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CONFERENCE PAPER · LOW-CARBON BUILDINGS

Solar Spectral Regulation for Energy-Saving Greenhouses Using Thermoresponsive Hydrogel: PDH hydrogel as a representative case

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ABSTRACT

Greenhouses enable intensive and stable crop production, but summer irradiation can introduce excessive solar heat into the enclosed space and increase the demand for ventilation, evaporative cooling or mechanical refrigeration. Conventional glass and plastic films provide high transmission, whereas shade nets and fixed coatings suppress the whole spectrum and often reduce photosynthetically active radiation (PAR). This paper evaluates a thermoresponsive PDH hydrogel as a passive covering material for front-end solar spectral regulation in energy-saving greenhouses. The study combines wavelength-resolved transmittance data with photon-weighted PAR analysis, energy-weighted near-infrared (NIR) assessment, chlorophyll-a matching and a transient heat-balance model for a representative glass greenhouse in Wuhan. The hydrogel remained comparatively transparent at low temperature and entered a light-scattering state after heating, indicating a temperature-triggered modulation mechanism related to phase separation in the polymer-water network. Spectral weighting showed that the material reduced both PAR and NIR transmission as temperature increased, but the reduction was stronger in the heat-contributing NIR region. At 35 °C, the effective PAR and NIR transmittances were 39.13% and 26.71%, respectively. The transmitted red/blue photon fraction and chlorophyll-a matching index changed only slightly, suggesting that the hydrogel mainly decreased intensity while largely retaining PAR spectral quality. Thermal simulation further indicated that PDH coverage reduced the cumulative overheating degree from 85.21 °C h to 40.26 °C h, a decrease of about 53%. The results show that thermoresponsive hydrogel covers can reduce source-level solar heat input while retaining useful photosynthetic light, although outdoor durability, water retention, encapsulation and crop-specific validation remain essential for practical deployment.

KEYWORDS Greenhouse energy saving, Solar spectral regulation, Thermoresponsive hydrogel, PDH hydrogel, Photosynthetically active radiation

1. Introduction

Controlled-environment greenhouses regulate crop-growing conditions through envelope structures and environmental-control systems, thereby reducing the dependence of crop production on season and weather. They are important for vegetables, flowers and high-value horticultural products, yet their ability to maintain a suitable indoor environment normally requires energy and water inputs. Under summer or high-irradiance conditions, transmitted solar radiation raises air temperature, leaf temperature and the temperature of soil, water and structural components. Once heat gain exceeds natural ventilation, envelope heat loss and crop transpiration, cooling load is formed and must be removed by downstream systems.

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From an energy-saving perspective, the cover is the first element that determines how much solar radiation enters the greenhouse. Photosynthetically active radiation in the 400-700 nm range is needed for photosynthesis and dry-matter accumulation, whereas near-infrared radiation contributes little directly to photosynthesis but is readily converted into sensible and radiative heat inside the enclosure (McCree 1971; ASTM International 2020). Conventional glass and plastic films satisfy the basic requirement for daylight but lack fine spectral selectivity. Fixed shade nets, curtains and coatings reduce temperature by lowering total radiation input, but they also reduce crop-available PAR. This creates a trade-off between cooling and growth-light preservation, which is especially relevant in warm regions and during midday solar peaks (Abdel-Ghany *et al.* 2012; He *et al.* 2021).

Previous thermochromic-hydrogel studies have mainly been developed in the context of smart windows, where luminous transmittance, solar modulation and building energy saving are the dominant evaluation criteria. Greenhouse applications impose a different requirement because transmitted solar radiation simultaneously acts as a heat source and as the photon supply for crop photosynthesis.

This paper therefore treats PDH hydrogel as a representative thermoresponsive covering material and evaluates whether it can shift greenhouse cooling from end-stage compensation towards front-end spectral regulation. The central question is whether a passive hydrogel layer can preferentially reduce heat-contributing wavelengths during hot periods while preserving a usable PAR environment for crops. The main methodological contribution is a greenhouse-oriented light-thermal evaluation framework that combines photon-weighted PAR transmission, energy-weighted NIR transmission, crop-related spectral-quality indicators and transient overheating assessment. In this way, thermoresponsive covering performance is evaluated from both crop-light and greenhouse-energy perspectives.

