

Laboratory-Scale Screening of Boron Nitride-Reinforced Hydrogel Cooling Layers for Passive Thermal Management of Photovoltaic Modules

Soundarya Shankar
itssoundarya.shankar@gmail.com

ABSTRACT

The rapid expansion of solar photovoltaics has increased interest in passive cooling materials that can reduce module temperature without additional electrical power. This study evaluated boron nitride (BN)-reinforced hydrogel sheets as rear-mounted cooling layers for miniature photovoltaic panels under controlled indoor irradiation. Hydrogels were fabricated from a poly(vinyl alcohol), κ -carrageenan, bovine gelatin, and cellulose nanocrystal matrix with 0, 3, 7, or 10 wt.% hexagonal BN. Each BN loading was tested with and without a flexible graphite foil interlayer. Thermal performance was measured across three independent 3 h irradiation runs, while swelling, three-hour water loss, and time-resolved voltage behavior were also analyzed. The graphite-free 7 wt.% BN sample, BN7G0, produced the strongest thermal response, reaching a mean midpoint temperature of 32.76 ± 0.28 °C and an 8.06 °C reduction relative to the uncooled control. BN10G0 also showed substantial cooling, with a 6.79 °C reduction. The 7 wt.% BN hydrogel had the highest swelling response, 823.81%, and retained most of its mass during irradiation, losing 4.97% over 3 h. However, water loss did not scale directly with cooling, since BN3G0 showed the highest relative water loss but only modest temperature reduction. These results indicate that cooling depended on a balance of water storage, water loss, filler loading, and interfacial configuration rather than evaporation or BN loading alone. Voltage measurements remained stable but did not establish photovoltaic power improvement. Overall, BN7G0 was the strongest formulation within this laboratory-scale screening study and provides a basis for future direct thermal, electrical, and outdoor durability testing.

Keywords: solar photovoltaics; passive cooling; hydrogel; boron nitride; graphite foil; thermal management; photovoltaic temperature control; evaporative cooling; freeze-thaw hydrogel; polymer composite; rear-mounted cooling layer; simulated sunlight; laboratory screening

1. INTRODUCTION

The increasing deployment of solar photovoltaics (PV) reflects the broader transition from fossil-fuel-based energy systems toward low-carbon electricity generation. Bamisile et al. (1) reviewed

the environmental factors affecting solar photovoltaic output and identified temperature as one of the dominant variables governing PV performance. In crystalline silicon modules, elevated operating temperature reduces electrical efficiency, increases thermal stress, promotes hotspot formation, and contributes to long-term material degradation. Bamisile et al. (1) further noted that PV output commonly decreases by approximately 0.4-0.5% per °C rise in temperature.

To mitigate overheating, both active and passive cooling strategies have been investigated. El Kassar et al. (2) provided a comprehensive review of phase change materials (PCMs) for photovoltaic thermal management and described their ability to absorb thermal loads during phase transition, while also identifying major constraints including low thermal conductivity, leakage risk, added mass, and encapsulation requirements. Lee and Kim (3) reviewed organic-based phase-change thermal interface materials for electronics cooling and showed that thermally conductive interface layers can enhance heat transfer, although material integration and interfacial design can introduce additional performance tradeoffs. These limitations have motivated the development of lightweight, conformal, and low-maintenance passive materials for PV thermal regulation.

Hydrogel-based cooling layers provide a distinct passive thermal-management pathway compared with PCM-based systems. Rather than relying primarily on latent heat storage, hydrogels can retain water and support water-mediated heat dissipation during irradiation. This makes them attractive for lightweight PV cooling applications where passive operation and simple rear-surface integration are desirable (4-6,11,12,14). However, plain hydrogels are limited by their relatively low intrinsic thermal conductivity, which can restrict heat transfer from the PV rear surface into the bulk cooling layer (7). Therefore, a more effective hydrogel-based cooling material may require both water-retention capacity and thermally conductive filler reinforcement.

In the present study, hexagonal boron nitride was selected as the thermally conductive filler because it is widely used as a thermally conductive but electrically insulating ceramic additive. The goal was not to prove a universal BN percolation threshold, but to evaluate whether varying BN loading changed the thermal response of a water-rich hydrogel cooling layer under the same laboratory irradiation conditions.

Recent studies have demonstrated the potential of hydrogel materials for passive PV cooling. Lapsirivatkul et al. (4) reported a lightweight hydrogel system for passive cooling of solar cells, while Liu et al. (5) developed a biomimetic thermo-responsive hydrogel coating for passive photovoltaic cooling based on self-adaptive water management. Fang et al. (6) described a low-maintenance hygroscopic composite for evaporative cooling of solar panels and emphasized that sustained water release during daytime operation is more important than maximizing one-time water uptake alone. Xie et al. (11) investigated thermally responsive hydrogels for passive temperature regulation under direct sunlight, Yang et al. (12) demonstrated hydrogels with dual cooling and warming functions for year-round photovoltaic performance enhancement, Pandey et al. (13) experimentally evaluated a hydrogel-based passive thermal-management system for battery cooling, and Ye et al. (14) reported a radiative-coupled evaporative-cooling hydrogel for above-ambient heat dissipation. Together, these studies indicate that hydrogel-based thermal regulation depends on coupled effects of water retention, water mobility, evaporation behavior, thermal transport, and material stability under sustained irradiation.

A persistent limitation of hydrogels, however, is their low intrinsic thermal conductivity. Qin et al. (7) addressed this limitation using boron nitride (BN) networks in dual-functional phase-change hydrogels for electronics cooling, demonstrating the role of BN in enhancing thermal transport within hydrated soft materials. Wang et al. (8) examined the influence of BN shape and size on thermal conductivity, rheological behavior, and passive cooling performance in composite systems. Zhang et al. (9) further reported that boron nitride nanosheets can participate in connected thermally conductive networks within electrically insulating polymer matrices. These studies support the use of hexagonal boron nitride (h-BN) as a thermally conductive yet electrically insulating filler for PV-cooling hydrogels. On that basis, the present study employed a high-purity h-BN powder with an average particle size below 7 μm to evaluate filler loading effects while maintaining electrical insulation and process compatibility.

The hydrogel formulation investigated here was based on PVA, κ -carrageenan, bovine gelatin, and CNCs. Firdaus et al. (10) reported a high-performance ionic conductive 3D-printed cell-free hydrogel for soft tissue engineering based on a related multicomponent PVA/CNC-containing system, showing that physically crosslinked hydrogel architectures can provide water-rich and mechanically stable structures. In the present study, PVA was selected as the primary matrix because it forms physically crosslinked networks through freeze-thaw treatment. Kappa-carrageenan was incorporated to strengthen hydrophilic network formation, gelatin was used to improve compliance and intermolecular interactions, and CNCs were added to reinforce structural integrity.

Most prior passive PV cooling approaches emphasize heat storage, heat spreading, or water-mediated cooling as separate functions (2-6,11,12,14). Fewer studies directly examine how water retention, thermally conductive filler loading, and rear-surface interfacial design interact within the same hydrogel-based PV cooling system. This gap is important because practical passive cooling performance depends not only on the intrinsic cooling capacity of the material but also on how efficiently heat enters, spreads through, and is dissipated by the cooling layer during sustained irradiation (3,7-9).

BN-reinforced hydrogel cooling sheets were therefore fabricated and mounted on the rear surface of photovoltaic panels, with and without graphite foil at the interface, and tested under simulated indoor irradiation in a controlled environment. This study was designed to evaluate the balance between water-retentive hydrogel cooling and thermally conductive composite cooling within a single material system. The objective was to determine how BN loading and interfacial design influenced passive thermal performance during sustained 3 h irradiation exposure and to compare those thermal trends with time-resolved voltage behavior, water-swelling response, and representative 3 h water-loss behavior.

