

# Modulating Thermochromic Properties of Thermally Adaptive PNIPAM Hydrogels for Energy-Saving Smart Windows

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## Abstract

Conventional windows are inefficient in energy preservation and fail to lighten issues such as dazzling sunlight. This study explores the development of smart thermochromic hydrogels for self-regulating windows to reduce unnecessary energy consumption, automate sunlight blocking, and improve visual comfort in buildings. Poly (N-isopropylacrylamide) PNIPAM's unique phase transition behavior near human comfort temperatures (30-35 °C) forms the basis of its smart window functionality, where the material undergoes reversible optical changes from transparent to opaque as it crosses its lower critical solution temperature. This study focuses on modifying PNIPAM thermochromic hydrogels by incorporating hydroxypropyl cellulose (HPC) and polyacrylamide (PAM) to enhance their phase transition behavior, mechanical properties, and thermal responsiveness. Different compositions of PNIPAM-HPC and PNIPAM-PAM hydrogels were synthesized via free radical polymerization, and their properties were systematically analyzed. Experimental results reveal that PAM incorporation effectively tunes the phase transition temperature, with 5% PAM content elevating the transition point beyond 45 °C, which is much higher than that in the PNIPAM standard specimen. In other words, PAM makes the window much more difficult to create a transition into visual opaque position. HPC modification enhances mechanical robustness but introduces more pronounced shrinkage behavior due to amplified hydrophilic dehydration effects, with higher HPC content (2.5 wt%) samples exhibiting 1.5 °C greater surface temperature than lower concentration (0.625 wt%) counterparts which means that HPC is beneficial to make the windows transit more easier, but not really for recyclable and reversible use. These findings position PNIPAM-based hydrogels as highly promising candidates for next-generation smart windows, additionally pointing the road to offering substantial energy savings potential through autonomous solar heat gain regulation, improved visual comfort, and compatibility with existing window manufacturing processes. The study further identifies key research directions, including enhancement of cycling stability and integration with photothermal nanomaterials to boost responsiveness, paving the way for the development of advanced adaptive building envelopes that dynamically balance energy conservation with occupant comfort requirements. This work provides both fundamental insights into stimuli-responsive polymer systems and practical guidelines for their implementation in sustainable applications.

## Keywords

Smart Window, Thermochromic Hydrogel, Building Energy-Saving, Adaptive Envelope