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New Sustainable Atmospheric Water Harvester for Multi-Daily Freshwater Supply

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ABSTRACT

With increasing water scarcity, atmospheric water harvesting (AWH) provides a sustainable solution by extracting liquid water directly from water vapor. Among emerging AWH sorbents, metal–organic framework (MOF) is particularly attractive due to its high porosity and strong water uptake. However, MOF-based devices are typically either passive limited to once-daily cycles or active systems that require external electricity. This study presents a sustainable atmospheric water harvesting device that collects water multiple times per day without external electricity using hand-operated vacuum pump and a low-temperature sink. To improve portability, MOF powders were immobilized as beads within a porous sponge, achieving water uptake comparable to powders but with faster uptake rates. Vacuum assistance reduced the cycle time by up to 75.5% and increased the water yield per cycle by up to 31.4% under controlled test conditions. In prototype operation, 10 g of MIL-101(Cr) produced about 7 g of water within 1 hour using a hand-operated vacuum pump, compared to about 5 g over 3.5 hours without vacuum assistance. These results validate a multi-cycle, electricity-free harvesting strategy for water-scarce environments.

Keywords: Atmospheric water harvesting; Metal–organic frameworks (MOFs); Vacuum-assisted desorption; Hand-operated vacuum pump; Low-temperature sink; Bead/film immobilization; Porous sponge scaffold; Rapid multi-cycle collection

INTRODUCTION

Atmospheric water harvesting (AWH), referred to as a method of collecting water from the atmosphere by condensation, offer a promising solution to freshwater scarcity (1). According to a UNICEF report released in March 2023, 190 million children in 10 African countries are suffering from water shortage problem, which causes more than 1,000 children under the age of 5 to lose their lives every day (2). In particular, the water shortage problem is getting worse as population growth is added to climate change (3). To solve this water shortage problem, research on how to collect clean water from atmosphere is steadily progressing. Representative studies for water harvesting include a method of forming fog in a net (4), but there is a limitation that this can only be used where and when fog occurs. Recently, research on harvesting water using porous materials with excellent water adsorption ability has been actively conducted.

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Metal-Organic Frameworks (MOFs) are a class of porous material consisting of metal clusters coordinated to organic ligands to form crystal structure. Due to their extraordinarily large surface area and pore volume, MOFs possess unique adsorption/desorption properties such as a large water-adsorption capacity and a great diversity of water-adsorption isotherms. Due to such properties, MOFs have been widely used as adsorbents to harvest water from air (5).

Omar M. Yaghi *et al.* reported passive water harvesting device MOF-801(Zr) using MOF-801 as the water adsorbent and exhibiting an average productivity of 0.1 L per 1 kg of MOF per day at relative humidity levels as low as 20% a day in Arizona Desert (6). This device has drawbacks that it is not difficult to obtain a sufficient amount of water whenever necessary because water can be harvested only once a day. The same Yaghi team provided a MOF-303(Al)-based multicyclic water harvesting device with an external power source, which exhibits an average productivity of 1.3 L per 1 kg of MOF per day (7). This device requires active heating and cooling for water production. Wang *et al.* provided a device coupling a passive device using MIL-101(Cr) coated on a copper foam plate, and 24 h thermoelectric power generation (8). The device showed improved water product results 0.925 L per 1 kg of MOF per day, but such result uses too complicated system consisting of a dual-functional coating layer, low efficient solar-to-electricity system, and an air-cooling condenser. Almassad *et al.* reported water harvesting device using aluminum-coated trays with MOF-801, which was adapted depending on the weather/seasonal conditions, with water production up to 1.2-2.6 L per 1 kg of MOF per day (9). This device requires huge space and external electric power.

Most of previous studies have the disadvantage of only being able to harvest water once a day because it only utilizes sunlight heat, or it requires external electrical power. In this study, unlike previous studies, a water harvesting device was developed that can harvest drinking water several times a day without external electric energy and is not bulky enough to be portable.

The main features of this study are the use of reduced pressure and increased MOF exposure area for improving water harvesting efficiency. The typical passive water harvesting device merely uses day and night temperature difference for water vapor adsorption and release. The new device of this study uses reduced pressure in addition to the temperature difference. A vacuum pump is used to evacuate the air inside the water harvesting device, allowing the water vapor trapped in the MOFs to quickly release due to reduced pressure. In addition, the new device of this study uses increased MOF exposure area for obtaining enough amount of water. Specifically, the MOFs are beaded or distributed in a three-dimensional structure on a sponge so that all the MOFs are well in contact with the air. Further, the MOFs are coupled with a removable lid of the water harvesting device. During water adsorption, the lid is removed from the device to fully expose the MOFs to water vapor. The plurality of removable lids with MOF can be used in one harvest device multiple cycles of day since the time for the water harvesting is shortened by the use of hand-operated vacuum pump.