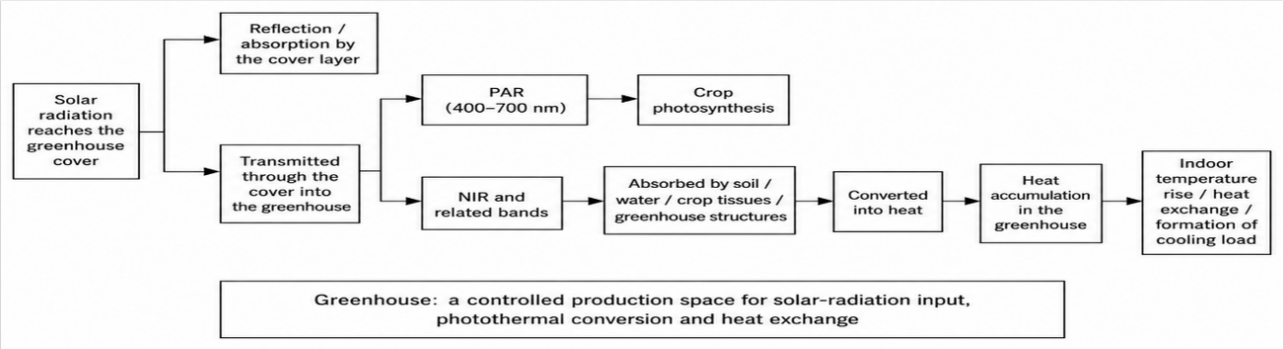

Figure 1. Greenhouse energy-conversion pathway and the position of front-end spectral regulation.

2. Spectral regulation and hydrogel mechanism

2.1. Solar spectrum and greenhouse heat load

Solar radiation incident on a greenhouse cover contains ultraviolet radiation, visible radiation and near-infrared radiation. Their roles are not equivalent. Moderate ultraviolet radiation affects plant morphology and secondary metabolism, but excessive ultraviolet exposure may cause stress. PAR is the spectral region most directly linked with photosynthetic photon capture. NIR, although part of the incoming short-wave solar spectrum, is mainly absorbed by crop tissues, irrigation water, soil and greenhouse structures and then converted into heat. This difference makes NIR an important target for source-level thermal control (Mutwiwa *et al.* 2017; Thakur *et al.* 2025).

A spectrally selective cover should therefore be assessed by more than total transmittance. High visible-light transmission may be favourable in winter or under weak light, while high NIR transmission during summer may increase overheating risk. Similarly, a low total transmittance may

cool the greenhouse but can lower photosynthesis. A useful greenhouse cover should balance PAR retention, NIR suppression, diffuse-light distribution, response temperature and long-term outdoor stability. This evaluation logic differs from architectural smart-window assessment, where daylighting and building cooling normally dominate the objective function (Zhang *et al.* 2023; Xu *et al.* 2024).

2.2. Thermoresponsive hydrogel mechanism

Thermochromic hydrogels contain hydrophilic polymer networks and a large fraction of water. For typical lower-critical-solution-temperature systems, the polymer chains remain hydrated and optically homogeneous below the response temperature, so light scattering is weak and the material appears transparent. When the temperature rises, polymer-water interactions weaken, polymer segments contract, water is expelled from local domains and phase separation occurs. The resulting refractive-index contrast between polymer-rich and water-rich domains increases refraction and scattering, decreasing direct transmittance and increasing haze (Zhou *et al.* 2014; Li *et al.* 2019).

For greenhouse application, this scattering is a double-edged effect. Moderate diffusion can improve canopy light distribution and reduce strong upper-leaf illumination, while excessive opacity lowers the photon flux available to the crop. The ideal material therefore should not pursue maximum turbidity alone. It should respond near the temperature at which overheating begins, reduce NIR transmission more strongly than PAR transmission, and retain a crop-suitable red/blue balance inside the PAR band. The present PDH case is used to demonstrate this coupled optical and thermal evaluation route.

3. Methods

3.1. Spectral weighting

The measured spectral transmittance of PDH hydrogel at different temperatures was combined with the AM1.5 reference solar spectrum. For agricultural PAR evaluation, spectral irradiance was converted into spectral photon flux density because photosynthesis is governed by photon absorption rather than by energy flux alone. The photon flux density was calculated as:

$$\Phi(\lambda) = \frac{E(\lambda)\lambda}{hcN_A} \times 10^6 \tag{1}$$

where Φ(λ) is the spectral photon flux density, E(λ) is the spectral irradiance, λ is wavelength, h is the Planck constant, c is the speed of light and N_A is the Avogadro constant. Effective PAR transmittance at material temperature T was then calculated by photon weighting:

$$\tau_{\mathrm{PAR}}(T) = \frac{\int_{400}^{700} \Phi(\lambda)\tau(\lambda,\ T)\, d\lambda}{\int_{400}^{700} \Phi(\lambda)\, d\lambda} \tag{2}$$

The effective NIR transmittance was evaluated over 700-2500 nm using spectral energy weighting, reflecting its primary contribution to heat input. To examine whether the material changed the internal quality of PAR, transmitted photon flux was also compared with the relative absorption spectrum of chlorophyll a, and the red/blue photon fraction was calculated. These indicators distinguish intensity loss from spectral-quality distortion.