2. MATERIALS AND METHODS

The experimental design consisted of two treatment variables: BN loading and interfacial configuration. BN loading was varied at 0, 3, 7, and 10 wt.% to evaluate the effect of thermally conductive filler concentration. Each BN loading was tested either without graphite foil, labeled G0, or with a flexible graphite foil interlayer, labeled G1. The resulting treatment groups were BN0G0, BN3G0, BN7G0,

BN10G0, BN0G1, BN3G1, BN7G1, and BN10G1. An uncooled photovoltaic panel without a hydrogel layer was used as the control.

2.1. Materials

Poly(vinyl alcohol) (PVA) was used as the primary matrix polymer. The material was Polyvinyl Alcohol, Laboratory Grade, 87% Hydrolyzed, 500 g (The Curated Chemical / Innovating Science, USA). Bovine gelatin derived from cow hides was used as the proteinaceous secondary network component. The material was Perfect Bovine Gelatin, 660 g, 100% beef gelatin (Perfect Supplements, USA). Refined κ -carrageenan powder was used as the polysaccharide gelling component. The material was Pure Refined Kappa Carrageenan, 100 g / 4 oz (Modernist Pantry, USA).

Hexagonal boron nitride powder was used as the thermally conductive filler. The material was MUY BN Ultra High Purity h-BN Powder (ZYP Coatings, USA), with BN content $>99.9\%$ and average particle size $<7\ \mu\text{m}$. Flexible graphite foil used as the interfacial layer was Flexible Graphite Foil/Sheet, 12 in $\times$ 40 in, thickness 0.005 in, 99% carbon. Cellulose nanocrystals were used as a reinforcing nanophase. The CNC material was CelluRods 110L (CelluForce Inc., Canada), a water suspension of hydrophilic sulfated cellulose nanocrystals containing 8 wt.% solids with average particle size 88 nm. Distilled and deionized water was used during formulation and processing.

2.2. Hydrogel Fabrication

Fig. 1.

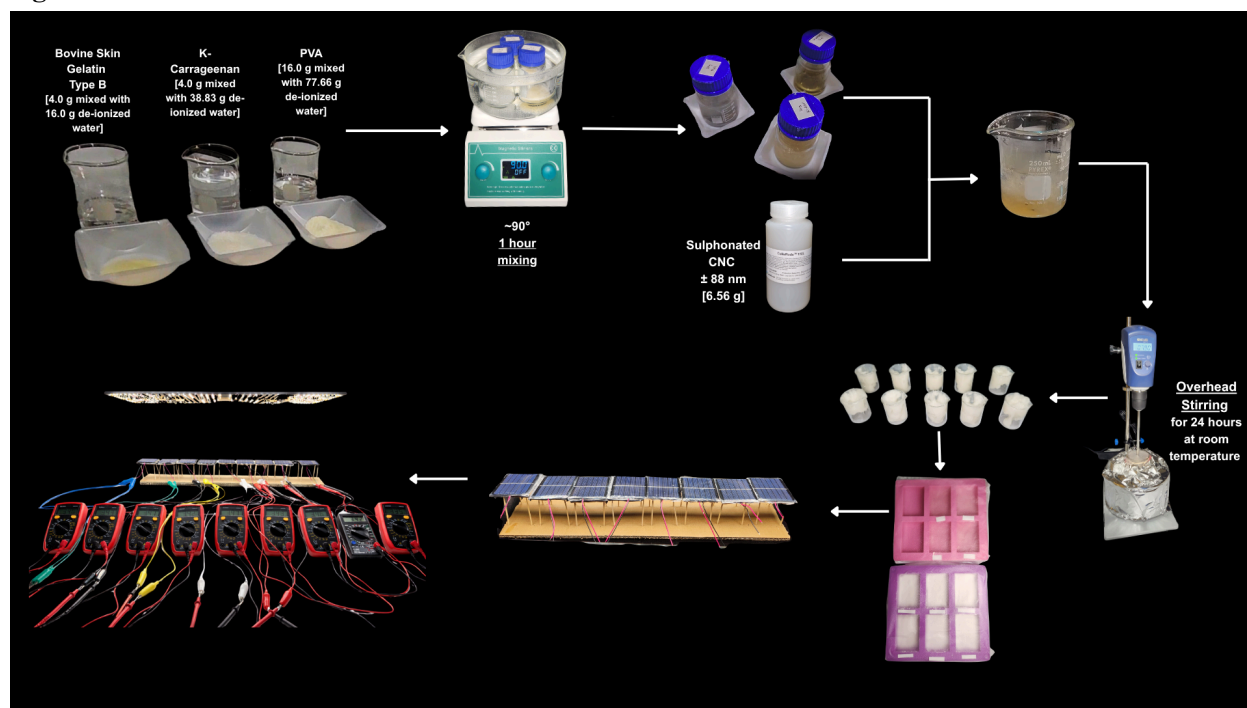


Fig. 1. Fabrication and testing workflow for BN-reinforced hydrogel PV cooling layers. The workflow shows separate preparation of gelatin, κ -carrageenan, and PVA precursor solutions; hot mixing at approximately 90 °C; incorporation of CNC and BN; overhead-stirrer homogenization; casting into silicone molds; freeze-thaw processing; rear mounting onto miniature photovoltaic panels; and indoor irradiation testing with simultaneous temperature and voltage monitoring.

Precursor solutions were prepared separately by mixing 4.0 g bovine gelatin with 16.0 g deionized water, 4.0 g κ -carrageenan with 38.83 g deionized water, and 16.0 g PVA with 77.66 g deionized water. The precursor solutions were heated to approximately 90 °C and mixed for 1 h to promote dissolution. CelluRods 110L cellulose nanocrystal suspension was prepared separately prior to incorporation. Across all formulations, the polymer composition was held constant at 10 wt.% PVA, 2.5 wt.% gelatin, and 2.5 wt.% κ -carrageenan, while BN loading was varied at 0, 3, 7, and 10 wt.% to isolate the effect of filler content within the tested formulation space.

After precursor preparation, the solutions were combined with the CNC suspension and BN filler. The mixtures were homogenized using overhead stirring at room temperature for 24 h to improve filler dispersion and matrix uniformity. The mixed formulations were cast into silicone molds and sealed with airtight plastic film to minimize evaporative loss and maintain dimensional consistency during freeze-thaw crosslinking. Physical crosslinking was induced by five freeze-thaw cycles, with freezing carried out at approximately -10 to -12 °C and thawing at room temperature. Freeze-thaw processing was selected because it provides a practical route for physically crosslinking PVA-based hydrogels without chemical crosslinkers and can improve structural stability in water-rich polymer networks (10).

The airtight sealing step applied during casting and freeze-thaw processing was used to minimize evaporative loss and maintain dimensional consistency during hydrogel formation. During PV testing, the hydrogel layer was used as a rear-mounted cooling sheet rather than as a fully engineered sealed module package. Therefore, the mass-loss measurements were included to provide a first estimate of whether water loss occurred during the 3 h irradiation period.

Table 1. Hydrogel formulation and treatment matrix.

Sample Code	PVA (wt.%)	kappa-Car (wt.%)	Gelatin (wt.%)	BN (wt.%)	Graphite Foil
BN0G0	10	2.5	2.5	0	No
BN3G0	10	2.5	2.5	3	No
BN7G0	10	2.5	2.5	7	No
BN10G0	10	2.5	2.5	10	No
BN0G1	10	2.5	2.5	0	Yes
BN3G1	10	2.5	2.5	3	Yes
BN7G1	10	2.5	2.5	7	Yes
BN10G1	10	2.5	2.5	10	Yes

Table 1 defines the experimental treatment matrix. The polymer composition was held constant across hydrogel formulations, while BN loading and graphite-foil configuration were varied to evaluate the effects of filler content and interfacial design.

2.3. Water Swelling Ability Test

For water absorption testing, 1 cm × 1 cm × 3 mm hydrogel samples were first dried in an oven at 94 °C for 24 h to determine dry mass and then immersed in water for 24 h to determine swollen mass. One swelling specimen was measured for each BN loading (n = 1 per formulation); therefore, the swelling measurements are reported as descriptive values without replicate uncertainty.

