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Closing the Evapotranspiration Loop: A Bio-Derived Hygroscopic Composite for Self-Sufficient Irrigation in Arid Agriculture

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ABSTRACT

More than 70% of agricultural water is lost through evapotranspiration (ET), a critical yet underexploited resource. We present a sustainable evapotranspiration-assisted irrigation (EAI) system that couples multi-source ET/atmospheric water harvesting with precision drip irrigation in a closed loop. A green, scalable hygroscopic composite (SMLC) built on a sphagnum-moss scaffold integrates salt, zwitterionic polymer, and a thin photothermal layer, enabling high uptake (6.42 g g^{-1} at 30-60% RH) and solar-driven release. Desorption liberated 50%, 74%, and 89% of stored water within 120 min at 0.5 kW m^{-2}, 1.0 kW m^{-2}, and 1.5 kW m^{-2}, respectively; the composite sustained 15 sorption-desorption cycles with <5% capacity fade. Multi-scale validation, from dynamic vapor sorption of microscale samples to bulk device tests, confirmed reliable performance. In a one-week greenhouse trial, the EAI device kept stable soil moisture and supported dryland barley and wheat growth without external water input. Solar-driven on/off cycles synchronized with diurnal/weather changes ensured efficient water recovery and utilization. The harvested water met WHO quality standards, and a screening life-cycle analysis indicated low cost (~$2.08/unit), low energy demand, and modest environmental impact. Overall, this work demonstrates a scalable, eco-friendly approach to transforming ET losses into a renewable irrigation source, advancing climate-resilient agriculture in arid regions.

Keywords Evapotranspiration water; water-energy-food; material; system; cycling

1. Introduction

Water, food, and energy form the core nexus of sustainable development [1, 2], with agriculture standing as the largest consumer of freshwater resources [3, 4]. Irrigated agriculture alone accounts for approximately 70% of global freshwater withdrawals and produces 40% of the world´s food [5-7]. Evapotranspiration (ET) is a critical process linking water and energy transfer in the soil-plant-atmosphere continuum, playing a key role in water balance studies [8, 9]. However, more than 70% of this water input-up to 90% in certain regions is lost through ET [10], with crop transpiration being the dominant pathway [11]. Producing 1 kg of maize can transpire nearly 200 kg of water [12]. With global warming intensifying atmospheric demand, ET-driven water loss is accelerating, aggravating water scarcity and threatening food security [13, 14]. Recycling ET water has emerged as a strategy to conserve water and stabilize yields by closing on-farm water cycling [15-17].

Recent advances in water-harvesting materials provide potential solutions. Metal-organic frameworks (MOFs) [18] and covalent organic frameworks (COFs) [19] offer tunable porosity and high sorption capacity, while superabsorbent hydrogels [20] and hygroscopic salts [21] enable fast sorption-desorption kinetics and strong water affinity. These developments have inspired atmospheric water harvesting (AWH) systems and irrigation-support devices[22]. Evaluations of agricultural hydrogels show very high uptake and improved soil-water retention with context-dependent benefits [23-26]. Yet field translation is limited by leaching, ion competition, swelling effects, and durability across wet-dry cycles. Thus, we target an air-side, bio-derived hygroscopic composite that immobilizes salt and polymer in a continuous, highly wettable pore network, supports thin photothermal coatings for mild solar release, and enables low-energy diurnal cycling. Natural bio-based scaffolds are attractive, but common options show

structural limits: cellulose pulp compacts in thick slabs [27]; coir is coarse with limited micro/mesoporosity [28]; other peat substitutes (e.g., composted bark, green-waste compost) have discontinuous microstructures that hinder tri-network integration [29]. In contrast, sphagnum moss provides a hierarchically porous, multichannel scaffold with hyaline cells, low through-thickness resistance, and uniform anchoring of salts/polymers, and supports thin photothermal coatings-enabling rapid diurnal sorption-desorption and reduced salt crystallization/leaching. Dry-state prefabrication allows compact transport with on-site rehydration.

Here we propose an integrated Evapotranspiration-Atmospheric Water-Irrigation (EAI) system that recycles ET/atmospheric water into irrigation water through a closed-loop cycle. The core is a green, scalable super-hygroscopic composite (SMLC) built on the sphagnum moss scaffold, embedding hygroscopic salts (LiCl), zwitterionic polymers (MDMAPS), and photothermal additives (carbon black) into a tri-network. This synergy enables multimodal water capture via capillary condensation, salt hydration, and polymer sorption, followed by a solar-driven release process, in which photothermal conversion efficiently harnesses natural sunlight to trigger rapid desorption and water recovery. Passive operation aligns with crop transpiration and, with drip irrigation, synchronizes cycles with demand, converting ET losses into a renewable supply. We report performance, water quality, cost, and screening LCA to demonstrate scalability for arid agriculture. Together, these innovations establish a scalable and sustainable pathway for enhancing agricultural water-use efficiency, strengthening crop productivity, and improving resilience in arid and semi-arid regions.

