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All-natural, eco-friendly composite foam for highly efficient atmospheric water harvesting

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ABSTRACT

Water is vital for life, yet about 10 % of the world population lacks access to it. The atmosphere is a ubiquitous and abundant water reservoir, equivalent to 10 % of the freshwater in all lakes on earth. Existing absorbent materials for atmospheric water extraction, such as silica gels, zeolites, and metal-organic frameworks, suffer from either low water capture capacity or expensive and hazardous fabrication processes. Here we demonstrate an all-natural, eco-friendly composite foam with high performance in atmospheric water harvesting in both non-arid and arid environments, solely powered by natural sunlight without any other energy input. The composite foam is made of natural and earth-abundant cellulose and graphite via an aqueous process (no organic solvent used), followed by carbonization and LiCl doping. The foam can absorb water over 670 % of its weight from an atmosphere at 90 % relative humidity (RH) and quickly release 95 % of absorbed water under sunlight irradiation in 1 h. Remarkable daily water production of 1.24 g g⁻¹ day⁻¹ in an arid environment (30 % RH) and 2.83 g g⁻¹ day⁻¹ in a non-arid environment (30 % –60 % RH) has been achieved, outperforming existing absorbent materials. The all-natural composite foam is also eco-friendly and non-toxic, promising a feasible and efficient green solution to atmospheric water harvesting.

1. Introduction

Water is crucial for all life forms, yet water shortage is a surging global crisis [1–5]. Although 70 % of the earth's surface is covered by water, only 2.5 % of the water on earth is freshwater [6,7]. Water scarcity becomes increasingly severe due to population growth and climate change. Currently, about two-thirds of the world's population, or four billion people, live without sufficient access to fresh water for at least one month of the year. Half a billion people worldwide face severe water scarcity all year round [8]. The World Economic Forum has listed water crises among the top-five risks in terms of impact to society for eight consecutive years [9]. Tremendous efforts have been dedicated to developing water desalination technologies [10], such as electrodialysis [11,12], reverse osmosis [13,14], and capacitive deionization [15,16]. These technologies, however, require high energy consumption and strongly rely on brine water sources, which can hardly be used in land-locked nations and rural areas away from coastal line [17].

Earth's atmosphere is a ubiquitous and abundant water reservoir,

equivalent to 10 % of the fresh water stored in all lakes on earth [18]. Throughout the earth's 100-600-meter-thick atmospheric boundary layer, each cubic meter of air contains 4-25 g of water vapor [19]. Taking advantage of purity and ubiquity, atmospheric water is considered an enormous freshwater resource that can be easily replenished by water evaporation and atmospheric circulation, making it a promising alternative for harvesting water in water-deficient areas. Various strategies to directly extract water from the air have been explored, e.g., fog harvesting, dewing, and sorbent-assisted water harvesting [20-22]. Various absorbents, such as silica gels, zeolites, metal-organic frameworks (MOFs), and hygroscopic salts, are used to achieve sorbent-assisted water harvesting from the air [2,17,23-27]. Silica gels and zeolites feature interconnected pores to hold water by absorption and capillary condensation and are common desiccants due to their low price and easy processability. However, the water capture capacity of these commonly used desiccants is low (only up to 40 % of its weight), limiting their applications in efficient atmospheric water harvesting. Recently, there is growing interest in using MOFs for atmospheric water

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harvesting due to their better water capture capacity and lower water regeneration temperatures compared with conventional desiccants such as silica gels and zeolites [28,29]. Nevertheless, suffering from the complicated preparation technology and a large amount of organic solvent consumption during fabrication, MOFs remain challenging to be manufactured and used on a large scale.

Hygroscopic salts, such as LiCl and CaCl₂, possess advantages such as remarkable water capture capacity in a wide range of relative humidity (RH), low price, abundant reserves, and free of environmental pollution, making them promising water harvesting materials [30]. However, hygroscopic salts are likely to deliquesce after absorbing moisture from the air, resulting in leakage of hygroscopic salts and a subsequent decrease in water capture capacity. Porous materials (e.g., foams and aerogels) can serve as a matrix for hygroscopic salts to overcome the leakage problem. Nanofibrillated cellulose (NFC), a low-cost, abundant, and sustainable material, is widely used to construct three-dimensional porous structures due to its outstanding mechanical strength, impressive flexibility, and large surface areas [31-34]. Here we demonstrate an all-natural, eco-friendly composite foam with high-performance atmospheric water harvesting. The composite foam is made of cellulose and graphite (both natural and earth-abundant) via an aqueous process without any organic solvent. The cellulose/graphite foam is then carbonized and doped with LiCl (termed as LiCl@CGNFC). The LiCl@CGNFC foam can absorb water from the atmosphere at 90 % RH up to over 670 % of its weight and quickly release 95 % absorbed water under sunlight irradiation in 1 h. In a typical 1 h uptake - 1 h release cycle at 90 % RH, the water harvesting capability of as-made LiCl@CGNFC foam can be up to 1.23 g g^{-1} in one cycle, with a stable water harvesting performance in 10 cycles. A LiCl@CGNFC-based atmospheric water harvesting device is developed, which can achieve a remarkable daily water production of 1.24 g $g^{-1}\ day^{-1}$ in an arid environment (30 % RH) and 2.83 g g^{-1} day⁻¹ in a non-arid environment (30 %–60 % RH), outperforming existing absorbent materials. Furthermore, the all-natural LiCl@CGNFC foam is eco-friendly, as revealed by the ecotoxicity testing. These findings suggest a feasible and efficient green solution to atmospheric water harvesting, promising to address the water scarcity crisis.