3.2. Thermal balance and overheating index

A lumped transient heat-balance model was used to translate spectral regulation into greenhouse temperature behaviour. The indoor air temperature was determined by solar heat input, envelope heat exchange, ventilation heat removal and heat capacity of the greenhouse air and internal surfaces. In simplified form, the balance was written as:

$$C\frac{dT_{\mathrm{in}}}{dt} = Q_{\mathrm{solar}} - UA_{\mathrm{env}}\left(T_{\mathrm{in}} - T_{\mathrm{out}}\right) - \rho c_p \dot{V}\left(T_{\mathrm{in}} - T_{\mathrm{out}}\right) \tag{3}$$

where C is effective thermal capacity, Q_{solar} is the transmitted solar heat input, U is the envelope heat-transfer coefficient, A_{env} is envelope area, T_{in} and T_{out} are indoor and outdoor temperature, ρ is air density, c_p is specific heat and $\dot{V}$ is ventilation flow rate. The overheating risk was expressed as cumulative overheating degree:

$$\mathrm{ODH} = \sum \max\left(T_{\mathrm{in}} - T_{\mathrm{th}},\ 0\right)\Delta t \tag{4}$$

where T_{th} is the overheating threshold. This time-accumulated indicator captures both peak temperature and duration of thermal stress, which is more informative than a single maximum temperature for greenhouse operation (Zhang *et al.* 2020).

The model was intended for comparative evaluation rather than detailed prediction of the spatial greenhouse microclimate. The greenhouse air and internal thermal mass were represented by a single effective temperature and heat capacity. The envelope heat-transfer coefficient and ventilation rate were assumed to remain constant during each simulation, while spatial temperature gradients, short-term wind fluctuations and explicit crop-transpiration dynamics were not resolved separately. Solar heat input was determined from the transmitted radiation under the corresponding covering condition. The same model structure and boundary conditions were applied to both the baseline and PDH-covered cases so that their relative thermal performance could be compared consistently. These simplifications may influence the absolute predicted temperature and should therefore be considered when interpreting the simulation results.

4. Results and discussion

4.1. Temperature-dependent spectral transmittance

Figure 2 shows that PDH hydrogel exhibited clear thermally responsive optical modulation. At 15 °C and 25 °C, the material maintained high transparency across much of the visible spectrum, indicating that the covering would allow natural light harvesting under low thermal load. At 35 °C and above, transmittance decreased markedly over both visible and near-infrared regions. This behaviour is consistent with the hydrogel changing from a hydrated homogeneous state to a phase-separated scattering state after heating.

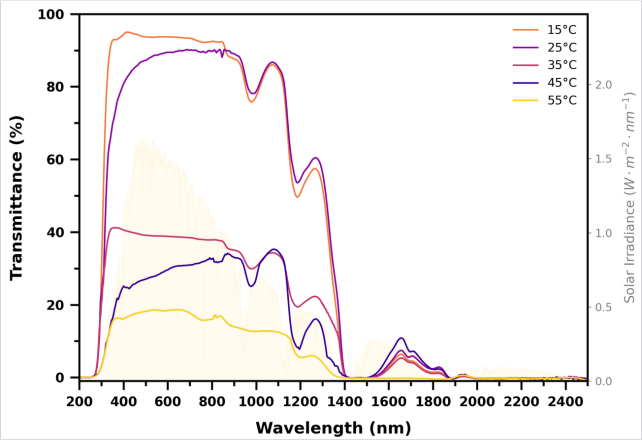

Figure 2. Spectral transmittance of PDH hydrogel at different temperatures.

The decrease was not uniform across the spectrum. The NIR region experienced strong attenuation after the material entered the high-temperature state, while a portion of PAR was retained. This behaviour is relevant for greenhouse energy saving because the material does not simply act as a fixed shade. Instead, its optical state follows the thermal environment, making it more suitable for periods when excess solar heat is the dominant problem.