The objective of this study is to develop a sustainable atmospheric water harvesting device that supplies freshwater multiple times per day via repeated sorption–desorption cycles using a hand-operated vacuum pump, without external electricity. It aims to provide practical daily water yields to help address water scarcity in islands, deserts, and other water-stressed or disaster-affected regions.

METHODS AND MATERIALS

Materials

Zirconium tetrachloride (99.5%), fumaric acid (99%), N,N-dimethylformamide (DMF) (99.8%), chromic nitrate nonahydrate (99%), terephthalic acid (99%), hydrofluoric acid (48%), methanol (99.8%), ferric chloride (97%), trimesic acid (95%), formic acid (98%), acetic acid (99.7%), and PIM-1 were purchased from Sigma-Aldrich. All chemicals and solvents were of reagent grade and used without further purification.

Synthesis of MIL-100(Fe)

0.015g (3 mmol) of FeCl3 and 0.019 g (3 mmol) of trimesic acid (H_3BTC) were dissolved in 30 mL of N,N-dimethylformamide (DMF) (11). The reaction solution was transferred in teflon-lined autoclave and thermally treated at 40 °C for 40 h. The crystallization of reaction product is followed by its recovery through centrifugation. The product was washed many times with DMF, methanol and finally dried overnight at 20 °C.

Synthesis of MIL-101(Cr)

2.007 g of Cr $(NO_3)_3 \cdot 9H_2O$ (5.0 mmol) dissolved in water and 0.823 g of terephthalic acid (5.0 mmol) dissolved in DMF were sequentially added to 100 mL beaker. 0.38 mL hydrofluoric acid was dropwise added to the mixture (12). The mixed solution was stirred constantly for 0.5 h. The liquid mixture was transferred to a 100 mL Teflon-lined autoclave and the reactor was sealed. The reaction autoclave was placed in a 3−550 A programmable Muffle furnace (Vulcan Co., United States) and continuously heated at 160 °C for 24 h. After the reaction completed, the autoclave was cooled to room temperature. The products were filtered and sequentially washed with hot water and hot DMF at 65 °C for 4 h to remove unreacted monomers and other impurities. Finally, the resulting product was obtained by vacuum drying oven at 130 °C for 24 h.

Synthesis of MOF-801

Starting materials zirconium tetrachloride ($ZrCl_4$), fumaric acid (H_2FC), acetic acid (AA), formic acid (FA), DMF, methanol were purchased from commercial suppliers and used without further purification (13). In a typical procedure, 0.2008 g of $ZrCl_4$ was dissolved in 20 mL of DMF under magnetic stirring, then 46.6 μL of deionized water was added. After complete dissolving, 0.10 g of H_2FC was poured to the clear solution. The mixture in a closed glass vessel was placed into a preheated oven at 40 °C for 8 hours. After cooling to room temperature, white precipitates were collected using centrifugation, washed two times with DMF and one time with methanol, and dried at 20 °C overnight.

Characterization and chemical analysis

Electron microscope images of MIL-100(Fe), MIL-101(Cr) and MOF-801 were taken by Tescan Vega 3 scanning electron microscope. Powder X-ray diffraction patterns of MIL-100(Fe), MIL-101(Cr) and MOF-801 were recorded with Bruker D8 Advance. Typically, data were collected between 3-50° with a step width of 0.0195° and a total data collection time of 30 min.

Design of proof of concept device for water harvesting with vacuum pump

For proof of concept, water harvesting device with vacuum pump was designed (Figure 1). MOF container was fabricated using a container with a lid that MOF was put in or taken out, which is connected to a vessel. The MOF container is placed in a constant temperature chamber, which can be controlled to keep a desired temperature. One end of vessel is connected to MOF container while the other end of the vessel connected to a vacuum pump. The middle part of the vessel between MOF container and vacuum pump is immersed in a water bath at a cool temperature. A Millipore Chemical Duty Pump (Cat. No. WP6111560) is used as the vacuum pump, and the vacuum pressure (approximately –0.1 atm) is confirmed using the built-in manual pressure gauge of the Millipore Chemical Duty Pump.