2. Results and discussion

Fig. 1a shows a schematic of the typical approach to fabricating the LiCl@CGNFC foam for atmospheric water harvesting. First, NFC is prepared by an oxidation method from dried pulp which is described in the Supporting Information. Fig. S1 shows the nanostructure of the asprepared NFC nanofibers with a diameter of around 8 nm. NFC dispersion and graphite are mixed by ultrasonication to achieve a homogeneous slurry. NFC consists of hydrophilic functional groups (i.e., hydroxyl groups and carboxyl groups) and a hydrophobic backbone (i. e., C-H moieties). Generally, NFC is negatively charged due to the ionization of functional groups, which can facilitate NFC dispersion in water. Meanwhile, the hydrophobic backbone interacts with hydrophobic graphite flakes, which can directly assist graphite dispersion and exfoliation in water. The diameter of the graphite flakes reduces from 25-100 µm to 0.5-5 µm after ultrasonication (Fig. S2). Afterward, the graphite-NFC (GNFC) slurry is poured into mold boxes, followed by contacting with liquid nitrogen to form frozen solid blocks. The resulting frozen samples are then freeze-dried using a lyophilizer to become foams. The growth of ice crystals during freezing results in numerous connected channels in the foams. Subsequently, the foams are heated at 500 °C in a tube furnace to achieve carbonized foams (CGNFC). The CGNFC foams are immersed in LiCl solution and then heated in a 105 °C oven for drying, leading to the final LiCl@CGNFC foams. The LiCl@CGNFC foam is assembled with a magnifying lens and a container to serve as an atmospheric water harvesting device. The device can



Fig. 1. Schematic of the approach to preparing LiCl@CGNFC foam and its water harvesting performance. (a) Freeze-drying, carbonization, and coating are applied to prepare the LiCl@CGNFC foam. The last panel demonstrates a LiCl@CGNFC foam-based water harvesting device. (b) A comparison of the daily water production and water uptake capacity of various absorbents suggests the superior atmospheric water harvesting performance of the LiCl@CGNFC foam. (c) A radar plot for comparison among MOF-801, LiCl@HCS, and LiCl@CGNFC in terms of water uptake, water uptake speed (calculated at 30 %–35 % RH at saturation), water release speed (under 100,000 Lx irradiation), daily water production (at ambient conditions), and sustainability.

absorb atmospheric water when the lid of the container remains open, while the absorbed water can be released utilizing the concentrated sunlight by the magnifying lens and is collected by the container for further use.

Fig. 1b compares the performance of atmospheric water harvesting of various absorbents, including MOF801/G [35], MOF 801 [18,36], MOF303/G [35], LiCl@hollow carbon spheres (HCS) [37], LiCl/Mg-SO₄/activated carbon fiber (ACF) [38], LiCl/ACF [39], and LiCl@CGNFC foam. Water uptake capacity is defined as the weight of absorbed water (in grams) per gram of the absorbent material after equilibrium at a certain RH and temperature, which illustrates the maximum water uptake capacity in an ideal environment. Additionally, daily water production describes the weight of absorbed water (in grams) per gram of the absorbent material in one day after several harvesting cycles, which demonstrates the practical water harvesting capacity in a certain environment. In both arid environments (i.e., RH \leq 30 %) and non-arid environments (i.e., 30 % < RH < 60 %), the LiCl@CGNFC foam shows outstanding water uptake capacity and daily water production among all the absorbents compared, demonstrating its potential to harvest atmospheric water in a wide range of environment. The water uptake capacity of the LiCl@CGNFC foam is measured to be 0.93 g g⁻¹ (30 % RH) and 1.57 g g⁻¹ (50 % RH) at saturation, respectively. The LiCl@CGNFC foam presents the highest water uptake capacity (0.93 g g⁻¹) at 30 % RH, in comparison to MOF 801 (0.26 g g⁻¹) at 30 % RH and LiCl@HCS (0.70 g g⁻¹) at 35 % RH at saturation. Fig. S3 shows the remarkable water uptake capacity of the LiCl@CGNFC foam in the wet environment (90 % RH, 25 °C, 6.78 g g⁻¹) which is at least more than 2 times higher than other reported water harvesting materials. Water uptake speed and water release speed are defined as the weight of absorbed water and released water per gram of the absorbent material per hour (g g⁻¹ h⁻¹), respectively, and are two key factors to evaluate the water harvesting performance of materials. When the RH is about 30 %, the water uptake speed of the LiCl@CGNFC foam at saturation (0.21 g g⁻¹ h⁻¹) is higher than that of MOF 801 at saturation



Fig. 2. Morphologies, spectrum analysis, and thermostability of the GNFC, CGNFC, and LiCl@CGNFC foams. (a-c) A photograph (a) and SEM images (b,c) of the GNFC foam. (d-f) A photograph (d) and SEM images (e,f) of the CGNFC foam. (g-i) A photograph (g) and SEM images (h,i) of the LiCl@CGNFC foam, showing the porous structure and nanostructure of the foam. The inset in (i) shows scattered LiCl crystalline particles on the internal surfaces of the LiCl@CGNFC foam. (j) The FTIR spectra of the various foams, graphite, and NFC. (k) The UV-Vis spectra of the CGNFC, GNFC, and NFC. (l) The thermogravimetric curves of the various foams.

(0.04 g g⁻¹ h⁻¹) and LiCl@HCS at saturation (0.18 g g⁻¹ h⁻¹). The water release speed of the LiCl@CGNFC foam is 6.44 g g⁻¹ h⁻¹, significantly higher than that of MOF 801 (0.11 g g⁻¹ h⁻¹) and LiCl@HCS (2.51 g g⁻¹ h⁻¹). The exceptional water uptake and release speeds of LiCl@CGNFC lead to remarkable daily water production of the LiCl@CGNFC-based atmospheric water harvesting device (1.24 g g⁻¹ day⁻¹ in an arid environment, 30 % RH; and 2.83 g g⁻¹ day⁻¹ in a non-arid environment, 30 %–60 % RH). Fig. 1c and Table S1 compare the water uptake, water uptake speed, water release speed, daily water production, and sustainability of the LiCl@CGNFC foam with those of representative absorbents (i.e., MOF 801 and LiCl@HCS), demonstrating the promising potential of the LiCl@CGNFC foam as a high-performance and sustainable atmospheric water harvesting material.