4.2. PAR retention, NIR reduction and light quality

At 35 °C, the effective PAR and NIR transmittances were 39.13% and 26.71%, respectively. The higher retention of PAR relative to NIR indicates a degree of spectral discrimination in the thermally activated state, with stronger attenuation of the heat-contributing NIR region while a larger fraction of crop-useful PAR is retained.

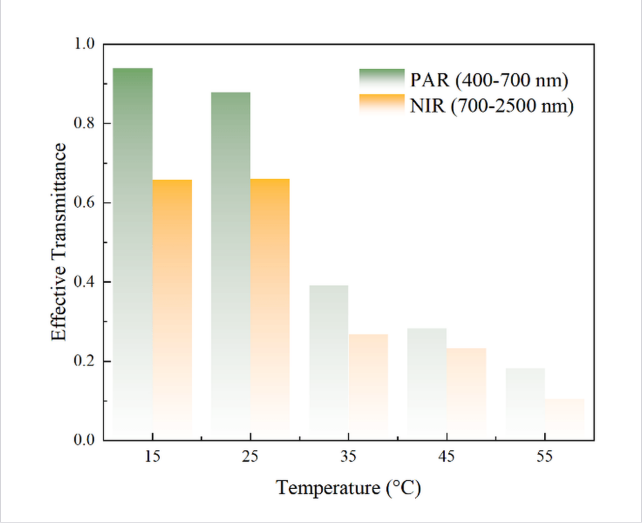

Figure 3. Effective PAR and NIR transmittance of PDH hydrogel at different temperatures.

Light-quality analysis showed that the chlorophyll-a matching index and red/blue photon fraction varied only slightly after heating. The material therefore mainly reduced the amount of transmitted light rather than severely reshaping the internal composition of PAR. For crops, this is important because PAR quality affects photosynthetic efficiency, morphology and dry-matter accumulation. The result suggests that PDH hydrogel can combine passive cooling with partial preservation of crop-relevant light quality, although crop trials are still needed to determine whether the remaining PAR is adequate for different species and growth stages.

Table 1. Main results and implications of the representative PDH hydrogel case.

Evaluation item	Result or observation	Greenhouse implication
Temperature response	Transmittance decreased after heating and scattering increased	Passive optical modulation can be triggered by hot conditions
Spectral selectivity	At 35 °C, effective PAR and NIR transmittances were 39.13% and 26.71%	NIR heat input was reduced more strongly than crop-useful PAR
Light quality	Chlorophyll-a matching and red/blue photon fraction changed slightly	The material mainly changed intensity rather than severely disrupting PAR composition
Thermal performance	Cumulative overheating degree decreased from 85.21 °C h to 40.26 °C h	Overheating duration and thermal stress can be reduced from a time-accumulation perspective

4.3. Thermal-regulation performance

Figure 4 presents the simulated indoor temperature response for the representative Wuhan high-temperature day. Compared with the baseline glass greenhouse, PDH coverage lowered the indoor temperature level and shortened the period during which the greenhouse remained above the overheating threshold. The reduction in cumulative overheating degree from 85.21 °C h to 40.26 °C h corresponds to an approximate 53% decrease. This simulated reduction should be interpreted as an indication of the potential thermal benefit under the specified model conditions rather than as a direct prediction of field-scale greenhouse performance. In practical operation, natural ventilation, crop transpiration, spatial temperature gradients and time-varying weather conditions may alter the actual thermal response.

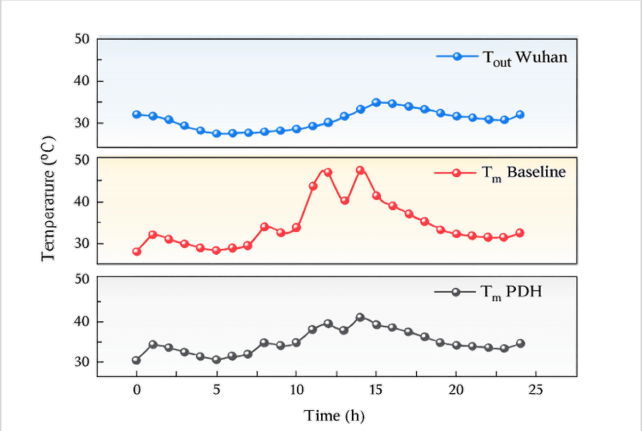

Figure 4. Simulated outdoor temperature and indoor temperature under baseline and PDH-covered conditions.

The thermal result should be interpreted together with the spectral result. A material with very low visible transmittance could also reduce overheating, but it may reduce growth light to an unacceptable level. The value of PDH hydrogel lies in its partial spectral discrimination and temperature-driven response. Its simulated cooling benefit becomes more pronounced under conditions associated with heat stress, while its low-temperature state provides higher transparency during periods when light availability is more valuable than thermal regulation.