Equation 1. Swelling ratio calculation

$$\text{Swelling ratio (\%)} = \left(\frac{W_s - W_d}{W_d} \right) \times 100\% \quad (\text{Eq.1})$$

Where:

- W_d is the dry mass
- W_s is the swollen mass after 24 h of water soaking

This measurement was included because hydrogel passive cooling depends not only on thermal transport but also on the amount of water stored in the network and the ability of that water to participate in heat dissipation during irradiation (4-6). The swelling test is therefore treated as a first-order measure of water-storage capacity, not as a direct measurement of evaporation kinetics during PV operation.

2.4. Water-Loss Measurement During Irradiation

Representative graphite-free hydrogel samples were weighed immediately before and after the 3 h irradiation exposure to estimate water loss during the same time scale used for thermal testing. One representative graphite-free specimen was measured for each BN loading (n = 1 per formulation); therefore, these water loss measurements are descriptive and do not include replicate uncertainty. Water loss was calculated as the difference between the before-test and after-test masses, and water-loss percentage was calculated relative to the before-test mass. This measurement was added to distinguish the observed laboratory cooling behavior more clearly from a purely sealed thermal-mass interpretation, while recognizing that continuous evaporation-rate data were not collected.

2.5. PV Cooling Assembly

Hydrogel sheets, each with a thickness of approximately 3 mm, were mounted on the rear surface of miniature photovoltaic panels (Kanayu, 3 V, 120 mA, polycrystalline, 60 × 55 mm). For selected groups, a flexible graphite foil interlayer was placed between the panel rear surface and the hydrogel sheet to evaluate the effect of interfacial modification. All experiments were performed in a controlled indoor environment without any competing light source other than the irradiation source. Each photovoltaic sample was placed at a fixed distance of 10 in from the light source to ensure comparable irradiation geometry among all tested conditions.

The panel area was approximately 33 cm² based on the 60 × 55 mm panel dimensions. Panel positions within the test array were randomly assigned for each independent thermal run rather than being held fixed across runs. This randomization was used to reduce the influence of systematic spatial variation within the irradiation field on any individual treatment condition. The assembly should be interpreted as a laboratory fixture for comparative screening rather than an optimized field-deployable PV mounting design. Contact pressure, interfacial thermal resistance, air-gap formation, adhesive effects, and panel-to-panel variation were not independently quantified.

2.6. Indoor Thermal and Electrical Testing

Indoor thermal and electrical testing was performed in a controlled environment using a VIVOSUN LumaLight 100 W full-spectrum LED grow light as the irradiation source. The 100 W LED unit was used to provide stable indoor irradiation during extended thermal exposure experiments. Temperature testing was performed across three independent 3 h runs for each sample condition and for the uncooled control. This duration was selected to evaluate sustained irradiation behavior rather than short-duration initial heating only. Ambient temperature during testing ranged from approximately 25 to 27 °C, while relative humidity ranged from approximately 30% to 48%.

Midpoint panel temperature was recorded for each condition during each thermal run. Voltage was recorded simultaneously using individual digital multimeters. Before testing, the multimeters were cross checked by connecting each meter to the same fully charged 9 V battery and comparing the measured voltage readings to assess inter-meter consistency. Multimeter assignments were subsequently rotated among sample conditions across the independent runs rather than remaining fixed to individual treatments. Panel positions within the irradiation array were also randomly assigned across runs.

Despite these controls, the voltage measurements were treated as preliminary electrical observations rather than as a complete measure of photovoltaic performance because current, fill factor, maximum power point, and full I–V characteristics were not measured.

2.7. Data Analysis

Midpoint temperatures from the three thermal runs were used to calculate the mean temperature and sample standard deviation for each configuration. The average temperature reduction relative to the uncooled control was calculated as the difference between the control mean temperature and the mean temperature of each hydrogel-cooled sample.

Equation 2. Temperature reduction calculation

$$\text{Temperature reduction (}^{\circ}\text{C)} = T_{\text{control}} - T_{\text{sample}}$$

where T_{control} is the mean midpoint temperature of the uncooled control and T_{sample} is the mean midpoint temperature of the hydrogel-cooled sample.

For electrical characterization, voltage was recorded continuously and simultaneously for all panels throughout the 3 h exposure period using multimeters. Average voltage values were used to assess time-dependent voltage behavior, voltage change from the initial value, and voltage-retention percentage. Voltage-only data were used only as preliminary electrical-stability information and not as a measure of PV power conversion. A complete PV-performance evaluation would require simultaneous voltage and current measurements under a controlled load, maximum power point behavior, fill factor, and conversion efficiency. Water-loss percentage during irradiation was calculated using the same mass-difference approach: water loss divided by pre-test mass multiplied by 100.

For the swelling test, percent weight increase after 24 h soaking was calculated using the swelling equation. Swelling and water-loss results were compared with graphite-free thermal performance to evaluate whether water storage and water retention were consistent with the observed cooling trend. Because direct thermal conductivity, heat-flux, and full evaporation-rate measurements were not performed, these comparisons were used for interpretation rather than proof of a single cooling mechanism.

Because each thermal condition was tested across three independent runs, statistical analysis was used as a screening-level comparison rather than as definitive proof of material ranking. A one-way analysis of variance (ANOVA) was used to evaluate whether midpoint temperature differed across sample groups. Selected pairwise comparisons were subsequently evaluated using Welch two-sample t-test because the sample standard deviations were not identical across groups. Due to the small sample size and multiple comparisons, p-values were interpreted cautiously and used to support descriptive trends rather than establish a universal material-performance hierarchy or prove physical mechanism.

3. RESULTS AND DISCUSSION

3.1. Principle and Fabrication Process of the Hydrogel Cooling Layer

The passive cooling layer evaluated in this study was designed as a rear-mounted thermal-management material for photovoltaic modules. The design integrates three intended functions. First, the hydrogel matrix acts as a water-containing passive cooling medium capable of absorbing heat from the PV rear surface and dissipating part of that heat through water-mediated thermal regulation. Second, h-BN is incorporated to support internal heat transport within the hydrogel while maintaining electrical insulation. Third, graphite foil is applied in selected groups to evaluate whether an interfacial layer could influence thermal transfer between the panel rear surface and the hydrogel sheet. This combined strategy was adopted because passive cooling performance depends not only on the cooling capacity of the bulk hydrogel but also on how efficiently heat enters and propagates through the cooling layer (3,7).

The hydrogel matrix was based on PVA, κ -carrageenan, bovine gelatin, and CNCs. PVA was chosen as the primary polymer because physical crosslinking through freeze-thaw cycling can produce stable hydrogel sheets without chemical crosslinkers. Kappa-carrageenan was selected because its hydrophilic

polysaccharide structure supports gel formation and water retention. Gelatin was incorporated to provide additional hydrogen-bonding interactions and improve matrix compliance. CNCs were used as a reinforcing phase to support network integrity.

The selection of h-BN was based on the thermal-management requirements of the PV cooling layer. The filler needed to be thermally conductive while remaining electrically insulating near the photovoltaic panel. Hexagonal BN satisfies these requirements because it is widely used as a thermally conductive but electrically insulating ceramic filler in polymer composites. The h-BN used in this study had >99.9% purity and an average particle size below 7 μm . This sub-10 micrometer particle size was selected to support dispersion during solution mixing while remaining large enough to potentially contribute to particle-particle contact within the approximately 3 mm hydrogel sheet. However, because direct structural characterization was not performed, any discussion of filler connectivity in this paper is treated as an interpretation to be tested rather than as a demonstrated microstructural fact.

