PVA-Based Composite Hydrogel via Phase Separation for High-Performance Atmospheric Water Harvesting

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Introduction

Currently, the imbalance between global water supply and demand is growing. Traditional water sources such as groundwater and surface water are overexploited, unevenly distributed and costly to transport. As a low-cost supplementary strategy, solar-driven atmospheric water harvesting shows great application potential [1].

Freshwater shortage has become a worldwide challenge restricting social and economic development. Traditional water collection methods are limited by geography, climate and infrastructure, making it difficult to meet daily water needs in remote and arid areas. Solar-driven atmospheric water harvesting is green and sustainable, capturing freshwater directly from air without extra water sources, featuring low carbon emissions, low operating costs and wide applicability [2,3].

The core bottleneck lies in hygroscopic materials. Hydrogels are promising due to high water absorption, adjustable structure and low cost, but traditional hydrogels cannot balance hygroscopic performance and mechanical robustness. Most suffer from weak structure, poor air permeability or slow water vapor diffusion [4,5].

PVA-based hydrogels have good mechanical properties and low cost, but conventional PVA hydrogels have small pores and slow moisture absorption. Pure phase-separated PVA also lacks sufficient hygroscopicity for practical use [6,7].

This work develops a PVA phase-separated composite hydrogel with an ultra-large pore structure for high-performance atmospheric water harvesting. The interconnected macroporous framework enhances air permeability and vapor diffusion, while hydrophilic modification greatly improves water absorption. The material achieves an excellent balance of air permeability, high hygroscopic capacity and structural stability. The facile and scalable preparation makes it promising for large-scale solar atmospheric water harvesting devices and provides new insights for practical water harvesting technologies..

EMaterials and Methons

The main raw materials include polyvinyl alcohol 1799 (PVA1799), carboxymethyl chitosan (CMCS), polyethylene glycol 2000 (PEG2000), acrylic acid (AA), acrylamide (AM), N,N'-methylene-bisacrylamide (MBA), ammonium persulfate (APS), glutaraldehyde, carboxylated carbon nanotubes, and lithium chloride (LiCl). All reagents were analytical grade and used as received without further purification.

The PVA-based composite hydrogel was fabricated via a low-temperature freeze-thaw phase separation method, consisting of two key steps: skeleton preparation and composite hydrogel synthesis.

PVA macroporous phase separation skeleton: A 7 wt% PVA, 2 wt% CMCS and 10 wt% PEG mixture was prepared at 95 ℃. After one freeze-thaw cycle for phase separation, the product was rinsed to remove PEG and CMCS, then cross-linked in 2.5% glutaraldehyde solution to obtain the macroporous skeleton.

PVA-based composite hydrogel: A solution containing AA, AM, MBA and APS was infiltrated into the skeleton. The sample was heated at 80 ℃ for 2 h, soaked in deionized water for 24 h, freeze-dried, impregnated in 5 wt% LiCl solution for 24 h, and freeze-dried again to yield the final hydrogel..

This mild, simple and scalable preparation route shows great potential for mass production and practical applications

