Development of a Janus Nanocomposite Hydrogel Based on Lignin and Polyelectrolyte sIPN for Enhanced Wastewater Treatment via Interfacial Solar Steam Generation

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Introduction:
This study aims to develop a multifunctional Janus hydrogel composed of lignin, fumed silica nanoparticles, and a polyelectrolyte semi-interpenetrating network (sIPN) for interfacial solar steam generation (ISSG) and ion-exchange-based wastewater treatment. Addressing salt fouling and low contaminant removal efficiency in current ISSG systems, the proposed Janus hydrogel integrates both hydrophilic and hydrophobic domains to optimize water transport, evaporation, and contaminant rejection.

Methods:
The Janus hydrogel was synthesized by integrating lignin as a bio-based functional filler and fumed silica as a nanostructured backbone into an sIPN composed of partially neutralized acrylic acid. The hydrophilic layer was designed using covalently crosslinked polyelectrolytes rich in carboxyl and hydroxyl groups, while the opposing hydrophobic layer was fabricated by surface-modifying fumed silica using long-chain alkyl silanes. The Janus interface was formed via controlled casting to ensure a stable interface between the two layers. Characterization techniques included FTIR, SEM, AFM, swelling ratio, ion-exchange capacity, and water evaporation efficiency under simulated solar irradiation.

Results:
The hydrogel demonstrated a swelling capacity exceeding 1000%, an ion-exchange capacity of 3.1 mmol/g, and over 90% heavy metal ion removal efficiency. The Janus structure enabled directional water transport and minimized salt accumulation at the surface. Solar steam generation efficiency reached 87% under 1 sun, with stable performance in saline and heavy-metal-contaminated wastewater.

Conclusions:
This novel Janus nanocomposite hydrogel offers a promising platform for sustainable wastewater treatment by combining lignin's functional versatility, silica's structural reinforcement, and the sIPN's tunable transport properties. The approach supports efficient and eco-friendly water purification using solar energy, aligned with global water sustainability goals.

Keywords: Janus hydrogel; Lignin-based nanocomposite; Ion-exchange, Interfacial solar steam generation