Synthesis of MOF bead and film

MOF beads and thin films were prepared by immobilizing MOF powders in PIM-1 (polymer of intrinsic microporosity) (10). Beads were formed by dropping a MOF/PIM-1 solution into methanol (phase inversion), then washed and vacuum-dried. Films were obtained by casting/doctor-blading the slurry onto glass or polytetrafluoroethylene (PTFE), evaporating solvent, releasing, methanol-exchanging, and vacuum-drying.

Thermal Gradient Evaluation

To evaluate the thermal gradient performance of the prototype, the removable lid containing MIL-101(Cr) was exposed to a 50 W halogen lamp while the lower part of the device was buried in soil maintained at 20 °C. Temperature sensors were placed on the sorbent-containing lid and the inner chamber to monitor

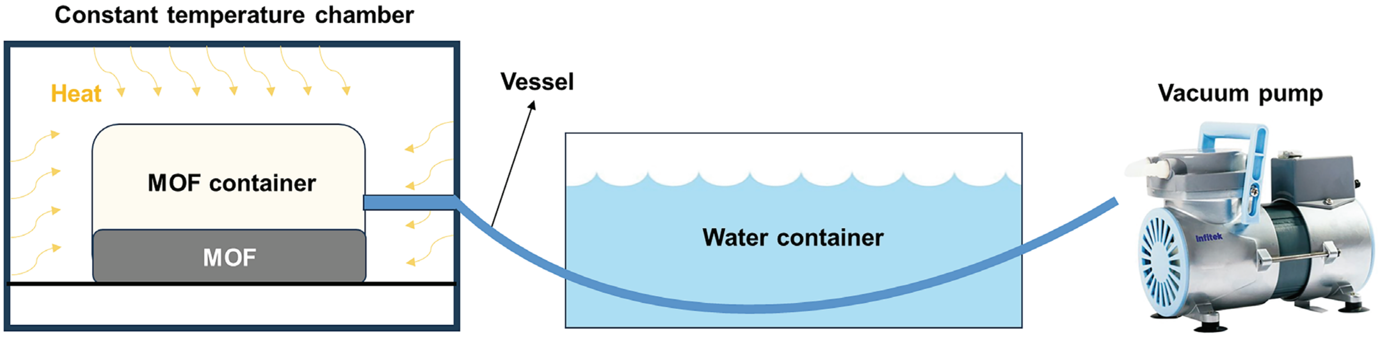

Figure 1. Schematic diagram of water harvesting device with vacuum pump.

temperature differences over time. Additionally, water harvesting trials were performed using 10 g of MIL-101(Cr), with and without a hand-operated vacuum pump.

Experimental Conditions and Safety Considerations

All adsorption and water harvesting experiments were conducted in triplicate (n = 3) using independently prepared samples to ensure reproducibility. Results are presented as mean ± standard deviation. All experiments were performed under ambient laboratory conditions, typically maintained at 20 ± 1 °C and 1 atm pressure, unless otherwise specified. In the synthesis of MOFs, including those involving hydrofluoric acid (HF), all hazardous chemicals were handled inside a certified fume hood with appropriate personal protective equipment (PPE), such as acid-resistant gloves, face shields, and lab coats. All waste was disposed of following the institutional hazardous chemical management procedures. All experiments were conducted in accordance with institutional laboratory safety protocols.

RESULTS AND DISCUSSION

Characterization of MIL-100(Fe), MIL-101(Cr), MOF-801

For use in water harvesting device, three types of MOFs, MIL-100(Fe), MIL-101(Cr), and MOF-801 were prepared following previously reported methods (11-13) as shown in Figures 2a and 2b. As shown in Figure 2c, the X-ray powder diffraction (XRPD) patterns of MIL-100(Fe), MIL-101(Cr), and MOF-801 were matched with simulated pattern, respectively. Therefore, it was confirmed that MOFs to be used in the water harvesting device were well synthesized.