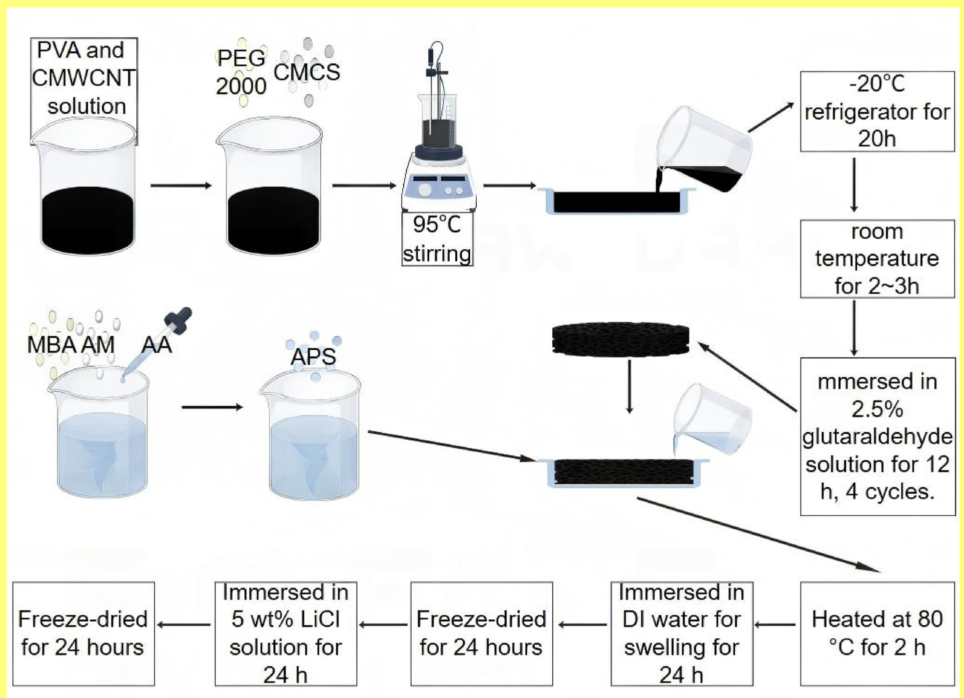

Fig. 1. Schematic illustration of the preparation process.

Characterization

Systematic characterizations were performed to investigate the microstructure and working mechanism of the hydrogel.The microstructure was observed by scanning electron microscopy (SEM). The hydrogel shows an interconnected 3D hierarchical macroporous structure with a rough, wrinkled surface. No pore blockage or collapse is observed, and the porosity is significantly improved compared with conventional PVA hydrogels. This structure provides fast diffusion channels for water vapor and increases active adsorption sites.

The macroporous structure is formed by phase separation between PVA and PEG during the freeze-thaw process. CMCS enhances the phase separation effect and enlarges the pore size. The hydrophilic PAA-PAM network and LiCl provide abundant hygroscopic sites. The synergistic effect of the porous framework, hydrophilic component and hygroscopic salt guarantees high moisture absorption efficiency and good stability.