2. Materials and Methods

2.1 Synthesis and characterization of SMLC

Synthesis. Sphagnum moss (0.5 g) was washed with deionized water and dried in an oven at 60℃ before being placed in mould. [2-(Methacryloyloxy)ethyl]dimethyl-(3-sulfopropyl)ammonium hydroxide monomer (DMAPS, 8.36 g) was completely dissolved in deionized (DI) water (50 mL) and purged with nitrogen for 10 min [30]. The initiator ammonium persulphate (APS, 14.2 mg) and cross-linker N,N'-Methylenebisacrylamide (MBSS, 5mg) were added to the above solution and sonicated for 10 min to form the reaction precursor (MDMAPS). Then lithium chloride anhydrous (LiCl, 0.25 g mL^{-1}) and carbon black (CB, 0.1 g mL^{-1}) were added to the precursor solution for cross-linking reaction to embed them into the polymer network to obtain the MDMAPS/LiCl/CB polymer solution. Afterwards, the solution was poured into the mould in which the sphagnum sponges was placed to fully fill in its plant pores and its physical cross-linking interstices. The mixture was reacted at 100 ℃ for 12 h to form a physico-chemical cross-linked network gel. The formed sphagnum graft gel was cooled to room temperature and then frozen and freeze-dried for 48h to finally obtain a sphagnum-based photothermal water-absorbent sponge (SMLC). All materials were stored under vacuum before testing.

Characterizations. Morphological and elemental features were examined using scanning electron microscopy (SEM; Hitachi S-4800, Japan) and energy-dispersive X-ray spectroscopy (EDS). Functional groups were analyzed by Fourier transform infrared spectroscopy (FTIR; Thermo Scientific Nicolet iS20, US). Raman spectra were recorded on a Horiba LabRAM HR Evolution spectrometer (HORIBA, Japan). Crystalline phases were determined using X-ray diffraction (XRD; Rigaku SmartLab SE, Japan). Thermal behavior and water-release/phase transitions were evaluated by simultaneous thermogravimetry–differential scanning calorimetry (TG-DSC; HITACHI STA200, Japan). Optical properties were evaluated by UV-Vis-NIR

spectroscopy (Hitachi UH4150, Japan). Wettability was measured by static contact angles (OCA 15EC, DataPhysics). The purity of harvested water was analyzed by ion chromatography (IC; Thermo Scientific ICS 5000+, US).

2.2 Water sorption/desorption Performance Tests

All SMLC samples were vacuum-dried at room temperature before testing.

Micro-scale sorption/desorption. Isotherms were measured using a dynamic vapor sorption analyzer (Aquadyne DVS) under controlled humidity and temperature. Water vapor sorption isotherm was obtained at 25 °C over a wide range of relative pressures (P/P0). Time-dependent sorption kinetics were measured at 25 °C under different relative humidities (30%, 60%, and 90% RH). Temperature-dependent sorption kinetics were measured at a fixed relative humidity of 30% RH under different temperatures (25, 35, and 45 °C).

Bulk-scale sorption. Disk samples (~3 cm × 1 cm) were tested in a constant temperature-humidity chamber (HWS-50, China) at 30%, 60%, and 90% RH. Sorption kinetics and equilibrium water uptake were evaluated.

Temperature and solar response. Adsorption was assessed at 25, 35, and 45 °C. Desorption was tested under solar simulator irradiation (CHF-XM500, China) at 0.5-1.5 $kW \cdot m^{-2}$. Mass change was tracked using an analytical balance (EX125DZH, China), and surface temperatures were recorded with an infrared thermal camera (UTi260A, China).

Desorption kinetics and durability. Temperature-controlled desorption tests were conducted using a dynamic vapor sorption analyzer (Aquadyne DVS), where samples pre-saturated at 90% RH were heated at 60 °C, 75 °C, and 90 °C to record desorption curves. Light-driven desorption was carried out under a solar simulator (CHF-XM500, China) equipped with an AM 1.5G filter, and the irradiance was precisely calibrated using a PL-MW2000 optical

power meter at 0.5-1.5 $kW \cdot m^{-2}$. To assess long-term stability, 15 consecutive sorption-desorption cycles were performed (sorption: 25 °C, 60% RH, 10 h; desorption: 75 °C, 30% RH, 2 h), and post-cycle equilibrium uptake was compared with the initial value to evaluate performance retention.

Harvested water quality. Ion chromatography was performed to detect possible leaching from SMLC composites, ensuring agricultural safety. The aquatic acute toxicity of the SMLC leachate was evaluated using a luminescent bacteria (Vibrio fischeri) assay according to ISO 11348-3:2007(E). Briefly, 4 g of SMLC were immersed in 200 mL of distilled water and shaken in a water bath for 3 h, and the filtrate was used as the test solution.

2.3 Design and working principle of the EAI system

To relieve crop growth in drylands from the constraints of soil-plant-atmosphere water balance, an Evapotranspiration-Atmospheric Water-Irrigation (EAI) system was designed (Fig. 1). The system follows a closed-loop concept and consists of two modules: multi-source water collection and precision irrigation redistribution. In the first module, the system harvests water from soil evaporation, plant transpiration, rainfall interception, and atmospheric moisture. This process relies on the SMLC material, which enables rapid water uptake and efficient solar-driven release. Collected water forms an on-site reservoir that recycles ET-derived vapor and buffers water supply during rainfall deficits. In the second module, harvested water is redistributed directly to the crop root zone via drip irrigation, minimizing surface evaporation and runoff. This adaptive mechanism maximizes water-use efficiency and supports crop growth under arid conditions.