5. Engineering integration and limitations

5.1. Integration strategy

Practical deployment requires the hydrogel to be integrated with a mechanically stable and weather-resistant cover. A feasible route is to encapsulate the hydrogel between two transparent glass or

polymer layers, forming a laminated module that can be installed on a roof, sidewall or replaceable shading panel. The external layer provides mechanical protection, while the inner hydrogel layer performs temperature-responsive light modulation. Edge sealing is necessary to reduce water evaporation and contamination, and modular installation would allow replacement after ageing or damage.

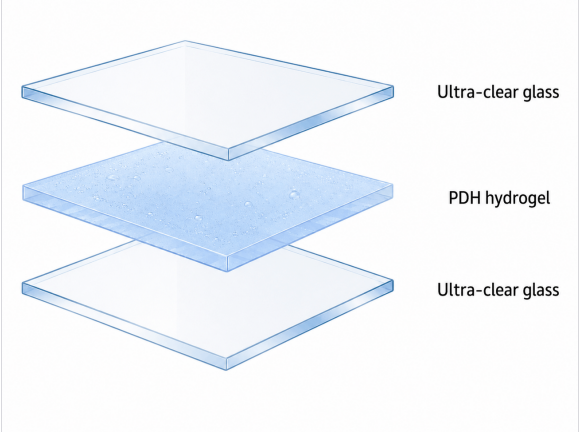

Figure 5. Encapsulation concept for a thermoresponsive PDH hydrogel covering module.

The material design should also be coordinated with crop and climate. In regions with strong summer radiation, a lower response temperature may be beneficial for earlier heat control. In weak-light seasons or for light-demanding crops, excessive attenuation must be avoided. Therefore, the transition temperature, hydrogel thickness, crosslinking density, water-retention strategy and surface protection should be tuned together rather than optimised independently.

5.2. Challenges and future work

Several engineering challenges remain before large-area greenhouse use. First, hydrogels contain water and may suffer from dehydration, swelling-shrinkage fatigue and freeze-thaw damage. Second, outdoor ultraviolet exposure, dust, fertiliser aerosols and cleaning processes can affect optical performance. Third, a hydrogel laminate must maintain adhesion and sealing under thermal cycling and wind load. Fourth, economic feasibility depends on large-area fabrication, installation cost and maintenance frequency.

The biological response also requires validation. The present evaluation focuses on spectral and thermal indicators, but greenhouse productivity depends on crop species, canopy structure, growth stage, leaf temperature, transpiration and local management. Future work should combine long-duration outdoor exposure tests, repeated heating-cooling optical cycles, full-scale energy measurements and crop-growth experiments. These tests should compare PDH coverage with glass, plastic film, shade net and NIR-selective commercial covers under the same climate and management conditions. Such validation would allow the predicted reductions in overheating to be assessed together with crop-level responses, including leaf temperature, photosynthetic performance and biomass or yield.

6. Conclusions

This paper evaluated PDH hydrogel as a representative thermoresponsive material for greenhouse solar spectral regulation. The material showed temperature-dependent transmittance modulation: it remained comparatively transparent at low temperature and became more scattering after heating. Spectral weighting showed that NIR attenuation was stronger than PAR attenuation in the high-temperature state; at 35 °C, the effective PAR and NIR transmittances were 39.13% and 26.71%, respectively. Light-quality indicators suggested that the hydrogel mainly reduced transmitted-light

intensity while largely maintaining the internal PAR composition relevant to chlorophyll-a absorption and red/blue balance.

The transient heat-balance simulation further indicated a reduction of about 53% in cumulative overheating degree under a representative hot day in Wuhan. These findings support the potential feasibility of shifting part of greenhouse cooling demand from downstream mechanical compensation to front-end adaptive spectral regulation. The technology is promising for passive summer cooling and integrated light-thermal management, but practical application still depends on long-term weatherability, encapsulation reliability, large-area manufacturing and crop-specific agronomic verification.

Declarations

Author contributions. Xinhuan Song: Data curation, Writing (original draft). Ying Yao: Investigation. Borui Cao: Validation. Yuxuan Li: Visualization. Jia Mu: Visualization. Shaofeng Yang: Investigation. Jiahui Tian: Investigation. Song Lv: Conceptualization, Methodology.
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Conflicts of interest. The authors declare no competing interests.
Data availability. The data are openly available in a public repository.

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