3.2. Characterization Rationale and Mechanistic Boundaries

A key requirement for hydrogel-based passive cooling is the ability to absorb and retain water while permitting heat dissipation during irradiation. Prior hydrogel cooling literature indicates that high water uptake alone does not guarantee strong cooling performance. Effective thermal regulation depends on the balance between stored water, water mobility, evaporation behavior, thermal transport, and material stability under irradiation (4-6,11,12,14). The water absorption and water-loss measurements therefore serve as first-order characterization of water-storage and water-retention behavior.

The addition of BN was expected to alter hydrogel function through competing mechanisms. On one hand, BN may improve heat transport by increasing thermally conductive pathways through the polymer matrix. On the other hand, excessive filler loading may reduce swelling capacity, hinder water mobility, promote agglomeration, or disrupt the hydrogel internal structure. Because direct thermal conductivity measurements and microscopic morphology characterization were not performed, mechanistic interpretation in this study is restricted to measured temperature behavior, swelling behavior, water-loss behavior, and known sample composition.

This boundary is important because the measured temperature reduction alone does not identify the governing heat-transfer process. The results are therefore interpreted as a laboratory-scale formulation comparison rather than a complete validation of evaporation, conductive heat spreading, or a BN percolation network.

3.3. Cooling Performance Under Simulated Indoor Irradiation

The thermal performance of the hydrogel cooling layers was evaluated under controlled indoor irradiation. The ambient temperature during the experiments was approximately 25-27 °C and the relative humidity ranged from approximately 30% to 48%. Each thermal run lasted 3 h, a duration selected to capture sustained passive cooling behavior rather than transient early-stage heating only.

Fig. 2.

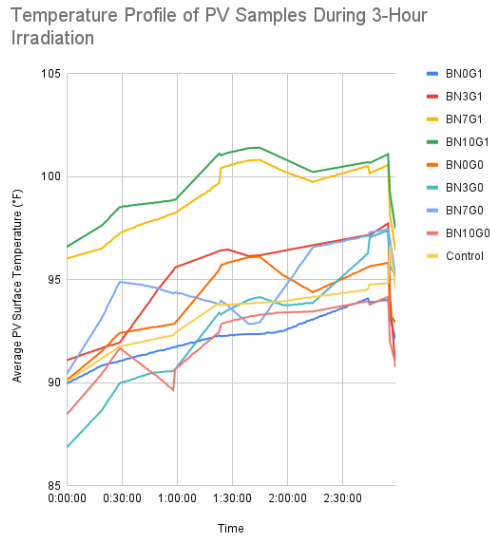


Fig. 2. Temperature profile of photovoltaic samples during 3 h irradiation. The temperature profile shows the time-dependent thermal behavior of the hydrogel-cooled PV samples and the uncooled control under sustained indoor irradiation. BN7G0 and BN10G0 maintained the lowest temperatures among the graphite-free samples. Several graphite-containing configurations did not show improved cooling, indicating that graphite foil did not enhance the assembled system under the present contact conditions.

The measured midpoint temperatures are summarized in Table 2.

Table 2. Midpoint panel temperatures recorded during three 3 h indoor thermal runs.

Sample	Run 1 (°C)	Run 2 (°C)	Run 3 (°C)
BN0G1	36.22	35.89	36.61
BN3G1	38.72	39.67	39.89
BN7G1	40.17	41.06	40.67
BN10G1	41.78	41.67	42.00
BN0G0	37.89	38.61	38.28
BN3G0	35.94	39.28	38.44
BN7G0	33.00	32.44	32.83
BN10G0	33.39	34.28	34.39
Control	41.00	40.28	41.17

Table 2 reports the midpoint panel temperature measured for each sample during each independent 3 h thermal run. These run-level measurements were used to calculate the mean temperature, standard deviation, and temperature reduction values summarized in Table 3.

Table 3. Average midpoint temperature and reduction relative to control, $n = 3$ thermal runs.

Sample	Mean Temperature (°C)	SD (°C)	Reduction vs. Control (°C)
BN0G1	36.24	0.36	4.57
BN3G1	39.43	0.62	1.39
BN7G1	40.63	0.44	0.18

BN10G1	41.82	0.17	-1.00
BN0G0	38.26	0.36	2.56
BN3G0	37.89	1.73	2.93
BN7G0	32.76	0.28	8.06
BN10G0	34.02	0.55	6.79
Control	40.82	0.47	0.00

Table 3 summarizes the primary thermal performance metrics. Lower mean midpoint temperature and greater temperature reduction relative to the uncooled control indicate stronger passive thermal regulation under this laboratory setup. BN7G0 produced the largest temperature reduction, followed by BN10G0.

Using the three independent midpoint-temperature measurements for each of the nine groups, a one way ANOVA indicated a statistically detectable overall difference in midpoint temperature among the tested groups, $F(8, 18) = 58.50$, $p = 2.61 \times 10^{-11}$. Selected pairwise comparisons were subsequently evaluated using Welch's two-sample t-test to account for unequal standard deviations between groups. Both BN7G0 and BN10G0 exhibited significantly lower midpoint temperatures than the uncooled control under the present experimental conditions. BN7G0 differed from the control with $p \approx 7.0 \times 10^{-5}$, while BN10G0 differed from the control with $p \approx 9.7 \times 10^{-5}$. A direct Welch comparison between BN7G0 and BN10G0 yielded $p \approx 0.038$. Because each condition included only three thermal replicates and multiple sample groups were evaluated, these values are interpreted cautiously as support for screening-level trends rather than as a definitive universal material ranking.

The comparatively high standard deviation observed for BN3G0, 1.73 °C, indicates lower run-to-run reproducibility for this condition relative to the other graphite-free samples. This variability may reflect local differences in filler dispersion, hydrogel-panel contact, water distribution, run-to-run experimental conditions, or panel-specific behavior during irradiation. Because microscopic morphology, thermal imaging, and direct interfacial characterization were not performed, the source of this variance cannot be assigned definitively.

Among all tested configurations, BN7G0 exhibited the lowest mean midpoint temperature, 32.76 ± 0.28 °C, corresponding to an 8.06 °C reduction relative to the uncooled control. BN10G0 also provided substantial thermal suppression, with a mean midpoint temperature of 34.02 ± 0.55 °C and a 6.79 °C reduction. In contrast, BN10G1 exceeded the mean temperature of the control panel. These results show that cooling performance depended on the assembled hydrogel-interface system, not on BN loading alone.

Fig. 3.

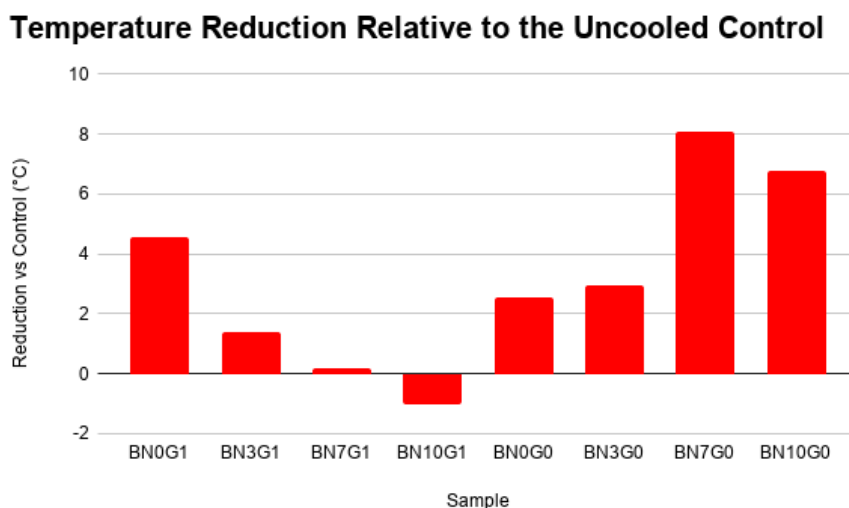


Fig. 3. Temperature reduction relative to the uncooled control. Temperature reduction was calculated as the control mean temperature minus the sample mean temperature. BN7G0 produced the largest reduction, 8.06 °C, followed by BN10G0 at 6.79 °C. BN10G1 produced a negative reduction, meaning that its mean temperature was higher than the uncooled control. The result emphasizes that cooling depended on both formulation and interface configuration.