2.4 System validation in greenhouse re-irrigation tests

The ET water reirrigation test was conducted from 25 September to 2 October 2024 in the greenhouse of IEDA-CAAS (Beijing). Excellent dry-crop varieties Kunlun 14 and Jinmai 47 were selected for barley and wheat, respectively. The seeds were selected, rinsed with deionized water, and surface-sterilized by immersion in 75% ethanol for 1 minute followed by 2% sodium hypochlorite solution for 10 min, then thoroughly washed with sterile deionized water three times. After sterilization, the seeds were placed in petri dishes with moist germination beds for about 3 days. After germination, they were transplanted in soil within the EA-irrigation device. A total of 24 seedlings were planted per device, including two rows of barley (Kunlun 14) and two rows of wheat (Jinmai 47), with 6 plants per row. The row spacing and plant spacing were approximately 5 cm, corresponding to an estimated planting density of ~400 plants/m², representative of typical dryland agricultural practices. The soil moisture content test was carried out on soil samples using the gravimetric method, where samples were weighed fresh, oven-dried at 105 °C to constant weight, and reweighed. Soil moisture was calculated as the percentage of water mass relative to the oven-dry soil mass (calculation formula provided in Supporting Information). The EAI device was operated continuously for 7 days without any external water input. The integrated system consisted of a hygroscopic material (SMLC) layer, a solar-driven desorption unit, and a gravity-assisted drip irrigation tube. The system was designed to collect atmospheric and plant-originated water vapor (from soil evaporation and plant transpiration) and reintroduce it into the root zone [21, 31, 32].

A pre-programmed irregular sorption-desorption cycle, coded as "4+2+1+2+1+14", was executed daily. Each numeral represents the duration (in hours) of sequential functional stages in a 24-hour period: 4 h desorption (primary solar-driven phase to release stored moisture from SMLC); 2 h sorption (atmospheric water vapor uptake); 1 h desorption (secondary heating pulse

to remove additional moisture); 2 h sorption (further vapor absorption in late afternoon); 1 h desorption (stabilization phase); 14 h resting/sorption (overnight water vapor harvesting under high humidity). These phases operated cyclically, passively responding to diurnal temperature and humidity fluctuations without active sensors. The desorption was facilitated by a photothermal layer (carbon black-modified surface), while sorption relied on the SMLC's intrinsic hygroscopicity. The water collected during desorption was guided into a sealed reservoir and released to the crop root zone through micro drip irrigation. A control group was established under identical soil conditions, but without the EAI system. No external irrigation was provided to either group during the 7-day period. Soil moisture content was measured every 12 h using the gravimetric method, with three replicates per group. Plant height and phenological status were recorded at Day 0 and Day 7.

2.5 Preliminary life-cycle considerations

A screening, material-centric life-cycle comparison was performed to contextualize the sustainability profile of the EAI system relative to conventional irrigation, MOF/COF-based water harvesters, and hydrogel/salt-based sorbents. The analysis covered four key stages: raw material sourcing, fabrication, operation-related aspects, and environmental considerations. The reference flow is one SMLC unit as fabricated in this study, assessed under a cradle-to-end-of-life boundary; disposal and recycling are discussed qualitatively where standardized datasets are not yet available. For the EAI material, we use empirical data from this work, including fabrication conditions, unit-cost proxies, cycling stability, and water-quality safety. Comparator technologies are normalized to one unit of similar size or nominal capacity using values compiled from published literature and reviews. Use-phase energy is not allocated at this stage because the focus is the material itself. Comparison criteria include material renewability,

fabrication energy intensity, cost, operational dependencies, cycling stability, and potential environmental risks. This screening assessment provides indicative results that highlight relative strengths and design trade-offs across approaches, while noting key drivers such as unit sizing, drying route, logistics, and regional datasets.

3. Results and Discussion

3.1 Structure and properties of the SMLC composite

To realize the proposed EAI concept, we designed a green, scalable material based on sphagnum moss as a core auxiliary component of the EAI system. Fig. 2a shows our conceptual schematic of a green photo-thermal water harvesting sponge developed by physical entanglement and chemical cross-linking using sphagnum peat as a framework. The synthesis can be divided into four main processes: 1) Sphagnum moss containing interconnected pores and a large number of hydrophilic chemical groups are physically entangled to form a "natural sponge skeleton" ; 2) Based on the anti-polyelectrolyte effect, the hygroscopic salt (LiCl) as a cross-linking agent and poly (sulfobetaine) form a new poly amphiphilic hydrogel, which is firmly embedded in the skeleton and pores of sphagnum peat (Fig. S1); 3) Carbon black (CB) is introduced into the polymer network to provide the photo-thermal conversion unit for the composite material (Fig. S2); 4) The composite material is freeze-dried to form an interconnected multistage porous topology (Fig. 2b). Also, MDMAPS hydrogel has zwitterionic groups of $-N(CH^{+}_{3})_{2}^{-}$ and $-SO_{3}^{-}$. The electrostatic interactions between cationic and anionic groups lead to the self-association of MDMAPS chains. This method explores the use of highly efficient natural water-absorbing plants as the foundation for water-absorbing and water-storing matrices. To enhance the material's water absorption and photothermal conversion properties, moisture-absorbing salts and high-performance carbon black are incorporated. Additionally, amphiphilic hydrogel polymers

are grafted onto the structure to ensure its stability. Through freeze-drying, a photothermal composite water-collecting sponge with a dual-network structure-both physically and chemically integrated-is ultimately formed (Fig. S3).