Fig. 2a shows the photo of a block of as-made GNFC foam. The scanning electron microscope (SEM) images (Figs. 2b and 2c) show the microscale porous structure of the GNFC foam, with a pore diameter of 100–150 μ m and a density of 0.006 g cm⁻³. After carbonization, the color of the foam changes from light grey to dark, and the volume shrinks to about 1/8 of the pristine volume (Fig. 2d), which leads to a denser foam with a pore size ranging from 25 µm to 100 µm (Fig. 2e and 2f) and a density of 0.029 g cm⁻³. The change of foam structure and density results from the loss of a large amount of hydrogen and oxygen during the carbonization in an argon atmosphere. To demonstrate the function of graphite, an NFC foam and a carbonized NFC (CNFC) foam without graphite are fabricated as shown in Fig. S4. The CNFC foam cannot maintain the porous structure and shrinks to about 1/30 of the pristine volume, substantially much more than CGNFC foam (which shrinks to about 1/8 of the pristine volume). This result could be ascribed to the excellent mechanical properties of the graphite. The graphite flakes are embedded into the cell wall, protecting the pore structure from shrinkage or collapse during the carbonization process. Therefore, the resulting foam would sustain a porous structure after carbonization. Fig. 2g-2i shows the appearance and microscale porous structure of the LiCl@CGNFC foam, whose volume and pore size are consistent with those of CGNFC foam after LiCl coating. The inset in Fig. 2i shows that the LiCl crystalline particles evenly scatter coat on the internal surfaces of the LiCl@CGNFC foam, resulting in an increase of the foam density to 0.092 g cm $^{-3}$.

Fig. 2j displays the Fourier-transform infrared (FTIR) spectra of the NFC, graphite, and various foams to illustrate different chemical compositions during the fabrication processes. The peaks at 1034 cm^{-1} can be attributed to the stretching vibration of the C-O due to the oxygenrich cellulose molecules in NFC and GNFC samples [40]. The peaks at 1407 cm⁻¹ and 1315 cm⁻¹ are ascribed to CH_2 wagging symmetric bending and asymmetric bending vibrations owed to the CH₂ groups on the backbone of cellulose. The peaks at 1600 cm^{-1} , which appear on the curves of NFC, GNFC, and LiCl@CGNFC, are due to ester C=O stretching vibrations (from the carboxyl groups on NFC) or bending mode of absorbed water [41]. The band ranging from 3200 cm⁻¹ to 3500 cm⁻¹ is due to the characteristic absorption of the O-H stretching vibrations on cellulose molecules and absorbed water. This band cannot be found on the curves of graphite and CGNFC foam due to the absence of oxygen in graphite and the removal of oxygen during the carbonization process, respectively. The LiCl@CGNFC foam exhibits excellent performance of light absorbance in a wide spectral range, from ultraviolet (UV) to near-infrared NIR (300-2000 nm), as shown in Fig. 2k. The CGNFC foam can absorb more than 90 % of light in the wavelength range of 300 -1200 nm compared to NFC foam (\leq 20 %) and GNFC foam (\leq 58 %), which can be ascribed to the remarkable light absorbance capability of amorphous carbon converted from the cellulose skeleton during the carbonization [42]. The wide spectral light absorbance of the CGNFC foam leads to high efficiency of solar-to-thermal conversion, which is crucial for water evaporation from the foam under sunlight irradiation.

The thermal stability of various foams is investigated in argon over a temperature range of 30 $^{\circ}$ C to 600 $^{\circ}$ C. Fig. 2l plots the weight loss curves

of the GNFC, CGNFC, and LiCl@CGNFC foams as a function of temperature. A major weight loss (60 %) of the GNFC sample occurs in the range of 180 °C to 320 °C, which can be ascribed to the thermal degradation of cellulose. Dehydration and decomposition of cellulose in this temperature range lead to the release of H₂O and CO₂ from the sample [43]. A small weight loss from 30 °C to 100 °C and followed by a plateau region from 100 °C to 600 °C for CGNFC, and LiCl@CGNFC samples are observed. The small weight loss from 30 °C to 100 °C to 100 °C is attributed to the evaporation of water from the samples, while the long plateau is due to the stabilization by pre-carbonization process. The LiCl@CGNFC foam remains thermally stable up to 600 °C, demonstrating a highly desirable feature as a potential solar-to-thermal conversion material.

LiCl, a soluble salt with notable deliquescent behavior in air, is employed for capturing atmospheric water vapor. Fig. 3a shows the morphology of the commercial LiCl crystals used in the present study. The size of the LiCl crystals is around 50 μ m. Video S1 illustrates the solid-to-liquid phase transformation of the LiCl crystals in 6 min at 50 % RH under room temperature. Fig. 3b compares the water uptake of the LiCl crystals at different RH as a function of time. For a given RH, the speed of water uptake of the LiCl crystals is shown to be rather constant. The higher the RH, the higher the speed of water uptake of the LiCl crystals (e.g., 0.001 g g⁻¹ h⁻¹ at 30 % RH, 0.027 g g⁻¹ h⁻¹ at 50 % RH, 0.047 g g⁻¹ h⁻¹ at 70 % RH, and 0.125 g g⁻¹ h⁻¹ at 90 % RH, at the first hour of water uptake, respectively, Fig. S5).

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The highly porous structure of the CGNFC foam provides large surface areas for LiCl doping. After the CGNFC foam is soaked in LiCl solution and then oven-dried, two types of LiCl particles form on the internal surfaces of the foam: LiCl nanoparticles (with a diameter of 100–500 nm, 100 times smaller than commercial LiCl particles) and snowflake-like structures, as shown in Fig. 3c. It is worth noting that the significantly small size of the LiCl nanoparticles and the dendrite nature of the LiCl flakes absorbed in the CGNFC foam lead to a remarkably larger specific surface area than that of the commercial LiCl particles, a highly desirable feature for water capture of large capacity and high speed.

