities of water in a controlled fashion, conform to irregular surfaces, and be chemically modified to absorb atmospheric moisture autonomously.

Despite this promise, the field faces three interrelated challenges that the studies reviewed here directly address. First, most hygroscopic hydrogel coatings have been applied to the rear surfaces of solar panels, where they are shielded from direct sunlight but also isolated from the primary heat source; deploying them on the front surface requires tight spectral control so that visible and near-infrared light reaching the photovoltaic junction is not attenuated. Second, the conventional non-porous hydrogel matrix exhausts its water reservoir within hours of operation and must be manually recharged; creating stable capillary-fed architectures that maintain continuous water supply over extended periods is a materials engineering challenge. Third, the rate of water release—not merely the total capacity—determines instantaneous cooling power, but this kinetic parameter had not been rigorously quantified until differential thermal analysis was applied to thermoresponsive systems.

This paper is structured as follows. Section 2 provides detailed summaries of each of the three source studies, preserving their individual design rationales and key findings. Section 3 draws cross-cutting comparisons across the three systems, identifying common principles and divergences. Section 4 discusses limitations and proposes directions for future research. Section 5 presents conclusions.

II. REVIEW OF INDIVIDUAL STUDIES

2.1 Spectrally Tailored Hygroscopic Hydrogels with Janus Interfaces (Li et al., Small 2026)

Li and colleagues addressed the most demanding variant of the front-surface cooling problem: deploying a hygroscopic membrane directly on top of the photovoltaic junction without impairing light collection. Their solution, denoted M3, is a two-layer composite hydrogel whose bottom layer (M2) and top layer (M1) are synthesized from the same zwitterionic copolymer of [2-(methacryloyloxy)ethyl]dimethyl-(3-sulfopropyl)ammonium hydroxide (DMAPS) and 2-hydroxyethylacrylamide (HEAA), but under radically different crosslinking and initiator conditions that produce opposite network architectures and hence opposite interfacial behaviors.

The bottom layer M2 was prepared at an extremely high polymer concentration of 65 wt%, with crosslinker and initiator present at molar ratios orders of magnitude below the conventional range. Under these conditions, chain entanglement rather than covalent crosslinks dominates the network, producing a mechanically robust material with a tensile strength of 10.5 MPa, fracture strain of 787%, and an adhesion strength on glass that reaches 1.52 MPa. The zwitterionic DMAPS units, present at 46 wt% within M2, coordinate lithium and chloride ions through electrostatic interactions that suppress LiCl crystallization even at a 10 wt% salt loading, effectively eliminating salt leakage. The top layer M1, by contrast, was prepared at only 20 wt% polymer with a high crosslinker-to-monomer ratio of 0.3% and a polyanionic cellulose (PAC) secondary component forming a semi-interpenetrating network. This architecture yields a highly crosslinked, brittle material with negligible adhesion to any substrate, a LiCl loading of 20 wt%, and high mid-infrared emissivity arising from the C–O–C stretching vibrations of the cellulose backbone and the sulfonate stretching of the DMAPS units.

The resulting bilayer membrane M3 (total thickness 3 mm, comprising equal 1.5 mm sublayers) displays a Janus functionality: the M2 side bonds firmly to the glass encapsulation of the solar panel while the M1 side presents an antifouling, non-adhesive outer surface that self-cleans under a damp cloth. Optically, M3 achieves approximately 90% average transmittance across the 270–1450 nm range that encompasses the photovoltaic absorption band of c-Si, while blocking near-infrared photons above 1450 nm that would otherwise contribute to panel heating. In the mid-infrared atmospheric transparency window of 8–13 μm, M3 achieves an average emissivity of 98.1%, enabling effective radiative heat rejection to the cold sky.

A key mechanistic discovery concerns directional water diffusion within the bilayer driven by osmotic pressure gradients. M2, with its highly entangled network, possesses a swelling ratio in LiCl solution of approximately 21.4 g/g, far exceeding the 4.5 g/g of M1. When moisture is absorbed at the M1/air interface, the osmotic pressure differential drives water migration from M1 into M2, effectively transferring the captured water from the surface into the bulk of the membrane where it is stored against leakage. This mechanism elevates the total 24-hour water uptake of M3 to 282 g m^{-2}, significantly above what either layer achieves independently. Reversibility was confirmed over 20 sorption–desorption cycles with no measurable degradation in capacity or salt distribution, and scanning electron microscopy with energy-dispersive X-ray spectroscopy showed unchanged elemental distributions across both layers after cycling.