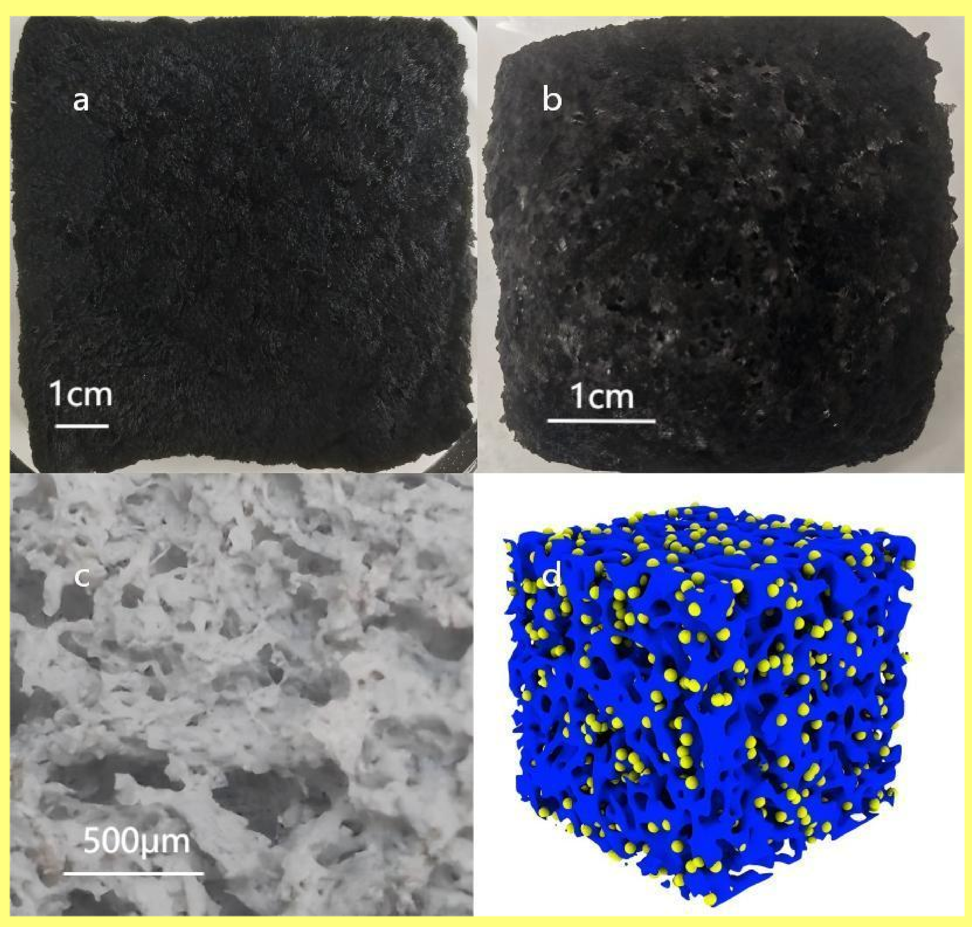

Fig. 2. Pure PVA phase-separated porous skeleton; swollen PVA-based composite hydrogel; freeze-dried composite hydrogel with 3D interconnected porous network; 3D structural model of composite hydrogel.

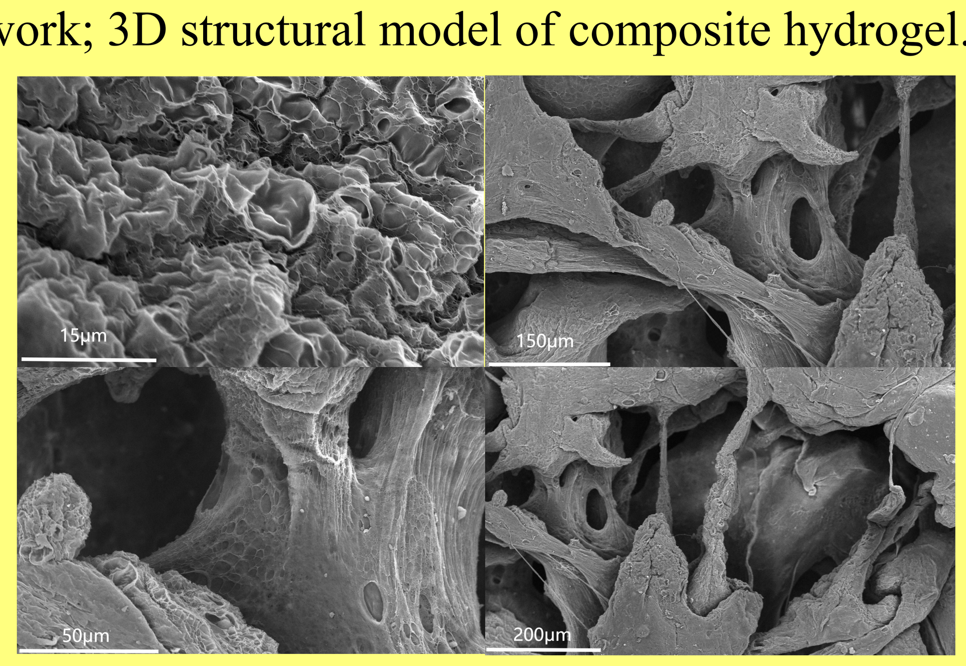

Fig. 3. SEM images of the PVA phase-separated composite hydrogel at different magnifications, showing its interconnected 3D porous network structure with hierarchical pore sizes.

Performance

The hygroscopic properties and photothermal regeneration performance were evaluated.At 25 °C and 90% relative humidity, the hydrogel achieves rapid water uptake. The saturated moisture absorption capacity reaches 2.58 g/g, and the absorption capacity at 6 hours is 1.72 g/g. After three adsorption–desorption cycles, the performance retention rate remains 90.9%, showing good cyclic stability.