Analysis of water uptake of MIL-100(Fe), MIL-101(Cr), MOF-801

15 g sample of each of MIL-100(Fe), MIL-101(Cr), and MOF-801 was placed in a room temperature (20°C, relative humidity (RH) 80%) water bath for 8 hours, with each condition tested in triplicate. The weight change was measured over 8 hours to determine the amount of water uptake by the MOFs. The results of water uptake per gram for each MOF are shown in Figure 3a. All three MOFs showed a tendency to saturate after 6 hours with minimal increase in water uptake. After 8 hours, MIL-101(Cr) showed the best water uptake performance with an increase of 71.0 ± 2.3 wt%, followed by MIL-100(Fe) (66.1 ± 1.8 wt%) and MOF-801 (12.4 ± 0.6 wt%), based on three independent replicate experiments, as shown in Figure 3b. MOF-801 showed excellent water uptake in a desert

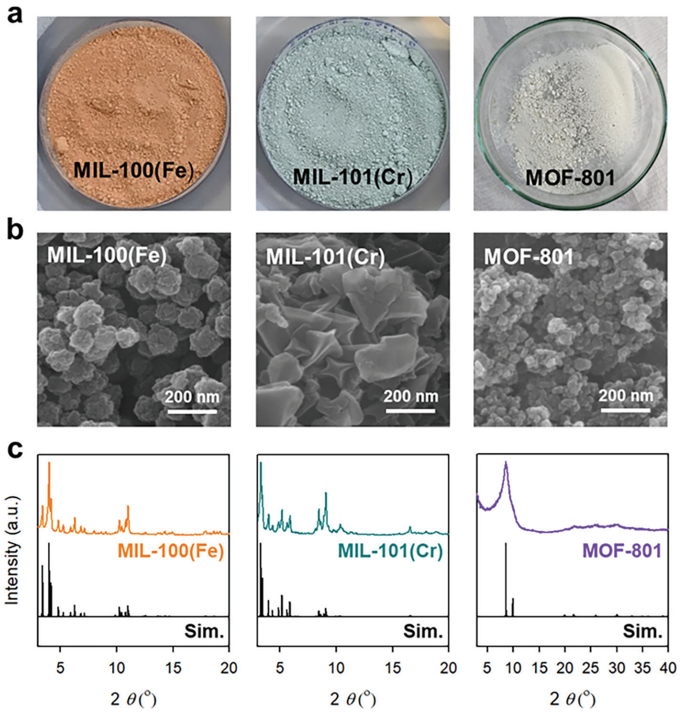

Figure 2. Synthesis and characterization of MIL-100(Fe), MIL-101(Cr), MOF-801. a) Photograph of as-synthesized MIL-100(Fe), MIL-101(Cr), MOF-801. b) Scanning electron microscopy images (SEM) (magnification 100,000x) of MIL-100(Fe), MIL-101(Cr), MOF-801. c) Powder X-ray diffraction (PXRD) patterns of MIL-100(Fe), MIL-101(Cr), MOF-801.

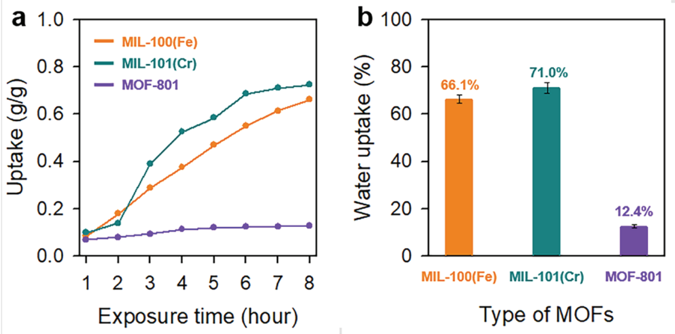

Figure 3. Water Uptake of MIL-100(Fe), MIL-101(Cr), MOF-801. a) Amount (g) of water uptake per 1 g of MOF exposed to moisture environments (RH 80%) during 8 hours. b) Weight percentage of water uptake based on each MOF's own weight after 8 h exposure.

environment in previous paper by Yagi *et al*. (6), but the sufficient amount of water uptake at room temperature were not observed in this experiment. Therefore, MOF-801 was excluded from the subsequent water harvesting experiments.

Analysis of water harvesting from MIL-100(Fe) and MIL-101(Cr)

15g of MOF was placed in a MOF container made in the manner described as in the section *Design of proof of concept device for water harvesting with vacuum pump.* The lid was closed, and the pressure was depressurized by connecting the other end of the vessel to a vacuum pump. The MOF container was placed in a constant temperature chamber at 40℃ and at least half of the vessel was immersed in a 20℃ water bath. 5-meter-long vessel was initially used for increasing the contact area between the vessel and the water in the bath, which would act as a water condenser. Unlike expectations, as the length of the vessel increased, the volume of the vessel caused the water to spread inside the vessel, making it difficult to accurately measure the amount of water harvested.