Scanning electron microscopy (SEM) was used to morphologically characterize the surfaces, pores, and cross-sections of natural biomaterial and composites. The natural sphagnum moss biomaterial has a semi-gourd-shaped leaf that resembles a ladle (Fig. 3a), with many bumpy protrusions and interconnected water holes (Fig. 3b). The thread-like skeleton all over the leaf cell membrane ensures that the cells do not collapse under water shortage conditions and enhances structural stability (Fig. S4). It can be seen from the cross-sectional view in Fig. 3c that the hollow cells of the sphagnum peat leaf blade are interlaced, which plays a role in storing and transporting water, and water can enter through the water pores through the hollow cells to be transported to the stem. Fig. S5 shows that MDMAPS has a vertically aligned pore structure that improves the diffusion kinetics of water molecules in the composite adsorbent. MDMAPS-LiCl was loaded on the natural porous skeleton of sphagnum moss and immobilized, and after freeze-drying, it formed an interconnected and open hierarchical pore network based on a well-preserved porous matrix structure (Fig. 3d-f). This hierarchical interconnected and mostly unobstructed pore structure facilitated the rapid diffusion and internal storage of water molecules. As seen from Fig. 3g, the doping of carbon black improves the roughness of the surface and pore walls of the SMLC composites, while the pore morphology and structure are unaffected, which results in a more pronounced photothermal performance while maintaining the original water-collecting and water-storing structures. Fig. 3h-j demonstrates the water absorption process of the SMLC composites, where the trapped moisture enters the pores and is transported to the interior of the material through the hollow channel. The energy-dispersive X-

ray (EDX) elemental mapping images show a uniform distribution of C, O, and N throughout the region and confirm that LiCl crystals have been successfully loaded on the surface of the biomaterial's pores and physically entangled skeleton. (Fig. 3j).

Fourier Transform Infrared Spectroscopy (FTIR), X-ray Diffraction (XRD), and X-ray Photoelectron Spectroscopy (XPS) were used as evidence to re-establish the chemical structure of SMLC. Fig. 3k shows the FTIR spectra of the sphagnum peat, MDMAPS, SML, and SMLC. The spectra of sphagnum peat and MDMAPS between 3000 cm^{-1} and 3690 cm^{-1} are due to the characteristic absorption of cellulose molecules and water-absorbing O-H stretching vibrations, respectively [33]. The peaks of SML and SMLC are blue-shifted at this position compared to sphagnum moss. Compared to MDMAPS, the peaks at 1070 and 1180 cm^{-1} representing the stretching vibrations of S-O in SML and SMLC show a significant change and shift, indicating that LiCl interacted with cationic and anionic groups in the MDMAPS polymer. Moreover, owing to the strong moisture absorption of LiCl, the relative water peak intensity at 1640 cm^{-1} increased significantly with the addition of LiCl [34]. The peaks of SML and SMLC at 1480 cm^{-1} and 1730 cm^{-1} are generated by the C-H stretching vibration of $-N(CH^{+}_{3})_{2}^{-}$ and the C=O stretching vibration in MDMAPS characteristic peaks [35]. The C=O in carboxylic acid groups, which are typical in CA (near 1350 cm^{-1}), were found to exist in SMLC, indicating that CA is contained in SMLC [36]. The crystallinity of single components and composites was analyzed by X-ray diffraction (XRD) analysis (Fig. 3i). Sphagnum moss and MDMAPS exhibited no significant diffraction peaks, indicating the amorphous nature of these two substances [37]. The characteristic diffraction peaks of SMLC were significantly attenuated and disappeared compared to pure LiCl, which proved that the interaction between Sphagnum-MDMAPS/CB and LiCl disrupted its original crystalline structural domains, resulting in a more dispersive and

complex-compatible structure. Pure CB exhibited characteristic diffraction peaks at 25.2° and 43.6°, but the characteristic peak disappeared in the CB-added composite SMLC, indicating that the complexation was successful and CB was uniformly dispersed in the Sphagnum-MDMAPS/LiCl network. The XPS analysis investigated the coordination model of the ligand in the complex. The peaks at 529.08, 403.08, 286.12, and 198.16 in Fig. S6 were attributed to oxygen (O1s), nitrogen (N 1s), carbon (C 1s), and chlorine (Cl 2p), respectively [38]. The results of the C1s spectrum (Fig. 3m) show the typical primitives of the SMLC skeleton, including C-C, C-O, and C=O peaks. The presence of O-Li bonds in the O1s spectrum (Fig. 3n) and N-H and C-N bonds in the N1s spectrum (Fig. 3o) indicated that MDMAPS is itself enriched in amino and amide groups, which directly serve as binding sites for LiCl loading. And, two split peaks at 198.98 and 197.48 eV in the Cl 2p spectrum (Fig. 3p) correspond to Cl 2p1/2 and Cl 2p3/2, respectively, which demonstrated that LiCl was doped into the composites in an intact form without the presence of dissociated LiCl crystals [32]. Finally, FTIR, XRD, and XPS also corroborated each other for the successful synthesis of composites.