The water harvesting performance of the LiCl@CGNFC foam depends on the LiCl loading, humidity, and temperature. As shown in Fig. 3d-3f, the initial water uptake speed (1.69 g g^{-1} h^{-1} at 90 % RH), measured by the slope of the curves in the first hour of water uptake, is 13 times higher than that of the microscale commercial LiCl particles $(0.13 \text{ g g}^{-1} \text{ h}^{-1} \text{ at } 90 \% \text{ RH})$. The water uptake then slows down until the LiCl@CGNFC foam is saturated with water. To investigate the effect of LiCl loading on the water uptake of the LiCl@CGNFC foam, different concentrations of LiCl solutions (2 wt %, 4 wt %, 6 wt %, and 8 wt %, respectively) are used to soak the CGNFC foams. The LiCl loading dependent experiment is performed at 90 % RH and 25 °C. With the increase of LiCl contents, 48 h water uptake capability rises, and the foam treated with 6 wt % LiCl solution shows the highest water uptake $(7.34~g~g^{-1})$ after 48 h in comparison to the foam treated with 2 wt % (6.33 g $g^{-1})$ and 4 wt % (6.78 g $g^{-1})$ LiCl solution (Fig. 3d). However, a descent of water uptake capability is observed for the foam treated with 8 wt % LiCl solution (5.13 g g^{-1}), which could be attributed to the blocked pores and channels in the foam by overloading LiCl. Even though the foam treated with 6 wt % LiCl solution shows the highest water uptake at 90 % RH and 25 °C, an overflow of LiCl solution is observed in a water uptake experiment for the LiCl@CGNFC treated with 6 wt % LiCl solution at 90 % RH and 35 °C (Fig. S6). The foam is oversaturated thus cannot hold the excess absorbed water, leading to the loss of LiCl along with water overflow, which causes a reduced water uptake speed of the foam in the subsequent cycle of atmospheric water uptake. However, the foam treated with 4 wt % LiCl solution does not show any overflow in a water uptake experiment at 90 % RH and 35 $^\circ C$ or even 45 °C. Thus, the LiCl@CGNFC foam treated with 4 wt % LiCl



Fig. 3. Water harvesting performance of the commercial LiCl particles and LiCl@CGNFC foam under different test conditions. (a) A photograph of commercial LiCl particles. (b) Water uptake measurement of LiCl particles at the same temperature (i.e., 25 °C) but different RH. (c) Two typical morphologies of the LiCl particles absorbed on the internal surface of the LiCl@CGNFC foam: LiCl nanoparticles (e.g., those highlighted in green) and snowflake-like structures (e.g., as highlighted in blue). The green and blue colors are for visual enhancement only. (d) The water uptake of the LiCl@CGNFC foams with different amounts of LiCl loading at 90 % RH and 25 °C as a function of time. (e) The water uptake measurement of the LiCl@CGNFC foams treated with 4 wt % LiCl solution at the same temperature (i.e., 25 °C) but different RH. (f) The water uptake measurement of LiCl@CGNFC foams treated with 4 wt % LiCl solution at the same RH (i.e., 90 %) but different temperatures.

solution is chosen to carry out the water uptake experiments. The mass percentage of LiCl is 51.45 % in the LiCl@CGNFC foams treated with 4 wt % LiCl solution. Fig. S5 compares the water uptake speed of the LiCl particles and LiCl@CGNFC foam treated with 4 wt % LiCl solution at 25 °C and different RH at the first hour of water uptake. The water uptake speeds of LiCl@CGNFC are 0.38 g g⁻¹ h⁻¹, 0.89 g g⁻¹ h⁻¹, 1.00 g g⁻¹ h⁻¹, and 1.69 g g⁻¹ h⁻¹, at 30 %, 50 %, 70 %, and 90 % RH, respectively, which are much higher than those of LiCl particles (Fig. S5) and can be attributed to the remarkably smaller size of the LiCl nanoparticles doped on the internal surface of the foam than that of the commercial LiCl particles. Furthermore, the 3-dimensional porous structure of the LiCl@CGNFC foam provides a larger interface area between the air and LiCl that is highly desirable for atmospheric water adsorption.

The influence of RH on the water uptake capability is investigated in the experiments. As shown in Fig. 3e, the water uptake capacities of the LiCl@CGNFC foams treated with 4 wt % LiCl solution are measured at 25 $^\circ\text{C}$ and 30 %, 50 %, 70 %, and 90 % RH, respectively, to illustrate the significant influence of RH on the water uptake performance. The 48 h water uptake at 90 % RH (6.78 g g^{-1}) is 7 times larger than that at 30 % RH (0.93 g g^{-1}). The water uptake kinetics curves demonstrate the foam can reach an equilibrium state at various times at different RH. The foam becomes saturated after 240 min, 360 min, 480 min, and 48 h at 30 %, 50 %, 70 %, and 90 % RH, respectively. The highest water uptake speed is presented in the first hour for all RH conditions. The water uptake measurement of the LiCl@CGNFC foams treated with 4 wt % LiCl solution at 90 % RH and at different temperatures (i.e., 15 °C, 25 °C, 35 °C, and 45 °C) is plotted in Fig. 3 f. The higher temperature, the larger 48 h water uptake capacity, which could be ascribed to the higher absolute water content in the air at a higher temperature.

To complete the circle of water harvesting, we next demonstrate water release from the LiCl@CGNFC foams under natural sunlight irradiation without any other energy input. The LiCl@CGNFC foam can

efficiently absorb sunlight and convert it into thermal energy to facilitate water evaporation from the foam for collection. The sunlight irradiation intensity could be lower than one sun (100,000 Lux, i.e., 100,000 Lx) in various environments, for example, on cloudy days or in nonsummer seasons. Hence, it is essential to investigate the influence of irradiation intensity on the water release performance of the foam to illustrate the practicality of the foam. Water release performance of LiCl@CGNFC foams treated with 4 wt % LiCl solution is measured in the ambient environment and under different intensities of irradiation. Fig. 4a presents the water release curves under different irradiation intensities (20,000–100,000 Lx). The water release speeds of the foam in the first hour of water release are 2.51 g g⁻¹ h⁻¹, 3.09 g g⁻¹ h⁻¹, 4.57 g g⁻¹ h⁻¹, 5.79 g g⁻¹ h⁻¹, and 6.44 g g⁻¹ h⁻¹ under the irradiation intensities of 20,000 Lx, 40,000 Lx, 60,000 Lx, 80,000 Lx, and 100,000 Lx, respectively (Fig. S7). With the increase of the irradiation intensity, the foam releases water faster, demonstrating the foam could release water in a wide range of solar intensity to harvest water in different environments. The LiCl@CGNFC foam treated with 4 wt % LiCl solution shows a remarkable water release speed, that is, 95 % absorbed water can be released under irradiation of sunlight in 1 h.