Indoor photovoltaic experiments under 1.0 sun illumination showed that M3-covered c-Si cells maintained surface temperatures 7.7°C lower than bare cells after 12 hours of continuous irradiation, with initial evaporative cooling powers exceeding 460 W m^{-2}. Outdoor experiments conducted over seven days in Qingdao, China, revealed peak temperature reductions of 12.1°C under calm-wind conditions and a peak power conversion efficiency improvement of 21.3%. Nightly radiative cooling reduced panel temperature to 6°C below ambient, increasing the effective relative humidity at the panel surface and thereby accelerating moisture re-absorption for the following day's cooling cycle. The membrane also demonstrated applicability to flexible organic polymer solar cells, maintaining approximately 98% of initial efficiency after 10,000 bending cycles at a radius of 5 mm.

2.2 Macroporous Hydrogels with Stable Water Transport via Freeze Casting (Tadano et al., J. Appl. Polym. Sci. 2024)

Tadano and colleagues approached the problem of cooling stability from the perspective of water transport engineering. Their insight was that conventional dense polyacrylamide hydrogels lose cooling effectiveness rapidly because water evaporated from the upper surface cannot be replenished from below fast enough to sustain the evaporative flux; within two hours at moderate heat inputs, the column tops dry out completely and cooling ceases. Their solution was to introduce a macroporous architecture in which organized columns of hydrogel material are separated by open channels that simultaneously serve as vapor-escape pathways and secondary convective paths for airflow enhancement.

The macroporous freeze-cast polyacrylamide hydrogel (FC-PAM) was synthesized by pouring an acrylamide/bisacrylamide/initiator precursor solution into a structured aluminum mold that defined a hexagonal array of cylindrical channels 6 mm in diameter, then cooling the assembly at −10°C to freeze the solution prior to UV-initiated cryopolymerization at −15°C for two hours. The slow cooling rate was deliberately chosen to promote random ice crystal nucleation and isotropic growth rather than the aligned lamellar microstructure associated with fast directional freezing; the resulting pores in the dried polymer are roughly circular in cross-section with a heterogeneous size distribution in the range of tens to hundreds of micrometers. The fully swollen FC-PAM hydrogel measures 68 mm in outer diameter, 11 mm in height, and weighs 30 g, placing it among the largest hydrogel specimens fabricated by a freezing-assisted route according to a survey of the literature.

Water absorption kinetics were characterized by dipping a dried FC-PAM disc in dye-stained water and recording the wetting front height with a camera. The liquid fully penetrated the 11 mm tall specimen within 3 seconds—a rate superior to other freeze-cast polyacrylamide geometries reported in the literature, though slightly below that of cellulose sponges. Analysis of the height-time relationship revealed two distinct power-law regimes: an early phase consistent with the Lucas– Washburn h ~ t^(1/2) scaling when macropores are being filled, transitioning to h ~ t^(1/5) behavior once the wetting front exceeds Jurin's height and capillary forces drive flow through the microporous network walls.

Cooling performance was evaluated by placing the FC-PAM hydrogel in thermal contact with an aluminum heating block supplied with controlled electrical power while tracking the equilibrium block temperature after 120 minutes. At a heat input of 7.7 W (equivalent to approximately 2.0 kW m⁻²), the FC-PAM hydrogel maintained the aluminum block at 72°C, compared to 142°C for the same block without any hydrogel—a reduction of 70°C. The conventional dense PAM hydrogel under the same conditions produced a monotonically rising temperature that reached 88°C after 120 minutes and continued to climb, confirming that the macroporous architecture and its associated capillary water supply are the critical distinctions. Under added airflow from a small fan, the FC-PAM hydrogel maintained even lower temperatures (for example, 52°C at 8.0 W input), and performance remained stable over the entire two-hour test duration with temperature variation below 5°C. A comparison against twelve published hydrogel cooling results showed that FC-PAM data points fell consistently below the trend line of all prior work on a plot of temperature with versus without cooling material, indicating superior cooling efficacy across the tested power range.

2.3 Lightweight PNIPAM/PAM Semi-IPN Hydrogels for PV Passive Cooling (Lapsirivatkul et al., Adv. Mater. Technol. 2025)

Lapsirivatkul and colleagues began with the thermoresponsive hydrogel concept pioneered by Rotzetter et al. in 2012, which showed that poly(N-isopropylacrylamide) (PNIPAM) undergoes a volume phase transition near 32–33°C, expelling absorbed water when the temperature exceeds this threshold and thereby generating a burst of evaporative cooling precisely when the photovoltaic surface is hottest. Their contribution was to systematically investigate how forming semi- interpenetrating polymer networks (semi-IPNs) of PNIPAM with three common hydrophilic polymers—poly(vinyl alcohol), poly(ethylene glycol), and polyacrylamide—modifies swelling ratio, water release kinetics, and ultimately cooling power, with the goal of identifying an optimal formulation for practical PV deployment.