3.2 Water sorption/desorption performance

3.2.1 Water sorption performance

To evaluate the water sorption performance, the water sorption isotherms of the SMLC material at 25°C were first measured using an accelerated surface area and porosity determination system as described previously. As can be seen in Fig. 4a, SMLC exhibits three stages of the absorption process involved in water vapor sorption: chemisorption of LiCl at 0-10% RH, deliquescence of $LiCl{\cdot}H_2O$ at 10% RH, and absorption of LiCl solution at >10% RH. The water absorption of SMLC increased from 0.40 g g^{-1} to 0.89 g g^{-1} at 10% RH from the deliquescence point. In the high-humidity environment, water weakly bonded to LiCl was

transferred to the sphagnum moss and MDMAPS networks and bonded to hydrophilic hydroxyl groups, raising the water uptake of SMLC to 8.99 g g^{-1} through multilayer sorption. And, the crystalline peaks in the SMLC disappeared after water absorption and saturation, which indicated that the crystal structure of LiCl in the composites disappeared to form an amorphous structure (Fig. 4b). This also proves the LiCl is completely dissolved and its core role of water trapping in SMLC composites spontaneously absorbs water from the surrounding atmosphere. Overall, the excellent structural composition of SMLC gives it an ultra-high water-absorption capacity, with water-absorption efficiencies of 1.40, 2.43, and 6.42 g g^{-1} at 30%, 60%, and 90% RH, respectively.

Humidity and temperature are key factors that influence the sorption performance of SMLC. Hence, we tested the sorption kinetics of SMLC at different humidities and temperatures to understand the environmental adaptivity of SMLC. Firstly, relative humidity of 30%, 60%, and 90% RH were set to represent three typical climatic environments: arid, semi-arid, and humid, respectively. Fig. 4c presents the dynamic sorption results of SMLC at these three different RHs. At 30% RH, within 5 hours is the rapid sorption phase of SMLC, capable of adsorbing 78% of saturated moisture, and at 60% RH, within 3 hours is the rapid sorption phase of SMLC, capable of adsorbing 75% of saturated moisture. Within 10 hours, sorption saturation was achieved at both 30% and 60% RH. At 90% RH, the time to reach sorption saturation is increased due to the high water content in the environment, but SMLC still achieves a sorption rate of 5.26 g g^{-1} within 10 hours. Generally, the water absorption rate increased with increasing RH, and the sorption saturation point was prolonged, but SMLC still maintained excellent sorption kinetics in different humidity environments. As can be seen in Fig. 4d, the environmental temperature also affects the water absorption capacity of SMLC. A slight

decrease in water sorption occurs as the temperature increases. However, the sorption rate of SMLC was accelerated when the temperature increased from 25°C to 35°C, which could be attributed to the fact that the increase in temperature made the chemical molecules inside the material that bind to water more active, enhancing the water absorption efficiency. The decrease in water absorption occurred when the temperature continued to increase up to 45°C, which may be due to the desorption of SMLC during the modification process being greater than the rate of water absorption. Also, SMLC showed satisfactory water sorption rate and water absorption rate compared to other reported water-absorbing materials for water sorption in arid (~30% RH), semi-arid (~60% RH), and humid (~90% RH) environments (Fig. 4e) [33, 39-45].

Performance differences between milligram-scale micro samples and real-world macro samples are often overlooked. To accurately assess the sorption characteristics, we measured the water sorption properties of gram-scale SMLC bulk samples (~3cm diameter, ~1cm thickness) at 10% to 90% RH (Fig. 4f). Although scaled-up gram-scale adsorbents are slightly inferior to that of microscopic samples, they still showed substantial water sorption properties (maximum water absorption efficiency of 4.69 g g^{-1}). This could be due to that monolithic adsorbent with high filling thickness and density are easily limited by higher vapor diffusion barriers and lower heat transfer rates, whereas the interconnected multistage porous topology composite formed by the LiCl, sphagnum moss, and MDMPAS improves its water collection and storage performance.

Sphagnum moss is a plant with a super-hydrophilic surface that is super-soaking [46]. As can be seen in Fig. S7, the multi-network dense structure formed by the polymer gel formed by MDMPAS filled with LiCl/CB with sphagnum moss has a super-hydrophilic and fully wetted surface, and the CB coating does not reduce the contact angle. SEM and optical microscopy provided a piece of more direct evidence to examine the water absorption process of SMLC. Fig.

4g is a real process of water droplet growth and migration in the SMLC recorded by a high-speed camera stereo microscope. Smaller water droplets progressively grow to form larger droplets and migrate to other parts of the SMLC, eventually forming the wetted surface seen in Fig. 4h. The additional characterizations further confirm the robustness and functional water states of SMLC. As shown in Fig. S8, the SMLC withstands a 200 g weight without cracking or collapse and rapidly recovers its original shape after load removal, demonstrating good mechanical stability and elasticity. The TGA/DSC results (Fig. S9) for SML and SMLC both display a single dominant mass-loss and broad endothermic event between 30 and 100 °C, attributable to evaporation of physically/weakly bound water, with similar onset and peak temperatures, indicating that incorporation of LiCl and carbon black does not introduce additional low-temperature degradation and that the composite is thermally stable within the operating range. Raman analysis of the O-H stretching region (Fig. S10) reveals deconvoluted peaks corresponding to weakly hydrogen-bonded free water (FW) and more strongly hydrogen-bonded intermediate water (IW) associated with the hydrated polymer-salt network; the prominence of IW suggests that SMLC hosts a substantial fraction of “activated” water with weakened hydrogen bonding, which facilitates low-energy desorption during solar-driven cycling [47].

