"Water Hungry" Regenerated Cellulosic Films and Fiber-Webs for Atmospheric Water Harvesting and Seawater Desalination

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Freshwater scarcity in arid regions is a serious issue currently, owing to the frequent variations in global climates, such as the Colorado River ongoing drought in 2026. Delignified wood and regenerated cellulose-based porous film and fiber web materials for sustainable atmospheric water harvesting (AWH) and seawater desalination techniques have potential to alleviate the freshwater scarcity crisis, while the continuous and large-scale manufacturing of these advanced cellulosic materials has some technical limitations. This editorial focuses on cellulose wet-screw extrusion-casting, blowing, and spinning techniques, which integrate with coagulation baths, to continuously large-scale manufacture regenerated cellulose-based porous films and fiber webs or nonwovens for the AWH and seawater desalination to regenerate freshwater. As an advanced large-scale manufacturing technique, melting extrusion 3D printed artificial wood- or natural fiber-based complexly structured bio-composite materials mimicking the artificial forests can further enhance AWH and seawater desalination techniques. These advanced cellulosic materials offer potential solutions to alleviate the scarcity of freshwater in arid regions and contribute to the drip irrigation-based sustainable agriculture.

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Regenerated Cellulose Porous Film Scalable Manufacturing for Atmosphere Water Harvesting and Seawater Desalination

As the main freshwater source suppliers for some Western States of the U.S. (*e.g.*, Colorado, Arizona, New Mexico, California and Nevada), the Colorado River is meeting the historical drought challenge now. Owing to this serious freshwater scarcity, some western cities like Denver, San Jose, Las Vegas, and Phoenix metropolitan areas currently enforce several restrictions on community freshwater utilization. Atmospheric water harvesting (AWH) technology, which collects water in the atmosphere by using advanced porous materials like covalent- and metal-organic frameworks is attracting significant attention for alleviating water-shortage issues. Considering their biodegradable limitations, this technology is highly desirable for developing sustainable materials for environmentally friendly AWH technology.

As we know, natural woods as hygroscopic materials can absorb atmosphere water. It is a research theme for wood scientists, finishing and coating wood and its composites against atmosphere water adsorption and absorption to enhance dimension stability. Inspired by the retrosynthesis analysis logic of organic chemistry from target molecules to precursor materials, why not modify wood materials to further enhance its atmosphere

water sorption for tackling freshwater scarcity, as thinking reversely about wood protection against water sorption? Again, let's go back to review the wood science knowledge as a take-home assignment, "*Sorption and Desorption of Hygroscopic Woods*." Delignified woods as all-cellulose composites and regenerated cellulose porous films *via* doping hygroscopic salts [*e.g.*, lithium bromide (LiBr) and lithium chloride (LiCl)] sound like promising sustainable materials for capturing and collecting atmosphere water to tackle freshwater scarcity.

Regenerated cellulose porous film materials are primarily prepared *via* the solution casting followed by freezing and supercritical drying methods, though these manufacturing approaches usually have dimensional limitations. The advanced techniques for manufacturing environmentally friendly, low-cost, and large-scale regenerated cellulose-based porous film materials are immediately attracting more attention for AWH applications. Considering the increasingly societal appeal to sustainability, large-scale manufacturing of regenerated cellulose films is also becoming a hot-spot research topic in the lignocellulose field, for the purpose of non-degradable polyolefin packaging film alternatives. However, due to its thermal sensitivity degraded in conventional melting-extrusion manufacturing, continuously large-scale manufacturing of regenerated cellulose porous films has some technical challenges. According to the previous regenerated cellulose technical processes for commercial products, cellophane and NatureFlex™ films (Du Pont, U.S., and Futamura, Japan) and lyocell and SaXcell® fibers (Lenzing, Austria, and SaXcell, Netherlands), the technical barrier in terms of continuous and large-scale manufacturing of regenerated cellulose films can be addressed by the integration of wet-screw extrusion technique equipped with thickness- and width-tunable slit nozzles and coagulation baths. Inspired by the polyolefin film melting extrusion blowing technical process, another technical process as wet-screw extrusion blowing also makes it possible to continuously manufacture the large-scale regenerated cellulose films (Fink *et al.* 1999), which integrates the circular nozzles coupling with wet-screw extrusion technique, air compressor cooling systems, and coagulation baths. Another technical limitation for scalable manufacturing of porous regenerated cellulose films results from the conventional freezing- or supercritical-drying protocols. Similar to gas separation membrane manufacturing methods in the chemical engineering field, the strategies of "*non-solvent induced phase separation*" or "*thermal-induced phase separation*" sound like a simple and straightforward approach to deal with the scalable porous film manufacturing restriction. These techniques are compatible with the wet-screw extrusion technique process of regenerated cellulose film materials. Additionally, porous structure and morphology of regenerated cellulose films as another critical factor directly impacts its capturing atmospheric water. A new concept of "*Hofmeister effect*" also named as "*ion-specific effects*," initially found in the protein structure study, can tailor the aggregation status of cellulose chains, thereby further optimizing the microstructures and mechanical properties of regenerated cellulose porous films. Considering its hydrophilic nature of cellulose, the simple, ambient temperature, and catalyst-free esterification reaction on the regenerated cellulose porous film from formic acids can be further proceeded to enhance its dimension-stability against water swelling. Fortunately, the formyl esterification reaction and Hofmeister effects on cellulose films, directly conducted in coagulation baths, are well-aligned with the wet-screw extrusion technical process for the large-scale manufacturing of regenerated cellulose porous films.