Fig. 4b demonstrates the water harvesting cyclic stability of LiCl@CGNFC foam, with the water uptake performed at 90 % RH and 25 °C and the water release performed in the ambient environment under one sun irradiation. In each water uptake-release cycle, the foam is allowed to absorb atmospheric water for 1 h, followed by exposed one sun irradiation for 1 h to release water. The weight of the absorbed water at the end of the first water uptake process is defined as 100 % residue water. As revealed in Fig. 4b, the foam shows a stable water harvesting performance with negligible degradation after 10 cycles of water uptake and release. The water harvesting capability of as-made LiCl@CGNFC foam can be up to 1.23 g g^{-1} in one cycle. The maximum absorbed water amount reduces modestly from 100 % (the first cycle) to 85.8 % (the third cycle) and then stabilizes at around 85 %

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Fig. 4. Water release performance of the LiCl@CGNFC foams treated with 4 wt % LiCl solution under different conditions. (a) Water release measurement of the LiCl@CGNFC foams under different intensities of irradiation. (b) The water harvesting cyclic stability of the LiCl@CGNFC foam. The water uptake (at 90 % RH and 25 °C)-release cycle is performed 10 times successively to illustrate good reusability of the foam. (c) The temperature variation of the foam at different positions in the ambient environment. The temperature of the top surface of the foam could be as high as 80 °C after 45 min irradiation. (d) Infrared thermal images of the foam under irradiation at different times (0–60 min) in side view and top view. (e) The water harvesting performance of an integrated device under natural sunlight. The water droplets run down the inner side wall of the container after 30 min sunlight irradiation. (f) The accumulative water production measurement of the device at ambient RH and 30 % RH on July 16, 2021, College Park, Maryland, US, 38.99° N, 76.94° W, 2 m elevation.

in the remaining 7 cycles. The modest reduction of water uptake in the initial cycles could be attributed to the agglomerations of some of the LiCl particles to form larger LiCl particles that restrain the water uptake speed [44]. After a few cycles, the size of the LiCl particles does not increase anymore, thus the water harvesting capacity of the LiCl@CGNFC foam becomes stable.

The temperature variations of the foam at different positions, i.e., the top surface, the bottom of the side surface, and the background are monitored throughout the water release process (Figs. 4c and 4d, Video S2). The foam shows a higher temperature than the background after 1 min irradiation, demonstrating its efficient solar-to-thermal conversion capability. The curves in Fig. 4c show two typical stages which are a rapid heating stage (at the first 2 mins) and a slow heating stage (after 2 min). Due to the direct irradiation, the top surface shows the highest temperature at a given moment, in comparison with a relatively low temperature at the bottom of the side surface. The heat is conducted from the top surface to the whole piece of foam. The temperature of the top surface and bottom of the side surface quickly rises to about 40 °C in 2 mins, which can facilitate the water evaporation from the foam. At first, the water stored near the surface evaporates. Meanwhile, the water

in the center and bottom of the foam replenishes the vacant pores near the surface through the interconnected channels and pores established during freeze-drying. After 1 h irradiation, about 95 % of the water evaporates from the foam.

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To demonstrate water harvesting in a natural environment, a LiCl@CGNFC foam is integrated with a plastic container and a magnifying lens to serve as a water harvesting device (Fig. 4e). During the water uptake phase, the lid of the container remains open so that the foam can absorb the atmospheric water. During the water release phase, the container is sealed so that the magnifying lens concentrates the sunlight to help facilitate water evaporation from the foam. The container provides surfaces for water vapor condensation and collection of the obtained liquid water. Exposed under sunlight irradiation, the foam transforms the sunlight energy into thermal energy leading to the temperature increase of the foam and absorbed water. The water evaporates from the foam. When the water vapor in the sealed container reaches saturation at a certain temperature, the vapor liquefies and condenses to form small water droplets on the inner surfaces of the

container (e.g., as shown in the last image of Fig. 4e). Small water droplets merge into larger water droplets and finally flow down along the wall under the effect of gravity. Fig. S8 shows the process of the formation of liquid water when the device is exposed to sunlight for 30 min. The daily water production of the device was carried out on July 16, 2021, at College Park, Maryland, US 38.99° N, 76.94° W, 2 m elevation. The meteorological data, i.e., temperature (27.2 °C - 37.9 °C), RH (32-66 %), and solar irradiation intensity (28.8 kLx - 130.1 kLx), are summaries in Fig. S9. It was a typical partly cloudy day in College Park, Maryland. The experiment was performed between 8:25 am and 19:00 pm at 30 % RH (arid environment) and ambient RH (non-arid environment) for 7 cycles, as shown in Fig. 4 f. The LiCl@CGNFC foambased device presents remarkable daily water production of 1.24 g g⁻¹ day^{-1} (arid environment, 30 % RH) and 2.83 g g⁻¹ day^{-1} (non-arid environment, 30 %-60 % RH) (Fig. 4f). The presented daily water production of the device exceeds that of other devices or materials demonstrated so far (Fig. 1b and 1c).