3.2.2 Water desorption performance

The difference between the RH inside the adsorbent and the environmental RH triggers desorption. As the temperature of the SMLC increases its saturated vapor pressure increases, leading to a decrease in its internal RH, which in turn leads to the release of water. Desorption kinetics is another important parameter for water harvesting. Fig. 5a shows the dynamic desorption curves of the microscopic samples reduced to a constant 30% RH after completion of water absorption saturation at high humidity (90% RH). The desorption of SMLC was completed

in 30 min, 120 min, and 180 min at working conditions of 60, 75, and 90 °C. SMLC retained 0.91 g g^{-1}, 0.54 g g^{-1}, and 0.26 g g^{-1} of water uptake during this process, which corresponds to 14%, 8%, and 4% of the initial water uptake. SMLC materials desorb up to 96% of the maximum amount of moisture. This demonstrates that SMLC has good desorption and water release properties and that external temperature conditions affect desorption. Since the adsorbent can only release water by solar-driven photothermal effect, UV-vis-NIR spectra of SMLC and SML were tested, and the results are shown in Fig. 5b. There are significant differences between the absorption spectra of SMLC and SML, especially in the visible (VI) and infrared (in) regions of the light, and the SMLC shows an intense and broad spectral absorption characteristic of more than 90%. CB doping into SML changed the color from straw to black and higher absorption values were observed, which suggests that CB is the main reason for the photothermal effect of SMLC. When sunlight hits the surface of CB, photons are absorbed, causing the temperature of the CB particles to rise. Using the principle of heat transfer, this temperature increase leads to the warming of the surrounding liquid, which results in energy conversion and utilization. Rapid warming of bulk SMLC samples can be achieved from 28.2 °C to 60.3 °C in 20 min at 1 sunlight intensity (Fig. 5c). As shown in Fig. S11, the distinct temperature difference between the SMLC region and its non-material surroundings demonstrates the material's effective and localized photothermal conversion capability. Similarly, in order to accurately assess the water release characteristics, we measured the water desorption properties of gram-scale SMLC bulk samples (~3 cm diameter, ~1 cm thickness) under sunlight at different intensity (Fig. 5d). At light intensities of 0.5, 1.0, and 1.5 kW•m^{-2}, SMLC could release 50%, 74%, and 89% of adsorbed water within 120 min, respectively. Desorption rates and efficiencies are affected by the intensity of sunlight, with the stronger the sunlight, the better the desorption. The incomplete dewatering

in this process may be caused by the hydration reaction that occurs when the RH is higher than 11% of the deliquescence point of LiCl. Nevertheless, as desorption can be completed relatively quickly in 80-180 min, multiple cycles can be performed in a single day to maximize the total sorption capacity. Water desorption can be divided into four stages: evaporation of water from the porous framework attached to the sphagnum moss, water desorption from bonding to the polymer matrix, evaporation of water from the LiCl solution, crystallization and chemical desorption of the LiCl hydrate (Fig. 5e). The longitudinal and transverse internal structure of SMLC further enhances the multifaceted pathway of water sorption-desorption. To ensure the sorption and desorption stability of SMLC, 15 consecutive sorption-desorption cycles were carried out, with 10 h of sorption at 25 °C & 60% RH and 2 h of desorption at 75 °C & 30% RH. After 15 cycles, the SMLC retained its pristine water harvesting ability, indicating that the material is adequate for subsequent practical applications (Fig. 5f). Fig. 5g and Table S1 compare the water uptake, rate of absorption, rate of drainage, daily water production and sustainability of different water harvesting materials, demonstrating the excellent performance and sustainable water harvesting potential of SMLC. Based on this, we postulated a schematic of the ET water absorption-storage-desorption process, as shown in Fig. 5h. Water vapor is transported from the surrounding air into the dry SMLC photothermal water-harvesting material where it is trapped and condensed into liquid water. Due to the hydrophilic nature of the sphagnum moss-based porous skeleton, the material can store the absorbed water in the form of pore filling and expansion.

3.3 Working Prototype of the EAI Farm

Based on the design principle described in Section 2.3, we established a functional prototype system, hereafter referred to as the “EAI Farm,” to demonstrate the practical