Cellulose dissolution and regeneration rely on the solvents, while some solvents have tricky procedures or difficulties in recycling or dealing with their waste, such as ionic liquids or deep eutectic solvents, which is another potential technical restriction, considering the increasing societal awareness of sustainability. Interestingly, molten inorganic salt hydrates as emerging green solvents (*e.g.*, $LiCl \cdot 2H_2O$ and $LiBr \cdot 3H_2O$) have unique merits, considering both dissolution and regeneration of cellulose and its wet-screw extrusion technical processing, such as fast dissolution of cellulose in a mild temperature, quick formation of its gelation upon decreasing temperature, and easy solvent recycling, which is an ideal solvent for the scalable manufacturing of regenerated cellulose porous films. Most importantly, some molten inorganic salt hydrates as family members of hygroscopic salts also possibly contribute to the AWH technique, which is likely involved in the wet-screw extrusion technical process for *in-situ* continuously scalable manufacturing of hygroscopic salts doping regenerated cellulose porous composite films, as an alternative to additional hygroscopic salt doping protocols.

For a broader viewpoint, considering its excellent dissolution property of molten inorganic salt hydrates for chitosan and cellulose derivatives like hydroxypropyl cellulose (HPC) and ethyl cellulose (EC), *etc.*, the wet-screw extrusion technique coupled with coagulation baths makes it possible to produce other regenerated biopolymer porous film materials for capturing atmosphere water. Given the excellent passive radiative cooling effects of delignified wood panels, also named as all cellulose composite panels, along with unique cholesteric liquid crystal properties of regenerated HPC, EC, and chitosan solutions, these regenerated chiral nematic liquid crystal films manufactured from the wet-screw extrusion technique display different structure colors, which can reflect sunlight with broader ranges of wavelengths, thereby displaying excellent passive radiative cooling properties. The unique passive radiative cooling effects of these photonic cellulose film materials can further promote atmosphere water condensation and thus enhance the freshwater collection efficiency, by their integrations with regenerated cellulose porous films-based AWH techniques.

Considering the abundant seawater and solar energy in California, Arizona, and Nevada, regenerated cellulose porous films have additional application in the solar-driven seawater desalination. For instance, the photo-thermal polydopamine (PDA) coated scalable regenerated cellulose porous films can contribute to the large-volume seawater desalination for freshwater regeneration. Inspired from the Louisiana bald cypress tree, nicknamed "*water-loving tree*," the PDA coated delignified wood also works for the seawater desalination, due to its unique gradient porous structure, while the manufacturing restriction of delignified woods at a large scale needs to be addressed. As advanced manufacturing techniques, scalable extrusion-based fused deposition modeling (FDM) 3D printed wood-based bio-composites (*e.g.*, polyamide 1010) with gradient porous structures also sound promising for seawater desalination.

Scalable Manufacturing of Regenerated Cellulosic Fiber Webs and Non-wovens, and Natural Fiber Composites for Atmosphere Water Harvesting

Inspired from a scenario of water droplets attached on spider-fiber webs in early mornings in Arizona, the regenerated cellulosic fiber webs are another type of advanced material that can contribute to the AWH technique in arid areas, such as the states of Colorado, Arizona, Nevada, and New Mexico. According to the extrusion-based wet-spinning technical processes of rayon, viscose, and lyocell fibers, regenerated cellulose

fibers with and without doping hygroscopic salts from the molten inorganic salt hydrates can be continuously large-scale manufactured by optimizing the screw-extrusion wet-spinning technical processes. For potential leaching problems of doping hygroscopic salts [*e.g.*, LiCl or calcium chloride ($CaCl_2$)], sulfate cellulose nanocrystals or alginate-like polysaccharides that stabilize the hygroscopic salts *via* charge interactions can be involved in wet-spinning protocols, thereby manufacturing high-performance AWH fiber materials. By following the regenerated cellulose porous film technical processes, the microstructure, morphology, and mechanical properties of regenerated cellulose fibers can be further optimized *via* the non-solvent induced phase separation, ionic-specific effects, and formyl esterification modification processes. These regenerated cellulose fibers can be further knitted into large-dimensionally regenerated cellulosic fiber webs for the AWH technique, by borrowing the sweater knitting technique from the textile industry. Developing intelligent regenerated cellulosic fiber webs is also desirable for the advanced AWH technique. For instance, the HPC, as a thermally responsive cellulose material, can take the hydrophilic and hydrophobic switching to potentially achieve the regenerated cellulosic fiber webs with sorption and desorption of condensation water dynamically. Electrospinning is another spinning technique for manufacturing regenerated cellulosic fiber webs, while its scalable manufacturing technical barriers result from the solvents, which require its dissolution of cellulose easily and evaporation quickly from regenerated cellulosic fiber mats. Polylactide nonwovens played a pivotal role in healthy protection during Covid-19, and its melting blown technique attracts more attention since that time. Similarly, regenerated cellulosic fiber nonwovens *via* the screw extrusion-based solution blowing technique also sounds promising for the AWH applications. By mimicking the AWH of *Opuntia dillenii* in desert regions and fog-harvesting coastal redwood trees, FDM 3D printed natural hemp and flax fibers-based bio-composites with diverse complex structures is another approach for contributing the AWH and hydrovoltaic electricity generation techniques (Li *et al.* 2025), potentially enabling the atmospheric water driven hydrovoltaic power generation for agricultural and forestry soil moisture sensors coupling with automated irrigation systems. In addition to these advanced cellulosic material developments, scientific popularization like education and outreach activities are equally important to increase public awareness in rational freshwater utilization.

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