For photothermal regeneration, the hydrogel can befully regenerated within 2 hours under 500 W/m² simulated sunlight. The fast regeneration rate and low energy consumption make it highly suitable for solar-driven atmospheric water harvesting applications.

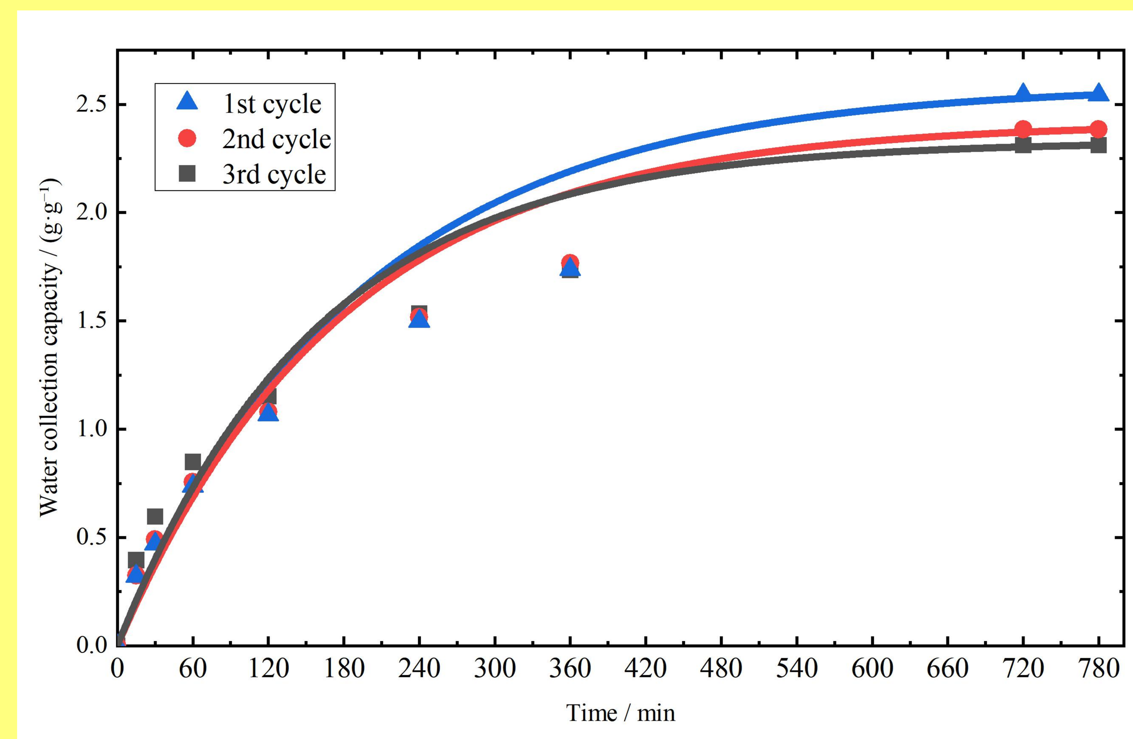

Fig. 4. Water collection performance of the hydrogel over three adsorption – regeneration cycles at 90%RH and 25 °C.

Conclusions

In this study, a PVA-based ultra-large pore hydrogel skeleton was fabricated via CMCS-assisted phase separation. Grafting a hydrophilic layer yielded a composite that balances high air permeability, moisture absorption efficiency and mechanical strength, overcoming conventional hydrogel bottlenecks.

SEM confirms a hierarchical interconnected macroporous structure for fast water vapor diffusion. The hydrogel shows saturated water uptake of 2.58 g/g at 90% RH and 90.9% performance retention after 3 cycles, revealing excellent stability.

In summary, the composite integrates large pores, high permeability, large water uptake and good stability, meeting practical demands for solar-driven atmospheric water harvesting. This work provides a feasible strategy for developing high-efficiency hygroscopic materials.

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