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Preparation of Wood Nanocellulose Composite Hygroscopic Aerogel and Its Atmospheric Water Harvesting Performance

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Abstract

With the increasing scarcity of global water resources, the development of efficient and sustainable freshwater acquisition technologies has become particularly important. The atmosphere contains a significant amount of freshwater, and the utilization of advanced water harvesting technologies to extract freshwater from the atmosphere has emerged as an effective solution. Among them, adsorption-based solar-driven atmospheric water harvesting technology has received widespread attention due to its excellent water harvesting performance. This review summarizes Fang Ying's master's thesis research on the preparation of wood nanocellulose composite hygroscopic aerogel (NPLA) and its application in the field of atmospheric water harvesting.

Keywords

Nanocellulose; Polypyrrole; Lithium Chloride; Aerogel; Atmospheric Water Harvesting.

1. Preparation of Nanocellulose and Its Application in Water Purification

Cellulose, the most abundant natural polymer material in nature [1], is a key structural component of plant cell walls. With its renewable, biodegradable, and environmentally friendly properties, cellulose has garnered significant attention in materials science. Nanofibrillated cellulose (NFC), derived from plant cell walls through chemical purification and mechanical fibrillation processes [2], exhibits unique structural and performance advantages. These include a high aspect ratio, large specific surface area, excellent hydrophilicity, and superior thermal stability, making it an ideal candidate for applications in water purification and sustainable materials.

NFC's hierarchical structure, consisting of nanofibrils with diameters in the nanometer range and lengths extending to micrometers, provides a mechanically robust and highly porous framework [3]. This structure enables efficient adsorption of contaminants, making NFC a versatile building material for hygroscopic gels. Its hydrophilic nature ensures rapid water absorption, while its thermal stability allows it to maintain structural integrity under varying environmental conditions. These properties have facilitated the development of advanced atmospheric water harvesting technologies, where NFC-based gels can efficiently capture and retain moisture from the air.

2. Preparation and Structural Characterization of NPLA

In Fang Ying's pioneering work, NFC was extracted from waste wood powder generated during poplar wood processing, utilizing a combination of chemical purification and mechanical fibrillation techniques [4]. This innovative approach not only provides a sustainable route for utilizing industrial waste but also ensures the production of high-purity NFC with uniform fibril dimensions.

To further enhance the functionality of NFC, it was integrated with polypyrrole (PPy) and lithium chloride (LiCl) through a solution displacement treatment to prepare a nanocellulose-based composite hygroscopic aerogel (NPLA) [5]. The NPLA exhibits a three-dimensional porous network structure, with spherical PPy particles uniformly distributed on the surface and LiCl particles embedded within the framework. This unique architecture is achieved through precise control of the synthesis parameters, ensuring optimal distribution of the functional components.

LiCl serves as an effective adsorbent for capturing moisture from the air, leveraging its high hygroscopicity. The porous network formed by NFC provides hydrophilic channels for water transport and retention, while PPy acts as a photothermal conversion material, absorbing sunlight and converting it into heat energy for efficient water evaporation. This synergistic combination of materials endows NPLA with multifunctional capabilities, making it a promising candidate for atmospheric water harvesting.

3. Hygroscopic Performance of NPLA

The hygroscopic performance of NPLA is a critical factor in its effectiveness for atmospheric water harvesting. Research results demonstrate that NPLA achieves a moisture absorption capacity of 82% of its own mass within 3 hours at 25ºC and 35% relative humidity (RH) [6]. This exceptional performance is attributed to the high hygroscopicity of LiCl and the hydrophilic nature of the NFC framework, which together enable rapid and efficient water capture and retention.

Compared to conventional desiccants such as self-indicating silica gels and 4A molecular sieves, NPLA exhibits superior dehumidifying performance. Its ability to maintain high hygroscopic efficiency across a wide range of humidity levels further underscores its versatility and potential for use in diverse climatic conditions. This adaptability makes NPLA a viable solution for addressing water scarcity in both arid and humid regions.

4. Photothermal Evaporation Performance of NPLA

The photothermal evaporation performance of NPLA is another key aspect of its functionality. Moisture-absorbed NPLA demonstrates excellent light absorption properties, with an absorption rate exceeding 92% across the wavelength range of 300-2500 nm [7]. This broad-spectrum absorption ensures efficient utilization of solar energy for water evaporation, even under low light conditions.

Under xenon lamp illumination, NPLA exhibits rapid water evaporation and heating effects. Experimental results show that under 2 sun illumination intensity, NPLA can completely evaporate the adsorbed water within 2 hours. This rapid evaporation rate is facilitated by the photothermal properties of PPy, which efficiently converts absorbed light into thermal energy. Furthermore, NPLA exhibits no significant performance decay after 10 water adsorption-release cycles, demonstrating excellent cycle stability and durability.

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5. Outdoor Atmospheric Water Harvesting Performance

The practical application of NPLA in outdoor atmospheric water harvesting has been extensively studied. A water collector developed using NPLA demonstrated remarkable performance in real-world conditions. A piece of hygroscopic gel weighing 53.63 g (dry weight of 23.87 g) collected 16.13 g of freshwater under solar illumination of 0.36-0.77 kW·m^-2 within 7 hours [8]. The collected water was colorless, pure, and met multiple water quality indicators of the national drinking water standard, highlighting its suitability for producing potable water.

This excellent water collection capability underscores the practical feasibility of NPLA in addressing freshwater scarcity in resource-limited regions. Its ability to operate efficiently under varying solar intensities and humidity levels further enhances its potential for widespread deployment in diverse environmental conditions.

6. Conclusions and Prospects

Fang Ying's research successfully developed a functionalized nanocellulose composite hygroscopic aerogel (NPLA) and systematically evaluated its hygroscopic and photothermal evaporation performance. NPLA demonstrates exceptional potential in atmospheric water harvesting, offering a sustainable and efficient solution to alleviate freshwater shortages. Its ability to capture and release water using solar energy not only promotes the resource utilization of waste materials but also provides a scalable technology for water-scarce regions.

Future research directions could focus on optimizing the preparation process to enhance the mechanical strength and durability of NPLA. Additionally, exploring its potential applications in other fields, such as desalination, soil moisture retention, and thermal management, could further broaden its impact. By integrating advanced materials and innovative design strategies, NPLA-based technologies could play a pivotal role in addressing global water and energy challenges, contributing to a more sustainable future.

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