The formation of water droplets on the condensation vessel was first observed after 12 ± 1 minutes when using MIL-100(Fe) and after 36 ± 2 minutes with MIL-101(Cr) (n =3), as shown in Figure 4. After 3 hours of operation under vacuum conditions, the total amount of condensed water was measured to be 0.34 ± 0.02 g for MIL-100(Fe) and 0.71 ± 0.03 g for MIL-101(Cr) (n = 3), as summarized in Table 1.

To assess the effect of vacuum on desorption and condensation efficiency, the same procedure was repeated without applying depressurization. In this case, 15 g of MOF was loaded into the container, the lid was sealed, and the setup was placed in a 40 °C constant-temperature chamber, with the lower portion of the condensation vessel immersed in a 20 °C water bath. Under these non-vacuum conditions, water droplet formation was observed after 49 ± 2 minutes for MIL-100(Fe) and 74 ± 3 minutes for MIL-101(Cr) (n =3), as shown in Figure 4. After 3 hours, the collected water amounts were 0.29 ± 0.03 g and 0.54 ± 0.02 g for MIL-100(Fe) and MIL-101(Cr), respectively based on triplicate experiments (n = 3), as indicated in Table 1.

Table 1. Water collected over 3 h using MIL-100(Fe) and MIL-101(Cr) under vacuum and non-vacuum conditions (20 °C bath, 40 °C chamber)

Type of MOFs	Vacuum	Water uptake for 3 hours (g)
FMIL-100(Fe)	O	0.34 ± 0.02
	X	0.29 ± 0.03
MIL-101(Cr)	O	0.71 ± 0.03
	X	0.54 ± 0.02

These comparative results quantitatively demonstrate the effect of vacuum assistance on both desorption kinetics and water collection efficiency. For MIL-100(Fe), the onset of droplet formation under vacuum occurred at 12 ± 1 minutes, compared to 49 ± 2 minutes without vacuum, representing a 75.5% reduction in condensation initiation time. Similarly, for MIL-101(Cr), droplet formation began at 36 ± 2 minutes under vacuum and 74 ± 3 minutes without vacuum, corresponding to a 51.4% reduction.

In terms of total condensed water after 3 hours, MIL-100(Fe) exhibited an increase from 0.29 ± 0.03 g (non-vacuum) to 0.34 ± 0.02 g (vacuum-assisted), equivalent to a 17.2% improvement, while MIL-101(Cr) increased

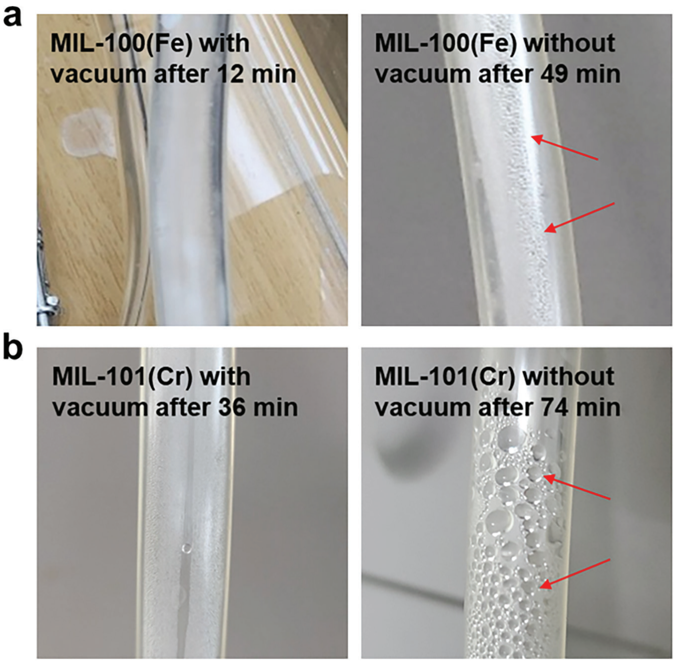

Figure 4. Water Harvest from MIL-100(Fe), MIL-101(Cr). Photographs of the formation of water droplets from a) MIL-100(Fe) with vacuum after 12 ± 1 min (left) and without vacuum after 49 ± 2 min (right). b) MIL-101(Cr) with vacuum after 36 ± 2 min (left) and without vacuum after 74 ± 3 min (right). The red arrows indicate the formation of water droplets.

from 0.54 ± 0.02 g to 0.71 ± 0.03 g, corresponding to a 31.4% increase. These data confirm that the application of vacuum not only accelerates desorption and condensation but also enhances total water yield across both MOF systems, reinforcing the role of pressure control in improving harvesting efficiency under the same thermal gradient conditions.