integration of SMLC composites into an ET water recycling framework (Fig. 6a). The device consists of 1) a greenhouse with a tilting removable roof, 2) a self-rotating SMLC placing tray, 3) heating lines, 4) a reservoir, 5) a temperature and humidity meter, 6) solar panels, 7) a motor, and 8) a control box, 9) drip irrigation tubes. To align water delivery with real-time crop requirements, the EAI device incorporates environmental sensing and passive control logic. Temperature and humidity sensors continuously monitor greenhouse microclimate conditions. Based on these inputs, the system dynamically regulates the sorption-desorption behavior of the SMLC composite through pre-defined open-close time cycles. These cycles are adjusted according to sunrise/sunset patterns and atmospheric conditions (e.g., sunny or cloudy days), ensuring that water is released during peak transpiration periods. The harvested water is stored in a reservoir and subsequently supplied to the root zone via drip irrigation, triggered by soil moisture thresholds or scheduled intervals. This decentralized, sensor-assisted approach enables on-demand water release without external energy or manual intervention. The dimensional design of the device and the actual photo of the component are shown in Fig. S12 and Fig. S13 respectively. The removable tilting roof serves three purposes: it is closed to prevent the loss of ET water when ET is strong, it opens to absorb more atmospheric water when the ambient humidity is higher, and the angle of the tilt makes it easier for the enriched water to flow into the reservoir. The self-rotating SMLC placing tray not only serves to hold the absorbent material in place, but also assumes the role of a wind turbine. Its rotating function accelerates the flow of gases, thus increasing the rate of absorption of ET and atmospheric water. The rotational speed control is shown in Fig. S14. A heating line is used to assist in the desorption of moisture from the SMLC. The temperature and humidity meter are responsible for monitoring greenhouse conditions. And solar panels, motors and control boxes are in charge of the operation of the

entire system. Finally, drip irrigation is carried out in accordance with the crop's water needs, whereby the water required by the crop is evenly and slowly dripped drop by drop into the soil of the crop's root zone through the tubing system and the irrigators mounted on the capillary tubes. The circuit within the EAI irrigation control system is shown in Fig. S15. The entire farm system is powered by a combination of solar photovoltaic panels and 50W 18V battery cells, ensuring that the control system and heating lines receive reliable and sufficient power to operate effectively.

3.4 Evapotranspiration water reuse Integrated Demonstration

Greenhouse trials were carried out at IEDA-CAAS (39.96°N, 116.33°E) to validate the working model, while sorption-desorption cycles were optimized to enhance water yield and system stability by aligning with diurnal weather patterns. Three irregular cycle modes were designed according to solar input and humidity conditions, with roof-opening timings shown in Fig. 6b and Table S2. Under sunny conditions, the system operated on a time-split cycle denoted as "4+2+1+2+1+14," where each numeral represents the duration (h) of sequential desorption (4 h, 1 h, 1 h) and sorption (2 h, 2 h, 14 h) phases within 24 h. This arrangement enabled multiple dynamic collection-release events per day. On cloudy days, a modified "4+4+2+4+2+8" cycle was employed, with extended desorption and transition phases to compensate for reduced solar intensity. These irregular cycles were tailored to ambient climatic rhythms, ensuring that water release coincided with peak crop transpiration demand.

Over a 7-day period, barley and wheat exhibited 19 cm-25 cm of growth without external irrigation or manual intervention (Fig. 6c). Daily water collection and release under sunny conditions are shown in Fig. 6d, with the green-expandable SMLC composite achieving an average release of 3.03 g g^{-1} d^{-1} within the EAI drip irrigation control system. Drip irrigation was

triggered on the fourth day using water stored in the reservoir. In the control group (without EAI or external irrigation), soil moisture declined steadily due to evaporative loss. By contrast, the EAI system maintained a relatively stable soil moisture profile throughout the 7 day trial (Fig. 6e), demonstrating its capacity to buffer evapotranspiration losses and sustain near-optimal root-zone conditions solely with internally recycled water. Soils from the EAI treatment and the control showed very similar values, indicating that the short-term experiment did not noticeably alter bulk soil chemistry (Table S3).

Water quality analyses further confirmed the ecological safety of the SMLC-based system. All ion concentrations in the harvested water remained well below WHO drinking water limits, with negligible lithium ion release (Fig. 6f). Under this worst-case leaching scenario, the leachate showed only 5% 15-min luminescence inhibition to Vibrio fischeri, indicating no obvious acute aquatic toxicity. Combined with the use of renewable sphagnum moss and a solvent-free synthesis route, these results highlight the system's sustainability, environmental compatibility, and potential for scalable deployment in arid and semi-arid agriculture. Collectively, the EAI system offers a green, low-cost, and field-ready strategy to recycle ET water, bridging materials innovation with agricultural sustainability and contributing to global efforts in securing food and water under climate change.

3.5 Life-cycle and sustainability implications

Beyond its functional performance, the EAI system offers clear advantages across the life cycle of agricultural irrigation technologies. Material sourcing relies on renewable sphagnum moss and common salts/polymers, avoiding the high-purity metals and solvent-intensive processes of MOF/COF sorbents or the synthetic residues of hydrogels (Table S4). Fabrication is low-energy (<100 ℃, solvent-free), reducing embodied carbon compared with high-temperature

solvothermal synthesis. Operationally, the system is nearly energy-autonomous, requiring only minimal photovoltaic-battery support, in contrast to continuous pump-driven irrigation (100-1000 W). Cost analysis (~$2.08 per unit) (Table S5) and safe water quality (Fig. 6f) further strengthen its scalability. FTIR spectra of SML and SMLC before and after one year of exposure to humid air (Fig. S16) show that the main bands-including the broad O-H stretching at 3000-3600 cm-1 and characteristic C=O/C-O/S-O vibrations in the fingerprint region-remain at nearly identical positions with only slight intensity changes. This indicates that the chemical structure of the sphagnum-based network is largely preserved and that no obvious degradation occurs even after long-term exposure to moist air. These factors collectively position the EAI system as a low-carbon, eco-friendly approach to water management in drylands. Scalability benefits from dry-state prefabrication and compact transport, with on-site rehydration to restore function [48]. Compaction is a controllable pre-processing step that can increase water retention, and bulk density is optimized to avoid loss of aeration [49]. Supply relies on cultivated/managed sources, not local wild harvesting in arid regions, which is consistent with indoor-agriculture practice for reusable media [46]. However, these life-cycle statements are preliminary and material-centric; outcomes depend on unit sizing, drying route, module lifetime and yield, transport logistics, regional datasets, and the use of proxies, so results should be interpreted as directional rather than definitive. Incorporating full life-cycle carbon accounting and field-scale deployment will be essential next steps to validate its long-term sustainability benefits.