3.4. Water Swelling Behavior and Relationship to Cooling Performance

The swelling test showed that all hydrogel samples absorbed substantial water after 24 h soaking. The percent weight increase ranged from 709.09% to 823.81% relative to oven-dried mass. The 7 wt.% BN hydrogel showed the highest swelling response, increasing from 0.21 g to 1.94 g, corresponding to an 823.81% increase in mass.

Table 4. Water swelling response of BN-reinforced hydrogel samples after 24 h soaking.

BN Content	Dry Weight Before Soaking (g)	Wet Weight After 24 h (g)	Weight Increase (g)	Percent Increase Due to Swelling
0 wt.% BN	0.11	0.89	0.78	709.09%
3 wt.% BN	0.16	1.42	1.26	787.50%
7 wt.% BN	0.21	1.94	1.73	823.81%
10 wt.% BN	0.19	1.73	1.54	810.53%

Table 4 reports dry mass, swollen mass, mass gain, and swelling percentage for each BN loading after 24 h of water soaking. The results quantify water-storage capacity and show that the 7 wt.% BN hydrogel had the highest swelling response.

Fig. 4.

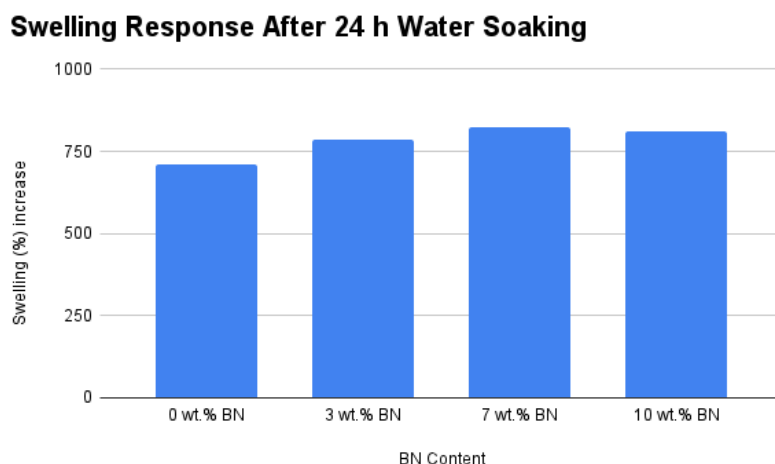


Fig. 4. Water swelling response of BN-reinforced hydrogel samples after 24 h soaking. All formulations absorbed substantial water after immersion, with swelling values from 709.09% to 823.81%. The 7 wt.% BN hydrogel showed the highest swelling response, while the 10 wt.% BN formulation showed a slight decrease.

The swelling results help explain, but do not fully determine, the cooling trend. The 7 wt.% BN hydrogel had the highest swelling response, and its graphite-free counterpart, BN7G0, produced the strongest thermal performance. BN10G0 also cooled effectively but showed slightly lower swelling than the 7 wt.% formulation. This pattern is consistent with an intermediate composition that preserved strong water storage while incorporating enough BN to influence thermal behavior. However, swelling was measured after 24 h immersion and should not be treated as a direct measurement of water release during irradiation.

Table 5. Combined swelling, water-loss, and graphite-free thermal performance summary.

BN Content	G0 Sample	Swelling (%)	Mean Midpoint Temp (°C)	SD (°C)	Reduction vs. Control (°C)	Water Loss During 3 h (%)
0 wt.%	BN0G0	709.09	38.26	0.36	2.56	5.68
3 wt.%	BN3G0	787.50	37.89	1.73	2.93	8.22
7 wt.%	BN7G0	823.81	32.76	0.28	8.06	4.97
10 wt.%	BN10G0	810.53	34.02	0.55	6.79	4.29

Table 5. compares swelling, water-loss, and graphite-free thermal performance. Thermal values represent mean $\pm$ SD from three independent thermal runs ($n = 3$), whereas swelling and water-loss values represent single measurements for each BN loading ($n = 1$) and therefore do not include replicate uncertainty.

For the graphite-free formulations, swelling percentage showed a descriptive relationship with temperature reduction. The Pearson correlation between swelling percentage and temperature reduction was approximately $r = 0.814$, while the correlation between swelling percentage and mean midpoint

temperature was approximately $r = -0.814$. However, these correlations are based on only four formulation level points, with one swelling measurement per BN loading ($n = 1$), rather than replicated swelling measurements. They therefore should not be interpreted as inferential statistical evidence and are reported only as formulation screening trends that motivate more detailed testing.

Fig. 5.

Swelling Response and Temperature Reduction for Graphite Free Samples

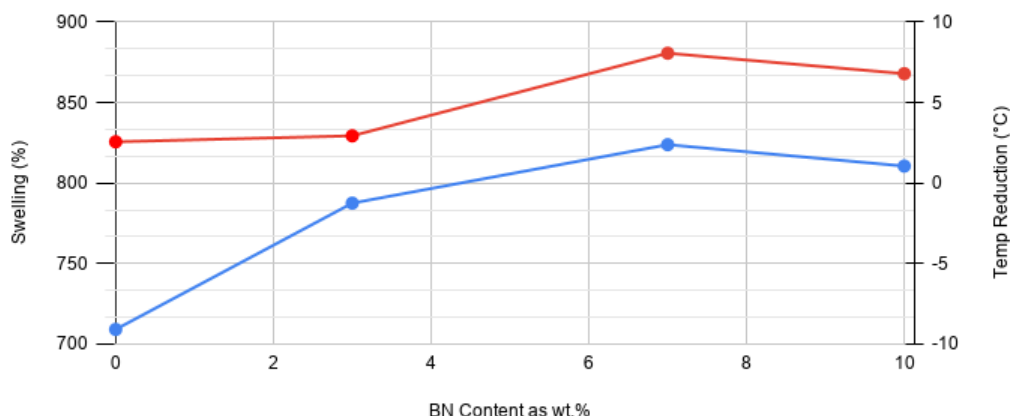


Fig. 5. Relationship between swelling response and graphite-free temperature reduction. The combined plot compares swelling percentage with temperature reduction for the graphite-free hydrogel samples. The 7 wt.% BN sample showed both the highest swelling response and the greatest temperature reduction, while the 10 wt.% BN sample showed slightly lower swelling and weaker cooling. The results suggest that the strongest passive cooling response resulted from an optimized balance between water storage and BN-assisted heat transport, rather than from maximum BN loading alone.

The combined swelling and thermal data show a non-monotonic response to BN loading. Cooling improved from 0 to 7 wt.% BN but decreased slightly at 10 wt.% BN. This behavior is consistent with a balance between water storage and filler content. At 7 wt.% BN, the hydrogel retained the highest measured swelling capacity and produced the largest temperature reduction. At 10 wt.% BN, additional filler did not further improve cooling, possibly because the higher solid loading began to compromise water storage, water mobility, contact conformity, or filler dispersion. These possibilities require direct thermal and structural characterization before they can be confirmed.

3.5. Water-Loss Behavior During 3 h Irradiation

A central thermodynamic question in hydrogel cooling is whether the material behaves only as a temporary heat sink or whether water leaves the system during heating. To address this at a first-order level, graphite-free samples were weighed before and after the 3 h irradiation test. All G0 samples showed measurable mass loss, indicating that the test configuration was not a perfectly closed thermal mass

during the experiment.

Table 6.