Semi-IPN hydrogels were synthesized by radical polymerization of N-isopropylacrylamide in the presence of dissolved linear polymer (PVA, PEG, or PAM), with di(ethylene glycol) diacrylate as crosslinker. The linear polymer component is physically entangled within the PNIPAM network but not covalently bonded to it. Compositions were varied from 5 to 30 wt% secondary polymer, and the effects on swelling ratio (SR) and water release ratio (WR) were measured. Among all compositions tested, 15 wt% PNIPAM/PAM demonstrated the highest SR of 30—a 57% improvement over pure PNIPAM at SR = 19—and the fastest water release: 82% of absorbed water expelled within the first 10 minutes at 60°C. The superior performance was attributed to scanning electron microscopy observations that revealed a fine, regular sponge-like pore structure in the 15 wt% PNIPAM/PAM hydrogel; higher PAM loadings introduced plate-like wall structures that partially blocked pore channels, reducing the release rate.

A key methodological innovation was the application of differential thermal analysis (DTA) to directly quantify specific cooling power (SCP). The hydrogel sample was maintained at a setpoint temperature of 60°C while the instrument recorded the additional heat flux required to sustain this temperature against the endothermic cooling by water evaporation. Using hexacosane as a calibration standard, the raw DTA signals in microvolts were converted to watts. The 15 wt% PNIPAM/PAM hydrogel exhibited the largest endothermic DTA peak, corresponding to an SCP of 1.86 W g⁻¹—52% greater than pure PNIPAM at 1.20 W g⁻¹. Importantly, the specific cooling capacity (total enthalpy normalized by mass) was nearly identical for all compositions at approximately 2060–2160 J g⁻¹, confirming that all samples ultimately dissipate the same amount of heat per gram of water; the distinguishing factor is the rate at which this heat is released, which is controlled by pore structure and the hydrophilicity of the secondary polymer network.
Applied to the rear surface of commercial polycrystalline silicon solar cells under 1000 W m⁻² simulated sunlight, the 15 wt% PNIPAM/PAM hydrogels reduced the cell temperature from 70°C to approximately 47°C over three repeated heating cycles—a reduction of 23°C. This contrasts with the 15°C reduction obtained with pure PNIPAM hydrogels, representing a 53% improvement. The average power conversion efficiency of the cooled cells rose from 12.2% to 13.7%, a relative improvement of 12.3%. The fully swollen mass of hydrogel required per unit cell area was approximately 5.1 kg m⁻², compared to the 26–52 kg m⁻² typically cited for phase-change materials

achieving comparable temperature reductions. A stability test confirmed that only 5.6% of the PAM component was expelled from the gel during extreme dehydration at 70°C for 12 hours, suggesting good phase stability of the semi-IPN system under operating conditions.

III. CROSS-CUTTING THEMES AND COMPARATIVE ANALYSIS

3.1 The Central Role of Water Transport Kinetics

All three studies converge on the insight that water transport kinetics—not total water storage capacity—is the primary determinant of sustained cooling performance. Tadano et al. demonstrated this through direct comparison of dense and macroporous PAM hydrogels containing equal amounts of water; the dense system lost cooling efficacy within two hours as capillary replenishment failed to match the evaporative demand, while the macroporous system maintained stable temperatures for the full two-hour experimental window. Lapsirivatkul et al. established the same principle analytically: despite PNIPAM/PVA and PNIPAM/PAM hydrogels containing similar total water masses, the PNIPAM/PVA system retained water tenaciously (releasing only 30% after 180 minutes) and achieved a modest temperature reduction, while the PNIPAM/PAM system expelled 82% within ten minutes and delivered a dramatically larger cooling effect. Li et al. engineered directional inter-layer water diffusion by osmotic pressure gradient, ensuring that water absorbed at the surface is continuously transferred deeper into the membrane structure where it is protected from premature evaporation and where it can participate in the evaporative process closer to the heat source.