The LiCl@CGNFC foam consists of carbonized NFC, graphite, and LiCl, all of which are environmentally friendly [45,46]. To demonstrate the low environmental impacts of the LiCl@CGNFC foam, we carry out seed germination toxicity tests. In each test set, two cilantro seeds are buried in soil together with a piece of LiCl@CGNFC foam (13 mm \times 8 mm \times 5 mm in size) in proximity (Figs. 5a and 5b). Five of such test sets are carried out at the same time. Under regular sunlight and with appropriate water irrigation, all 10 seeds germinate successfully and ultimately grow up as healthy cilantro plants of height ranging from 10 cm to 70 cm after 2 months. Fig. 5c and S10 show the snapshots of the growth process of the test sets. Fig. 5d shows that the roots of the mature cilantro plant wrap around the LiCl@CGNFC foam buried nearby. Further examination by digging out the foam piece and cleaning the soil reveals that the cilantro plant roots penetrate through the foam in multiple places (Fig. 5e and 5f). For the control experiment, we also carry out seed germination tests in natural soil without our composite foam. Fig. S11 shows the growing status of the cilantro plants in natural soil is comparable with that of the plants with the composite foam presenting in the soil under their roots. The above ecotoxicity tests and the control experiments demonstrate that the LiCl@CGNFC foam poses no appreciable negative impacts on the germination and growth of cilantro plants, suggesting that the LiCl@CGNFC foam is eco-friendly.

3. Conclusions

We demonstrate an all-natural, eco-friendly LiCl@CGNFC foam with remarkable atmospheric water harvesting performance in both non-arid and arid environments, solely powered by natural sunlight without any other energy input. The LiCl@CGNFC foam is capable of absorbing water from the atmosphere at 90 % RH by over 670 % of its own weight and quickly releasing 95 % of the absorbed water under irradiation of sunlight in 1 h. The exceptional water harvesting performance of the foam is shown to be stable over 10 cycles of water uptake-release process with a water harvesting capacity of up to 1.23 g g^{-1} in each cycle. A LiCl@CGNFC-based water harvesting device is developed and presents a remarkable daily water production of $1.24 \text{ g s}^{-1} \text{ day}^{-1}$ in arid environment (30 % RH) and 2.83 g g⁻¹ day⁻¹ in non-arid environment (30 %-60 % RH). The LiCl@CGNFC foam is made via an aqueous process with no organic solvent used and shows no appreciable negative impact in seed germination toxicity tests. These findings suggest a sustainable solution to highly efficient and robust atmospheric water harvesting that holds promise to address the surging global crisis of water shortage.

4. Experimental section

4.1. Materials

The Kraft bleached dried softwood pulp (Grande prairie NBSK) and the graphite powder (3060) were obtained from International Paper and ASBURY Carbons INC, respectively. The NFC used in this study is prepared by a 2,2,6,6-tetramethylpiperidine (TEMPO) oxidation method from the dried pulp. The details of the experimental information are summarized in Supporting Information. Sodium carbonate, TEMPO, sodium bicarbonate, sodium bromide, sodium hydroxide solution (available chlorine 10–15 %) were purchased from Sigma-Alrich. Lithium chloride was obtained from ACROS Organics. All the chemicals are used without further purification.



Fig. 5. Cilantro seeds germination and plant growth tests to evaluate the ecotoxicity of LiCl@CGNFC foams. (a,b) In each test set, a piece of LiCl@CGNFC foam is buried in soil together with two cilantro seeds in proximity. Five test sets are carried out at the same time. (c) Snapshot photos of one test set show the successful germination of the two seeds and the healthy growth of the cilantro plant during the 64-day test. The final height of the plant by the end of the test is about 70 cm. (d) The LiCl@CGNFC foam is wrapped around by the roots of the cilantro plant. (e,f) The foam piece is cleaned out from the soil and cut open to show the penetration of the roots through the foam, showing strong evidence of no appreciable toxicity of the LiCl@CGNFC foam to the cilantro plant.

4.2. Preparation of the LiCl@CGNFC foam

0.5 wt % NFC and commercial graphite powder are mixed with a solid mass ratio of 1:20 by a mechanical mixer (IKA RW20 digital mixer, USA) to obtain a graphite/NFC dispersion. The resulting dispersion is performed under ultrasonic treatment through an ultrasonic homogenizer (Model 505, 500 W, 0.5-inch probe, Fisher Scientific, USA) for 90 min to achieve a graphite/NFC slurry. The graphite/NFC dispersion with certain graphite to NFC mass ratios is made by mixing the slurry with 1 wt % NFC dispersion. The graphite/NFC dispersion is transferred into a cubic container followed by freezing by contacting liquid nitrogen. The frozen samples are then freeze-dried by a freeze-drier (Free-Zone 1.0 L Benchtop Freeze-Dry System, Labconco, USA) to produce the CGNFC foam. The CGNFC foams are produced by annealing the GNFC aerogel at 500 °C in a tube furnace (OTF-1200X-S, MTI Corporation, China) for 2 h under an argon atmosphere. The CGNFC foams are soaked in LiCl solution (different concentrations) and are applied in a vacuum chamber (AccuTemp-19 Vacuum oven 110 V, Across International, USA) to fill all the pores and channels using LiCl solution. At last, the samples are totally dried in the oven at 105 °C.

4.3. Fabrication of the water harvesting device

A round hole is cut on the lid of a plastic container (diameter of 7 cm), which is used for the integration of a 5X magnifying lens by epoxy (Fig. 4e). A LiCl@CGNFC foam is fixed at the center of the bottom of the container. A small cubic plastic box is used for isolating the foam from the collected pure water.

4.4. Characterizations

The morphologies of the foam samples are characterized by Tescan XEIA3 SEM. The SEM samples are processed by gold sputtering before the test. An atomic force microscope (AFM, Cypher ES Environmental) is applied to characterize the morphology of the NFC. A spectrometer (Thermo Nicolet NEXUS 670 FTIR, USA) with 4 \mbox{cm}^{-1} resolution is adopted to obtain the FTIR spectra at room temperature. The transmittance-wavelength curves of various materials are measured by a UV-VIS-NIR spectrophotometer (UV-3600i Plus, SHIMADZU, Japan). Thermal gravimetric analysis is performed by a thermogravimetric analyzer (SDT 650 Simultaneous Thermal Analyzer, TA Instruments, USA) over a temperature range of 25 - 600 °C at a heating rate of 10 °C min⁻¹ under an argon atmosphere protection. All TGA samples are pre-dried at 80 °C for 2 h under vacuum before the TGA test. A fiber illuminator (OSL1, THORLABS INC, USA) is employed to offer a stable intensity of irradiation. An infrared thermal image camera (T450sc, FLIR Systems INC., USA) was used to monitor the temperature variation of foams under irradiation.