Sample	Mass Before Test (g)	Mass After 3 h (g)	Water Loss (g)	Water Loss (%)
BN0G0	0.88	0.83	0.05	5.68
BN3G0	1.46	1.34	0.12	8.22
BN7G0	1.81	1.72	0.09	4.97
BN10G0	1.63	1.56	0.07	4.29

Table 6. Water-loss response of representative graphite-free hydrogel samples during the 3 h irradiation test. Water loss was calculated as mass before testing minus mass after 3 h; percentage loss was calculated relative to the mass before testing. The results provide additional context for the observed cooling behavior. All graphite-free hydrogel samples showed measurable mass loss during the 3 h irradiation period, indicating that water loss occurred under the thermal testing conditions. BN0G0 lost 0.05 g, BN3G0 lost 0.12 g, BN7G0 lost 0.09 g, and BN10G0 lost 0.07 g. Expressed relative to before-test mass, the corresponding water-loss percentages were 5.68%, 8.22%, 4.97%, and 4.29%, respectively.

The water-loss data strengthen the interpretation of the thermal results but also show that the cooling trend cannot be explained by evaporation alone. BN3G0 showed the highest relative water loss, 8.22%, but reduced midpoint temperature by only 2.93 °C. In contrast, BN7G0 showed a lower water-loss percentage, 4.97%, while producing the largest temperature reduction, 8.06 °C. Therefore, the strongest cooling response was not simply the result of the highest water-loss rate. Instead, the results suggest that BN7G0 combined high water-storage capacity, moderate water retention during irradiation, and favorable formulation-level heat-transfer behavior.

The before-test masses were not identical to the 24 h swelling masses reported in Table 4. This difference is expected because the values can be affected by sample-to-sample variation, surface water removal before weighing, and partial dehydration between soaking and testing. Accordingly, the mass-loss results are interpreted as representative water-retention measurements for the graphite-free formulations rather than exact repeated measurements on the same swelling specimens.

3.6. BN Loading and Filler-Connectivity-Informed Interpretation

The non-monotonic cooling response can be interpreted using a filler-connectivity-informed framework, while recognizing that a true percolation threshold was not directly measured. In thermally conductive polymer composites, filler loading can influence heat transport by changing the degree of particle-particle proximity, contact density, and network formation within the matrix. At low filler loading, BN particles are more likely to remain isolated, limiting their ability to form continuous heat-transfer pathways. As BN loading increases, particle-particle interactions may become more frequent, allowing more effective internal heat transport through the hydrogel. However, beyond an optimal loading range, additional filler may produce diminishing returns by reducing swelling capacity, limiting water mobility, increasing filler aggregation, or disrupting the hydrated polymer network.

In the present study, the transition from 3 wt.% BN to 7 wt.% BN produced a substantially larger improvement in cooling performance than the transition from 0 wt.% BN to 3 wt.% BN. BN3G0 reduced midpoint temperature by 2.93 °C relative to the control, while BN7G0 produced a much larger 8.06 °C reduction. This sharp improvement suggests that the 7 wt.% BN formulation may have approached a favorable filler-connectivity region in which BN-assisted heat transport became more influential. This

interpretation is consistent with prior BN-composite studies showing that BN particle characteristics and filler networks can strongly influence thermal transport behavior (7-9).

However, the decrease in cooling performance from BN7G0 to BN10G0 indicates that higher BN loading did not produce a proportional thermal benefit. Although BN10G0 still performed strongly, its temperature reduction decreased to 6.79 °C, and its swelling response was slightly lower than that of the 7 wt.% BN hydrogel. This suggests that the 10 wt.% formulation may have exceeded the most favorable filler-loading range for this hydrogel matrix. At higher filler concentrations, improved conductive transport may be offset by reduced water uptake, restricted water mobility, altered pore accessibility, or filler aggregation.

Because direct thermal conductivity, evaporation-rate, and microstructural measurements were not performed, this interpretation should be treated as an inferred formulation-level explanation rather than a confirmed percolation threshold. A true thermal percolation threshold would require direct thermal-conductivity measurements across a broader BN-loading series and structural characterization, such as SEM/EDX mapping, to confirm filler dispersion and network formation.

3.7. Time-Resolved Voltage Behavior

Fig. 6.

Six Run Average Voltage Drop from Initial Value During 3 hour Irradiation

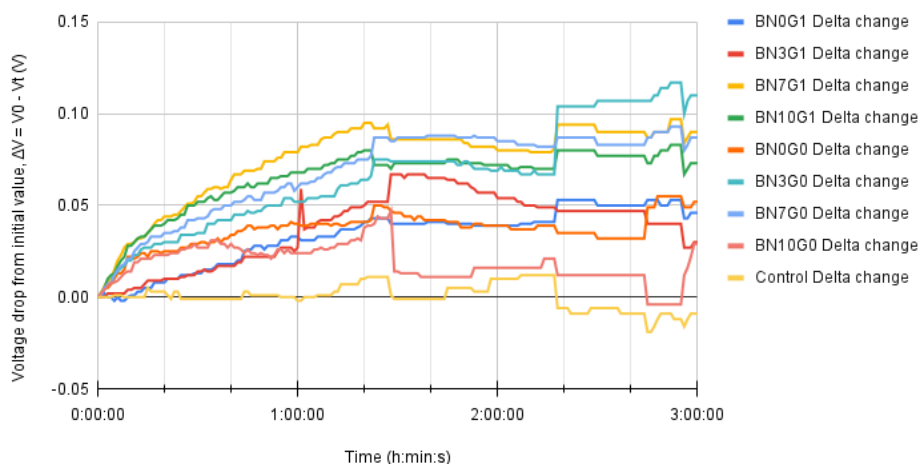


Fig. 6. Six-run average voltage drop from initial value during 3 h irradiation. Voltage drop was calculated as $\Delta V = V_0 - V_t$, where V_0 is the initial voltage and V_t is the voltage at each time point. Larger positive values indicate greater voltage loss relative to the initial measurement. Most hydrogel-cooled samples showed modest voltage decreases over the 3 h exposure, while the uncooled control remained comparatively stable with small fluctuations around the initial value. The voltage trends did not directly correspond to the thermal-performance ranking, indicating that voltage behavior should be interpreted as preliminary electrical-stability data rather than direct evidence of improved photovoltaic power output.

The averaged start-to-end voltage values are summarized in Table 7. Most hydrogel-cooled samples retained approximately 96.7-99.1% of their initial voltage. BN7G0, the strongest thermal performer, retained 97.43% of its initial voltage. BN10G0 retained 99.13%, the highest retention among the hydrogel-cooled samples. The uncooled control showed a small apparent increase, corresponding to 100.28% retention, which is likely due to measurement fluctuation or sample-specific electrical behavior rather than true performance improvement.

Table 7. Start-to-end voltage summary from the averaged 3 h voltage curves.

Sample	Initial Voltage (V)	Final Voltage (V)	Voltage Change, $V_0 - V_{\text{final}}$ (V)	Voltage Retention (%)
BN0G1	3.313	3.267	0.046	98.61
BN3G1	3.317	3.287	0.030	99.10
BN7G1	3.347	3.257	0.090	97.31
BN10G1	3.350	3.277	0.073	97.82
BN0G0	3.342	3.290	0.052	98.44
BN3G0	3.367	3.257	0.110	96.73
BN7G0	3.390	3.303	0.087	97.43
BN10G0	3.319	3.290	0.029	99.13
Control	3.171	3.180	-0.009	100.28

Table 7 summarizes initial voltage, final voltage, voltage change, and voltage retention for each sample based on the averaged 3 h voltage curves. The results indicate relatively stable voltage behavior across samples but no direct correspondence between maximum thermal reduction and maximum voltage retention.

Overall, the voltage results should be interpreted as preliminary evidence of electrical stability rather than direct evidence of enhanced photovoltaic output. Although BN7G0 and BN10G0 produced the strongest thermal suppression, neither condition showed a proportional voltage benefit under the present measurement conditions. A complete PV-performance evaluation would require simultaneous voltage and current measurements under controlled load, enabling maximum power output, fill factor, and conversion behavior to be assessed directly.