3.2 Network Architecture as the Primary Design Variable

Each study demonstrates a different strategy for controlling the polymer network architecture to achieve the desired transport properties. Tadano et al. used external physical templating via freeze casting, where ice crystals act as sacrificial pore formers that define macropores tens to hundreds of micrometers in diameter during cryopolymerization. The slow cooling rate produces randomly oriented, roughly circular pores that support the two-regime wicking behavior described by the Lucas– Washburn and capillary-pressure models. Lapsirivatkul et al. employed chemical network control by incorporating non-crosslinked linear polymer chains into the PNIPAM matrix during radical polymerization, creating a secondary interpenetrating architecture that modifies the pore density and surface hydrophilicity of the network without altering the primary PNIPAM chemistry. Li et al. differentiated network architecture between two macroscopic layers by varying initiator and crosslinker concentrations across a fourfold and a millionfold range, respectively, producing a highly entangled bottom layer and a highly crosslinked top layer within the same chemical system.

3.3 Cooling Mechanisms: Evaporative versus Hybrid

Tadano et al. and Lapsirivatkul et al. both operate purely through evaporative cooling: water vaporizes from the hydrogel surface, and the latent heat drawn from the underlying solid represents the entire cooling contribution. Their systems differ in how the evaporative flux is maintained (capillary feeding versus thermoresponsive expulsion) but share the same thermodynamic driving force. Li et al., uniquely, achieve hybrid cooling by combining evaporative and radiative mechanisms within a single material. During the day, solar-driven water evaporation provides the dominant cooling power, which they calculate as declining from approximately 460 W m^{-2} in the first hour to 89 W m^{-2} over 12 hours as the LiCl solution within the membrane concentrates. At night, when evaporation is negligible, the high mid-infrared emissivity of M3 enables radiative cooling to the sky, reducing panel temperature by approximately 6°C below ambient and simultaneously increasing effective relative humidity at the membrane surface to accelerate nocturnal moisture re-absorption.

3.4 Material Weight and Practical Deployment Considerations

One of the most practically significant findings across the three studies is the very different mass loading required relative to conventional phase-change materials. Lapsirivatkul et al. explicitly benchmarked PNIPAM/PAM hydrogels against PCMs and established a requirement of only 5.1 kg m^{-2} for a 23°C temperature reduction, compared to 26–52 kg m^{-2} for PCMs achieving 10–21°C reductions. The weight advantage stems from the high specific enthalpy of water vaporization (approximately 2250–2500 kJ kg^{-1} depending on temperature), which is more than two orders of magnitude larger than the latent heat of fusion of typical organic PCMs (150–250 kJ kg^{-1}). This means that hydrogels can deliver equivalent or superior thermal buffering with far less mass, reducing structural load on rooftop arrays and making the technology compatible with lightweight building-integrated photovoltaics. Li et al. implicitly operate in the same low-mass regime with a 3 mm membrane layer; Tadano et al. address a different deployment scenario (contact cooling of discrete electronic components and thermoelectric generators) where the absolute mass is less critical than the sustained temperature reduction.

3.5 Durability, Cycling, and Long-Term Stability

Durability assessment methodologies differ considerably across the three studies and reflect different primary failure modes. Li et al. performed 20 sorption–desorption cycles with gravimetric monitoring and post-cycling SEM–EDS analysis to confirm retained LiCl distribution, and supplemented this with 10,000 mechanical bending cycles on flexible solar cells to verify adhesion integrity. Lapsirivatkul et al. assessed phase stability by deliberately driving 15 wt% PNIPAM/PAM to complete desiccation at 70°C for 12 hours and characterizing the expelled residue by NMR spectroscopy; the small amount of PAM released (5.6% of the total) indicated adequate semi-IPN cohesion under extreme conditions. Tadano et al. confirmed stability through consistently flat temperature–time curves over the 30–120 minute window for all tested power inputs, contrasting sharply with the steadily rising temperature of the conventional dense PAM control. A gap that none of the studies fills is long-term outdoor durability over seasons: UV photostability, resistance to dust fouling and biological growth, and the effect of freeze–thaw cycles in cold climates remain open questions.

IV. LIMITATIONS AND FUTURE RESEARCH DIRECTIONS

Several limitations constrain the near-term deployment of the systems reviewed. The Janus hydrogel membrane of Li et al. operates under a cyclic day-night moisture exchange that depends on the ambient relative humidity exceeding a threshold at night; in arid climates where nocturnal humidity remains below 30–40%, the membrane may not recharge sufficiently to sustain daytime cooling beyond the first few operating cycles. The study was conducted over seven outdoor days in a coastal Chinese city with characteristically high nocturnal humidity, and systematic climate-sensitivity analysis across diverse deployment environments is absent from the current literature. Extending the system to rainfall-prone environments also requires investigation of whether the water-soluble LiCl is leached by precipitation; the authors' 15-day outdoor test showed no visible corrosion on the rear circuit, but quantitative leachate analysis was not performed.
The macroporous freeze-cast hydrogel of Tadano et al. requires a continuous external water source submerging the baseplate, which eliminates the system's independence from a liquid supply infrastructure. The authors acknowledge that incorporating hygroscopic salts into the macroporous matrix would enable atmospheric water harvesting, combining the structural water-transport advantages of the freeze-cast architecture with the self-adaptive replenishment demonstrated by salt- loaded systems elsewhere in the literature. The scalability of the freeze-casting process also merits attention: the current study employed a 70 mm × 70 mm mold cooled by a Peltier element, and extending this to square-meter-scale panels would require either large-format freezing equipment with tight temperature uniformity or modular tiling of smaller units, each of which introduces potential thermal bridging at inter-tile boundaries.