CRediT authorship contribution statement

Bo Chen: Methodology, Investigation, Data Processing, Validation, Formal analysis, Visualization, Writing – original draft, Writing – review & editing. Shuangshuang Jing: Methodology, Investigation. Qiongyu Chen: Methodology, Investigation. Yong Pei: Resources. Tao Deng: Resources. Bao Yang: Resources. Chunsheng Wang: Resources. Teng Li: Conceptualization, Methodology, Investigation, Supervision, Writing- reviewing & editing.

Declaration of Competing Interest

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.

Data availability

Data will be made available on request.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.nanoen.2023.108371.

References

- J. Lord, A. Thomas, N. Treat, M. Forkin, R. Bain, P. Dulac, C.H. Behroozi, T. Mamutov, J. Fongheiser, N. Kobilansky, Global potential for harvesting drinking water from air using solar energy, Nature 598 (7882) (2021) 611–617.
- [2] X. Zhou, H. Lu, F. Zhao, G. Yu, Atmospheric water harvesting: a review of material and structural designs, ACS Mater. Lett. 2 (7) (2020) 671–684.
- [3] D.K. Nandakumar, Y. Zhang, S.K. Ravi, N. Guo, C. Zhang, S.C. Tan, Solar energy triggered clean water harvesting from humid air existing above sea surface enabled by a hydrogel with ultrahigh hygroscopicity, Adv. Mater. 31 (10) (2019), 1806730.
- [4] M. Gao, L. Zhu, C.K. Peh, G.W. Ho, Solar absorber material and system designs for photothermal water vaporization towards clean water and energy production, Energy Environ. Sci. 12 (3) (2019) 841–864.
- [5] P. Poredoš, H. Shan, C. Wang, F. Deng, R. Wang, Sustainable water generation: grand challenges in continuously atmospheric water harvesting, Energy Environ. Sci. (2022).
- [6] S. Zhuang, H. Qi, X. Wang, X. Li, K. Liu, J. Liu, H. Zhang, Advances in solar-driven hygroscopic water harvesting, Glob. Chall. 5 (1) (2021), 2000085.
- [7] B. Chen, X. Zhao, Y. Yang, Superelastic graphene nanocomposite for high cyclestability water capture-release under sunlight, ACS Appl. Mater. Interfaces 11 (17) (2019) 15616–15622.
- [8] M.M. Mekonnen, A.Y. Hoekstra, Four billion people facing severe water scarcity, Sci. Adv. 2 (2) (2016), e1500323.
- [9] M. McLennan, The Global Risks Report 2021 16th Edition.
- [10] Y. Zhang, S.C. Tan, Best practices for solar water production technologies, Nat. Sustain. (2022).
- [11] S. Al-Amshawee, M.Y.B.M. Yunus, A.A.M. Azoddein, D.G. Hassell, I.H. Dakhil, H. A. Hasan, Electrodialysis desalination for water and wastewater: a review, Chem. Eng. J. 380 (2020), 122231.
- [12] R.C. Rollings, A.T. Kuan, J.A. Golovchenko, Ion selectivity of graphene nanopores, Nat. Commun. 7 (1) (2016) 1–7.
- [13] B. Van der Bruggen, Sustainable implementation of innovative technologies for water purification, Nat. Rev. Chem. 5 (4) (2021) 217–218.
- [14] Y. Yao, P. Zhang, C. Jiang, R.M. DuChanois, X. Zhang, M. Elimelech, High performance polyester reverse osmosis desalination membrane with chlorine resistance, Nat. Sustain. 4 (2) (2021) 138–146.
- [15] D. Deng, M.K. Luhasile, H. Li, Q. Pan, F. Zheng, Y. Wang, A novel layered activated carbon with rapid ion transport through chemical activation of chestnut inner shell for capacitive deionization, Desalination (2022), 115685.
- [16] L. Liu, C. Zhao, F. Zheng, D. Deng, M.A. Anderson, Y. Wang, Three-dimensional electrode design with conductive fibers and ordered macropores for enhanced capacitive deionization performance, Desalination 498 (2021), 114794.
- [17] N. Hanikel, M.S. Prévot, O.M. Yaghi, MOF water harvesters, Nat. Nanotechnol. 15 (5) (2020) 348–355.
- [18] H. Kim, S. Yang, S.R. Rao, S. Narayanan, E.A. Kapustin, H. Furukawa, A.S. Umans, O.M. Yaghi, E.N. Wang, Water harvesting from air with metal-organic frameworks powered by natural sunlight, Science 356 (6336) (2017) 430–434.
- [19] R.V. Wahlgren, Atmospheric water vapour processor designs for potable water production: a review, Water Res. 35 (1) (2001) 1–22.
- [20] K. Yang, T. Pan, Q. Lei, X. Dong, Q. Cheng, Y. Han, A roadmap to sorption-based atmospheric water harvesting: from molecular sorption mechanism to sorbent design and system optimization, Environ. Sci. Technol. 55 (10) (2021) 6542–6560.
- [21] N. Hanikel, M.S. Prévot, F. Fathieh, E.A. Kapustin, H. Lyu, H. Wang, N.J. Diercks, T.G. Glover, O.M. Yaghi, Rapid cycling and exceptional yield in a metal-organic framework water harvester, ACS Cent. Sci. 5 (10) (2019) 1699–1706.
- [22] A. LaPotin, Y. Zhong, L. Zhao, A. Leroy, H. Kim, S.R. Rao, E.N. Wang, Dual-stage atmospheric water harvesting device for scalable solar-driven water production, Joule 5 (1) (2021) 166–182.
- [23] J. Xu, T. Li, J. Chao, S. Wu, T. Yan, W. Li, B. Cao, R. Wang, Efficient solar-driven water harvesting from arid air with metal–organic frameworks modified by hygroscopic salt, Angew. Chem. Int. Ed. 59 (13) (2020) 5202–5210.
- [24] N. Hanikel, X. Pei, S. Chheda, H. Lyu, W. Jeong, J. Sauer, L. Gagliardi, O.M. Yaghi, Evolution of water structures in metal-organic frameworks for improved atmospheric water harvesting, Science 374 (6566) (2021) 454–459.
- [25] J. Yang, X. Zhang, H. Qu, Z.G. Yu, Y. Zhang, T.J. Eey, Y.W. Zhang, S.C. Tan, A moisture-hungry copper complex harvesting air moisture for potable water and autonomous urban agriculture, Adv. Mater. 32 (39) (2020), 2002936.