3.8. Interpretation of BN Loading and Interfacial Effects

The observed thermal trends indicate that BN loading and interfacial configuration influenced cooling performance in a coupled rather than independent manner. Among all tested samples, BN7G0 and BN10G0 exhibited the strongest cooling performance, indicating that under the present experimental conditions, the graphite-free configurations outperformed the corresponding graphite-containing groups. This result suggests that the addition of graphite foil did not improve thermal regulation in the current system and may have altered interfacial heat transfer or hydrogel cooling behavior in a way that reduced the net cooling effect.

The graphite-containing G1 samples did not exhibit the anticipated enhancement in cooling performance. Instead, increasing BN content within the G1 series was associated with progressively weaker thermal regulation, and BN10G1 exceeded the mean temperature of the uncooled control. This result suggests that the graphite foil may have increased the effective interfacial thermal impedance of the cooling assembly

rather than facilitating heat extraction from the photovoltaic panel. Although graphite can provide high in-plane thermal conductivity, the foil may have introduced imperfect contact, localized air gaps, reduced hydrogel-panel conformity, or a less favorable pathway for water-mediated heat dissipation at the rear surface. Because interfacial thermal resistance was not directly measured, this mechanism should be interpreted as a plausible explanation rather than a confirmed conclusion.

The electrical results further emphasize the need for caution in interpretation. Although BN7G0 and BN10G0 showed the greatest thermal suppression, they did not exhibit the highest voltage retention among the tested conditions. This indicates that reduced panel temperature did not translate into a directly proportional electrical benefit under the present measurement conditions.

3.9. Engineering-Scale Interpretation of Swelling Data

The present system differs from phase-change-material cooling approaches because it relies on a hydrated polymer network rather than a defined phase transition. The h-BN filler was included to address the low thermal conductivity normally associated with hydrogels while retaining electrical insulation near the PV panel. This combination makes BN-reinforced hydrogels a useful candidate platform for passive cooling research, but performance must be evaluated as a coupled material-and-interface problem rather than as a filler-only effect.

These estimates show both the benefit and the challenge of water-rich passive cooling. High water uptake can support temperature reduction, but the same water must either remain in the hydrogel as thermal mass or be consumed through evaporation. If evaporation is a major contributor, the water-consumption rate and rehydration interval become essential design metrics. If evaporation is restricted, the hydrogel may provide mainly transient thermal buffering. Therefore, practical deployment cannot be evaluated from temperature reduction alone. Future work must quantify water mass per unit area, dry hydrogel mass per unit area, BN mass per unit area, added module load, rehydration frequency, durability, manufacturability, and lifetime water demand.

Table 8. First-order mass-per-area estimates from 1 cm × 1 cm swelling specimens.

BN Content	Dry Mass (g/cm ²)	Swollen Mass (g/cm ²)	Absorbed Water (g/cm ²)	Estimated Swollen Mass on 33 cm ² Panel (g)	Estimated Water on 33 cm ² Panel (g)
0 wt. %	0.11	0.89	0.78	29.37	25.74
3 wt. %	0.16	1.42	1.26	46.86	41.58
7 wt. %	0.21	1.94	1.73	64.02	57.09
10 wt. %	0.19	1.73	1.54	57.09	50.82

Table 8 converts the 1 cm² swelling measurements into approximate mass-per-area and miniature-panel-scale values. The 1 cm × 1 cm swelling specimens were cut from hydrogel sheets of approximately the same 3 mm thickness as those mounted on the PV panels. These estimates assume that the swelling specimens are representative of the mounted hydrogel sheets, so they should be treated as first-order engineering estimates rather than final deployment metrics.

3.10. Comparison with Existing Passive Cooling Strategies

The present hydrogel-based cooling system differs from PCM-based passive cooling strategies in both mechanism and structure. PCM systems primarily regulate temperature through latent heat absorption during phase transition, whereas the hydrogel system investigated here relies on water-mediated thermal behavior within a flexible polymer network. The incorporation of h-BN was intended to address the low intrinsic thermal conductivity of plain hydrogels while preserving electrical insulation near the photovoltaic panel. This combined design positions BN-reinforced hydrogels as a possible lightweight passive cooling platform that integrates water retention, conformal rear-surface contact, and filler-assisted heat transport (2-9,11,12,14).

The present approach also aligns with recent hydrogel-cooling literature emphasizing sustained water management rather than only maximum water uptake. Earlier work has shown that practically useful hydrogel cooling materials must maintain stable water release and sustained thermal response under multi-hour irradiation (4-6,12,14). The strong thermal performance of BN7G0 and BN10G0 under 3 h exposure is consistent with the importance of sustained thermal regulation rather than early-stage cooling alone. However, because evaporation rate and water-loss kinetics were not measured, this study cannot determine whether the observed 3 h cooling would continue under longer operation.

At the same time, the current work should not be interpreted as demonstrating general superiority over existing passive cooling methods. The present study provides a controlled comparative evaluation of BN-hydrogel configurations under laboratory conditions. More complete benchmarking would require evaporation-rate measurements, direct thermal conductivity testing, thermal imaging, current-power analysis, and longer-duration outdoor stability measurements.

3.11. Implications Within the Experimental Scope

Within the scope of the present indoor tests, the results show that a rear-mounted hydrogel cooling layer can measurably reduce miniature PV panel temperature under sustained simulated irradiation. The best-performing configuration, BN7G0, lowered midpoint temperature by 8.06 °C relative to the uncooled control during 3 h exposure. BN10G0 also showed strong cooling, with a 6.79 °C reduction. These findings indicate that physically crosslinked hydrogel sheets reinforced with thermally conductive, electrically insulating fillers can function as effective laboratory-scale passive cooling materials under the tested conditions.

The data also show that formulation optimization is essential. Performance was governed not by BN loading alone, but by the combined effect of filler loading, water retention, interfacial design, and likely filler-connectivity behavior. The agreement between maximum swelling, strongest cooling, and moderate water loss at 7 wt.% BN suggests that passive-cooling performance depended on a balance between stored water and filler-assisted heat transport. This makes the 7 wt.% BN graphite-free hydrogel the strongest candidate among the tested formulations.

3.12. Limitations

This study has several limitations. First, the thermal dataset includes three indoor runs per condition, which is appropriate for preliminary screening but not for a definitive performance ranking. Second, thermal analysis relied on single-point midpoint temperature measurements and did not include full-field infrared imaging. Third, although water uptake and representative 3 h water loss were measured, continuous evaporation rate, water-release kinetics, and repeated wet-dry cycling were not measured. Fourth, direct thermal conductivity, thermal diffusivity, heat-flux, and interfacial thermal resistance were not measured, so the governing heat-transfer mechanism remains unresolved.

The BN-loading interpretation was inferred from cooling behavior and swelling response rather than direct structural or thermal characterization. The apparent optimum near 7 wt.% BN should therefore be interpreted as a functional result from this experimental matrix, not as a directly measured thermal percolation threshold. Confirming filler connectivity would require thermal-conductivity measurements across a broader loading range and imaging of BN dispersion within the hydrogel matrix.

The electrical analysis was also limited. Voltage was measured without simultaneous current, power, maximum power point, fill factor, or I–V curve data. Before testing, the multimeters were cross checked against a common 9 V battery to assess inter meter consistency, multimeter assignments were rotated among sample conditions across runs, and panel positions within the irradiation array were randomized. Nevertheless, because complete electrical characterization was not performed, the voltage data cannot be used to claim improved PV power generation.

Finally, the tests used miniature PV panels under indoor grow-light irradiation for 3 h. Outdoor irradiance, wind, weathering, day-night cycling, seasonal variation, long-term dehydration, and maintenance requirements were not evaluated. The results should therefore be viewed as laboratory-scale formulation evidence rather than field validation of a deployable PV cooling technology.

3.13. Perspectives

Future work should pair the present formulation comparison with direct measurements of water-release kinetics, evaporation rate, repeated hydration-dehydration cycling, infrared thermal imaging, and complete electrical output under controlled load. Structural characterization by optical microscopy or SEM/EDX mapping, together with FTIR or XRD analysis where appropriate, would help connect BN loading to hydrogel morphology and polymer-filler interactions.