The PNIPAM/PAM semi-IPN hydrogels of Lapsirivatkul et al. are inherently consumable in the absence of an atmospheric water harvesting mechanism: the three-cycle cooling experiment on solar cells shows declining average temperature reduction in later cycles as the water reservoir depletes, and no self-regeneration was demonstrated.

The authors propose incorporating hygroscopic salts as a future modification; this combination—thermoresponsive expulsion kinetics plus hygroscopic recharge—would create a self-adaptive system that bridges the gap between the current work and salt- loaded hygroscopic composites. A further concern is the volume phase transition temperature of PNIPAM at approximately 33°C, which is below the typical rear-surface temperature of solar cells under full sun but above ambient temperatures in temperate climates. In winter or early morning conditions, the hydrogel may remain in the fully swollen state and not release water until the cell warms sufficiently, potentially delaying the onset of cooling relative to when it is most needed.

Looking across all three systems, the most impactful future direction is the development of composite architectures that combine the structural advantages of macroporosity, the thermodynamic advantages of hygroscopic salt loading, and the kinetic advantages of thermoresponsive expulsion within a single material. Such a system would absorb atmospheric water during cool, humid periods (aided by salts), release it rapidly when the panel overheats (aided by a VPTT slightly above the panel's no-cooling equilibrium temperature), and distribute it evenly to the evaporative surface via a capillary-fed macroporous scaffold. Computational modeling of the coupled heat and mass transfer—integrating the Fickian and Darcian transport regimes identified by Tadano et al. with the vapor pressure thermodynamics of concentrated salt solutions quantified by Li et al.—would provide a rational framework for optimizing pore size, salt loading, and thermoresponsive transition temperature simultaneously.

V. CONCLUSIONS

Three recent studies reviewed in this paper collectively advance the engineering basis for hydrogel- based passive cooling of photovoltaic systems. The following principal conclusions emerge from this analysis:

1. Hybrid cooling through concurrent evaporation and sky radiation is achievable in a single bilayer hydrogel membrane (Li et al.) by differentiating the crosslink density, LiCl content, infrared emissivity, and adhesion properties of two layers fabricated from the same monomer system. The resulting spectrally tailored Janus membrane achieves over 90% optical transmittance in the photovoltaic absorption window, 98% mid-infrared emissivity, and a peak outdoor efficiency improvement of 21.3%.
2. Macroporous hydrogel architectures produced by freeze casting (Tadano et al.) maintain stable evaporative cooling for extended periods by sustaining capillary water supply from a reservoir through a pore network that simultaneously provides vapor escape channels and airflow paths. Temperature reductions up to 70°C above uncooled baselines are achievable, with performance further enhanced under forced-convection airflow.
3. Semi-interpenetrating polymer networks of PNIPAM and polyacrylamide (Lapsirivatkul et al.) achieve the highest specific cooling power of the systems reviewed, at 1.86 W g^{-1}, by combining the thermoresponsive phase-transition expulsion mechanism of PNIPAM with the high hydrophilicity and fine regular porosity conferred by the PAM component. A 23°C temperature reduction is achieved with only 5.1 kg m^{-2} of material, approximately 90% lighter than phase-change material alternatives.
4. Water transport rate—not merely total water capacity—is the dominant determinant of cooling performance across all three systems. This insight, established definitively by the differential thermal analysis methodology introduced by Lapsirivatkul et al. and corroborated by the kinetic and structural findings of Tadano et al. and Li et al., should guide future material design toward optimizing evaporative flux rather than storage volume alone.
5. A convergence opportunity exists in composites that combine macroporous scaffold design, hygroscopic salt loading for atmospheric water harvesting, and thermoresponsive expulsion kinetics within a single material system. Realizing such a

composite—together with rigorous outdoor durability testing across diverse climates—represents the critical next step toward commercial deployment of hydrogel-based photovoltaic cooling.

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