4 Conclusion

This work demonstrates a practical route to close the farm water cycle by converting ET losses into an irrigation source via an integrated EAI system and a bio-derived hygroscopic composite on a Sphagnum smoss caffold. The composite delivered high vapor uptake and robust

release under realistic conditions: 6.42 g g^{-1} at 90% RH, with a maximum of 8.99 g g^{-1} at high humidity; fast desorption under light (50%, 74%, 89% of stored water released within 120 min at 0.5 kW m^{-2}, 1.0 kW m^{-2}, 1.5 kW m^{-2}, respectively); and stable performance over 15 sorption-desorption cycles. Multi-scale validation confirmed repeatable operation from DVS micro-samples to bulk monoliths. In a 7-day greenhouse trial without external irrigation, the EAI device maintained soil moisture and supported barley/wheat growth to 19-25 cm. The recovered water met WHO ionic limits, and the material cost was $2.08 per unit. Life-cycle screening indicates advantages in renewable sourcing, low-temperature, solvent-free fabrication (<100 ℃), near-passive operation, and low unit cost, positioning the concept as a low-carbon, field-adaptable option for dryland water management. This study is a greenhouse feasibility demonstration using a compact micro-prototype, capturing early growth at a single site with limited agronomic metrics and a screening, material-centric life-cycle perspective. Future work will extend to longer and full life-cycle cultivation with larger, taller devices in open-field settings; broaden metrics to biomass, Water Use Efficiency, and yield; quantify ET vs. ambient contributions; evaluate long-term durability and water/soil safety; and advance to quantitative LCA and farm-scale techno-economics.

CRediT authorship contribution statement

Menglu Wang: Writing - original draft, Methodology, Data curation. Buchun Liu: Methodology, Conceptualization. Enke Liu: Writing - Review & editing, Validation, Funding acquisition. Saud-uz Zafar: Validation, Data curation. Joost Wellens: Methodology, Conceptualization, Review. Marie-Laure Fauconnier: Methodology, Conceptualization. Caroline De Clerck: Writing - review & editing. Xurong Mei: Writing - review & editing.

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Fig. 1. Evapotranspiration-atmospheric water closed-loop management schematic.

Fig. 2. (a) Design schematic of the sphagnum moss-based porous photothermal composite (SMLC); (b) Multi-network structure with salt, polymer and photothermal additive.

Fig. 3. SEM images of the surfaces, pores, and cross-sections of the (a-c) Sphagnum peat, (d-f) SML, and (g-i) SMLC; (j) EDS elemental mapping of the pores of the SMLC; (k) FTIR spectra of the Sphagnum peat, MDMAPS, SML, and SMLC; (l) XRD patterns of the Sphagnum peat, LiCl, CB, MDMAPS, and SMLC; High resolution XPS spectra of (m) C 1s, (n) O 1s, (o) N 1s and (p) Cl 2p for SMLC.

Fig. 4. (a) Water-sorption isotherm at 25 °C; (b) XRD before and after vapor uptake; (c) Sorption kinetics versus RH; (d) Sorption kinetics versus temperature; (e) Comparison with reported AWH sorbents; (f) Bulk versus micro samples; (g) Optical microscopy of droplet growth, coalescence and migration, scale bar 100 μm; (h) SEM after sorption at 25 °C and 60% RH for 10 min.

Fig. 5. (a) Dynamic sorption and desorption under varied conditions; (b) Optical absorption of SML and SMLC, AM1.5G weighted; (c) Infrared images before and after 1-sun exposure; (d) Desorption at 25 °C under 0.5, 1.0 and 1.5 kW m^{-2}; (e) Schematic of vapor flow during desorption; (f) Fifteen sorption–desorption cycles, sorption 25 °C and 90% RH, desorption 90 °C; (g) Radar plot comparing MOF-801, LiCl@CGNFC and SMLC; (h) Schematic of the absorption and desorption process.

Fig. 6. (a) Schematic design of EAI device; (b) Daily sorption and desorption times for sunny and cloudy days; (c) One-week plant images under EAI drip; (d) Daily water harvest and release; (e) Soil-moisture comparison between AWH-drip and control; (f) Ion concentrations in harvested water.

Declaration of interests

☒The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

☐The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

Graphical abstract

Highlights

- EAI system closes the evapotranspiration loop for self-sufficient irrigation.
- Bio-derived SMLC with hierarchical pores and multi-network sorption design.
- High water uptake (6.42 g/g) and stable solar-driven release at 30–60% RH.
- Sustains barley/wheat growth (19–25 cm, 7 days) without external water.
- Life-cycle assessment confirms low cost, low energy, and eco-friendly profile.