A particularly important next step is to test the BN-loading hypothesis with direct thermal-conductivity measurements across a denser loading series, such as 0, 1, 3, 5, 7, 10, and 15 wt.% BN. Plotting effective thermal conductivity against filler loading would show whether the performance maximum near 7 wt.% reflects a true network transition, a water-retention optimum, or a coupled effect of both.

Longer-duration and outdoor exposure studies are also needed. Future experiments should include I–V curve tracing, maximum power point tracking, controlled contact pressure, repeated wet-dry operation, and mass tracking over multiple cycles. These data would determine whether the cooling effect can

persist under realistic PV operating conditions and whether it produces a meaningful power-output benefit.

4. CONCLUSION

This study evaluated BN-reinforced hydrogel cooling layers as rear-mounted passive thermal-management materials for photovoltaic modules under sustained indoor irradiation. The cooling layer was based on a physically crosslinked PVA/ κ -carrageenan/gelatin/CNC hydrogel matrix, with BN incorporated at 0, 3, 7, and 10 wt.% and flexible graphite foil introduced in selected configurations as an interfacial layer. This experimental design enabled direct comparison of the coupled effects of thermally conductive filler loading, hydrogel water retention, and rear-surface interfacial configuration on PV thermal behavior.

Across three independent 3 h thermal runs, the tested configurations showed clear differences in midpoint temperature. BN7G0 produced the lowest mean temperature, 32.76 ± 0.28 °C, corresponding to an 8.06 °C reduction relative to the uncooled control. BN10G0 also cooled strongly, with a 6.79 °C reduction. These results show that formulation and interface selection influenced passive thermal response under the tested conditions.

The swelling and water-loss analyses further clarify this behavior. The 7 wt.% BN hydrogel showed the highest swelling response, with an 823.81% mass increase after 24 h water soaking, and BN7G0 lost 4.97% of its mass during 3 h irradiation. The fact that BN3G0 lost more water but cooled much less indicates that evaporation or water loss alone did not control the thermal trend. Instead, BN7G0 appears to have provided the most favorable balance among water storage, water retention, filler loading, and assembly-level heat-transfer behavior within the present experimental matrix.

The graphite foil interlayer did not improve thermal regulation in this assembly. The G1 series performed worse than the corresponding graphite-free samples at higher BN loadings, suggesting that the interlayer may have introduced contact or conformity penalties that outweighed any heat-spreading benefit. This result highlights the importance of interfacial design in hydrogel-based PV cooling systems.

Voltage measurements remained relatively stable during the 3 h exposure, but they did not track the thermal ranking and cannot be used to infer improved PV power output. Future work should include I-V characterization, maximum power point tracking, thermal-conductivity measurement, evaporation-rate analysis, microscopy of BN dispersion, controlled interfacial testing, and repeated wet-dry cycling.

Overall, the results identify BN7G0 as the strongest formulation within the present experimental matrix and support BN-reinforced hydrogels as promising lightweight passive cooling materials for further PV thermal-management investigation. However, the study should be interpreted as a laboratory-scale screening experiment rather than full validation of a field-ready PV cooling technology. Direct thermal-conductivity measurements, evaporation-rate analysis, microstructural characterization, calibrated I-V testing, and outdoor durability studies are needed before stronger mechanistic or deployment claims can be made.

REFERENCES

1. Bamisile, O., Acen, C., Cai, D., Huang, Q., & Staffell, I. (2025). The environmental factors affecting solar photovoltaic output. *Renewable and Sustainable Energy Reviews*, 208, 115073. <https://doi.org/10.1016/j.rser.2024.115073>
2. El Kassar, R., Al Takash, A., Faraj, J., Khaled, M., & Ramadan, H. S. (2025). Phase change materials for enhanced photovoltaic panels performance: A comprehensive review and critical analysis. *Energy and Built Environment*, 6(4), 655-675. <https://doi.org/10.1016/j.enbenv.2024.02.004>
3. Lee, W., & Kim, J. (2025). A comprehensive review of research on organic-based phase-change thermal interface materials for thermal management of electric devices: Methods, performance, and applications. *Polymer Testing*, 142, 108677. <https://doi.org/10.1016/j.polymertesting.2024.108677>
4. Lapsirivatkul, T., Boon-in, S., Crespy, D., & Pattanasattayavong, P. (2025). A lightweight hydrogel system for passive cooling of solar cells. *Advanced Materials Technologies*, 10(10), 2401285. <https://doi.org/10.1002/admt.202401285>
5. Liu, Y., Xu, W., Zhou, X., Perwez, A., Qin, G., & Zheng, X. (2025). Biomimetic thermo-responsive hydrogel coating for passive photovoltaic cooling via self-adaptive water management. *Small*, 21(26), 2502386. <https://doi.org/10.1002/sml.202502386>
6. Fang, H., Dang, S., Kumar, P., Wang, J., Xu, L., Zhu, Y., Almogbel, A., Albadri, A., De Wolf, S., & Gan, Q. (2025). Streamlined fabrication of an inexpensive hygroscopic composite for low maintenance evaporative cooling of solar panels. *Materials Science and Engineering: R: Reports*, 165, 101016. <https://doi.org/10.1016/j.mser.2025.101016>
7. Qin, L., Zhong, L., Qin, F., Wang, J., Xu, T., Song, M., et al. (2025). Dual-functional phase change hydrogels with boron nitride networks: High-performance thermal interface materials for electronics cooling. *Composites Science and Technology*, 272, 111386. <https://doi.org/10.1016/j.compscitech.2025.111386>
8. Wang, Y., Zhang, W., Feng, M., Qu, M., Cai, Z., Yang, G., et al. (2022). The influence of boron nitride shape and size on thermal conductivity, rheological and passive cooling properties of polyethylene composites. *Composites Part A: Applied Science and Manufacturing*, 161, 107117. <https://doi.org/10.1016/j.compositesa.2022.107117>
9. Zhang, J., He, L., Nie, M., Liu, X., & Tong, L. (2025). Polyarylene ether nitrile dielectric material with a thermally conductive network connected by crystals and boron nitride nanosheets. *Polymer Composites*. <https://doi.org/10.1002/pc.29799>
10. Firdaus, D. F., Kuswoyo, A., Garcia-Sampedro, A., Hoek, S., Ghazali, M. I. M., Zou, M., et al. (2026). High-performance ionic conductive 3D-printed cell-free hydrogel for soft tissue engineering scaffolds. *Advanced Composites and Hybrid Materials*, 9, 174. <https://doi.org/10.1007/s42114-026-01691-0>

11. Xie, D., Li, W., Richards, C. A., Gao, H., Chen, C., Miljkovic, N., et al. (2023). Thermally responsive hydrogels for passive temperature regulation under direct sunlight. *Advanced Photonics Research*, 4(4), 2200253. <https://doi.org/10.1002/adpr.202200253>
12. Yang, X., Liu, J., Zhou, Z., Liang, Y., Wu, J., Li, S., et al. (2025). Enhancing year-round photovoltaic performance using the dual cooling and warming functions of hydrogels. *Device*, 3(10), 100843. <https://doi.org/10.1016/j.device.2025.100843>
13. Pandey, M. M., Verma, S., Bhattacharyya, S., & Raza, M. Q. (2026). Experimental investigations on hydrogel-based passive thermal management system for battery cooling. *Journal of Thermal Science and Engineering Applications*, 18, 021007. <https://doi.org/10.1115/1.4070217>
14. Ye, Q., Huang, Y., Yao, B., Chen, Z., Shi, C., Sheldon, B. W., et al. (2026). Radiative coupled evaporation cooling hydrogel for above-ambient heat dissipation and flame retardancy. *Nano-Micro Letters*, 18(1), 50. <https://doi.org/10.1007/s40820-025-01903-0>