B. Chen et al.

- [26] D.K. Nandakumar, S.K. Ravi, Y. Zhang, N. Guo, C. Zhang, S.C. Tan, A super hygroscopic hydrogel for harnessing ambient humidity for energy conservation and harvesting, Energy Environ. Sci. 11 (8) (2018) 2179–2187.
- [27] F. Gong, H. Li, Q. Zhou, M. Wang, W. Wang, Y. Lv, R. Xiao, D.V. Papavassiliou, Agricultural waste-derived moisture-absorber for all-weather atmospheric water collection and electricity generation, Nano Energy 74 (2020), 104922.
- [28] A. Karmakar, V. Prabakaran, D. Zhao, K.J. Chua, A review of metal-organic frameworks (MOFs) as energy-efficient desiccants for adsorption driven heattransformation applications, Appl. Energy 269 (2020), 115070.
- [29] L. Hua, J. Xu, R. Wang, Exergy-efficient boundary and design guidelines for atmospheric water harvesters with nano-porous sorbents, Nano Energy 85 (2021), 105977.
- [30] F. Deng, C. Wang, C. Xiang, R. Wang, Bioinspired topological design of super hygroscopic complex for cost-effective atmospheric water harvesting, Nano Energy 90 (2021), 106642.
- [31] B. Chen, Q. Zheng, J. Zhu, J. Li, Z. Cai, L. Chen, S. Gong, Mechanically strong fully biobased anisotropic cellulose aerogels, RSC Adv. 6 (99) (2016) 96518–96526.
- [32] T. Li, EML Webinar Overview: Advanced materials toward a sustainable future—mechanics design, Extrem. Mech. Lett. 42 (2021), 101107.
- [33] U. Ray, S. Zhu, Z. Pang, T. Li, Mechanics design in cellulose-enabled highperformance functional materials, Adv. Mater. 33 (28) (2021), 2002504.
- [34] B. Chen, U.H. Leiste, W.L. Fourney, Y. Liu, Q. Chen, T. Li, Hardened wood as a renewable alternative to steel and plastic, Matter 4 (12) (2021) 3941–3952.
- [35] F. Fathieh, M.J. Kalmutzki, E.A. Kapustin, P.J. Waller, J. Yang, O.M. Yaghi, Practical water production from desert air, Sci. Adv. 4 (6) (2018) eaat3198.
- [36] H. Kim, S.R. Rao, E.A. Kapustin, L. Zhao, S. Yang, O.M. Yaghi, E.N. Wang, Adsorption-based atmospheric water harvesting device for arid climates, Nat. Commun. 9 (1) (2018) 1–8.
- [37] R. Li, Y. Shi, M. Wu, S. Hong, P. Wang, Improving atmospheric water production yield: Enabling multiple water harvesting cycles with nano sorbent, Nano Energy 67 (2020), 104255.
- [38] M. Ejeian, A. Entezari, R. Wang, Solar powered atmospheric water harvesting with enhanced LiCl/MgSO4/ACF composite, Appl. Therm. Eng. 176 (2020), 115396.
- [39] A. Entezari, M. Ejeian, R. Wang, Extraordinary air water harvesting performance with three phase sorption, Mater. Today Energy 13 (2019) 362–373.
- [40] S.S. Lal, S.T. Mhaske, TEMPO-oxidized cellulose nanofiber/kafirin protein thin film crosslinked by Maillard reaction, Cellulose 26 (10) (2019) 6099–6118.
- [41] A. Rani, S. Monga, M. Bansal, A. Sharma, Bionanocomposites reinforced with cellulose nanofibers derived from sugarcane bagasse, Polym. Compos. 39 (2018) E55–E64.
- [42] A. Geng, L. Meng, J. Han, Q. Zhong, M. Li, S. Han, C. Mei, L. Xu, L. Tan, L. Gan, Highly efficient visible-light photocatalyst based on cellulose derived carbon nanofiber/BiOBr composites, Cellulose 25 (7) (2018) 4133–4144.
- [43] Y. Peng, D.J. Gardner, Y. Han, A. Kiziltas, Z. Cai, M.A. Tshabalala, Influence of drying method on the material properties of nanocellulose I: thermostability and crystallinity, Cellulose 20 (5) (2013) 2379–2392.
- [44] A. LaPotin, H. Kim, S.R. Rao, E.N. Wang, Adsorption-based atmospheric water harvesting: impact of material and component properties on system-level performance, Acc. Chem. Res. 52 (6) (2019) 1588–1597.
- [45] H. Aral, A. Vecchio-Sadus, Toxicity of lithium to humans and the environment—a literature review, Ecotoxicol. Environ. Saf. 70 (3) (2008) 349–356.
- [46] X. Wang, Q. Xia, S. Jing, C. Li, Q. Chen, B. Chen, Z. Pang, B. Jiang, W. Gan, G. Chen, Strong, hydrostable, and degradable straws based on cellulose-lignin reinforced composites, Small 17 (18) (2021), 2008011.



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