Analysis of effects of exposure area of MOF in water harvesting

In the initial stage of this study, the experiment was conducted to evaluate the amount of water uptake with the MOF placed inside an Erlenmeyer flask. However, the water uptake amount of MOF placed inside a flask was very little even after sufficient time (more than 24 hours) had passed.

Based on the above, the exposure area of MOF to the air is identified as a significant factor of water uptake. The water uptake amount of MIL-101(Cr) was compared between the case where it was simply placed on Petri dish and the case where powder of MIL-101 was spread over the porous sponge. After placing the two samples in a water bath at room temperature (20℃, RH 80%) for 8 hours, the increased weights of each sample were measured. Based on the average of three independent experiments (n = 3), the Petri dish configuration showed a water uptake of 10.6 ± 0.3 g, while the sponge configuration exhibited 14.3 ± 0.3 g. As a result, the water uptake of those spread over the sponge was increased by approximately 34 percent compared to those simply on Petri dish (Figure 5).

To further investigate the influence of physical morphology on water uptake performance, MIL-100(Fe) was synthesized in three forms: powder, beads, and thin film (Figure 6a–c). Equal masses of each form were exposed to a controlled humid environment (20 °C, RH 80%) for 8 hours, with each condition tested in triplicate. The weight increase was measured to determine the amount of adsorbed water. As shown in Figure 6d, the powder form exhibited the highest water uptake (55 ± 1.9 wt%), followed by the bead form (51 ± 2.1 wt%), while the film form showed the lowest performance (20 ± 0.9 wt%). When normalized to time, the corresponding average adsorption rates were approximately 0.069 g H_2O $g^{-1}h^{-1}$ for the powder, 0.064 g H_2O $g^{-1}h^{-1}$ for the beads, and 0.025 g H_2O $g^{-1}h^{-1}$ for the thin film. These values highlight that both powder and bead forms enable faster water uptake compared to the film, likely due to their higher accessible surface area and pore exposure. Notably, despite the slightly lower net uptake, the bead form displayed a faster uptake rate, reaching a given adsorption level earlier because of its increased exposed surface area and vapor-accessible pathways. These results indicate that the physical form of the MOF, particularly its surface area and porosity, plays a critical role in adsorption capacity.

However, while the powder form showed superior adsorption, it presents practical challenges for device integration because it tends to disperse or spill during handling. In contrast, the bead and thin film forms,

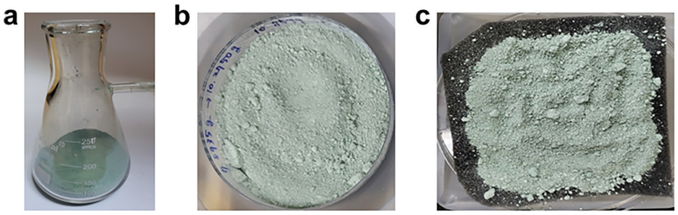

Figure 5. Evaluation of Effect of Exposure area for Water Uptake of MIL-101(Cr). a) MIL-101(Cr) in a Erlenmeyer flask. b) MIL-101(Cr) on petri dish. c) MIL-101(Cr) spread over porous sponge.

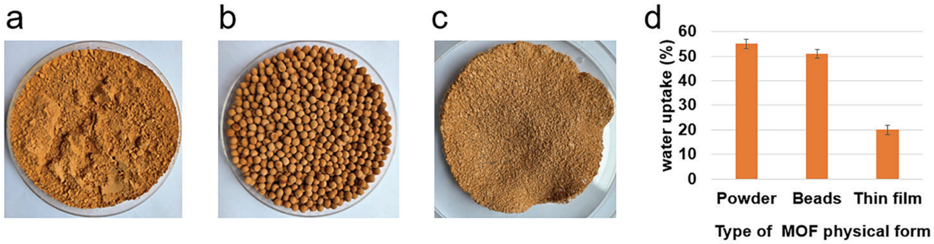

Figure 6. Evaluation of the effect of physical form on the water uptake performance of MIL-100(Fe). a) Powder form of MIL-100(Fe); b) Bead form of MIL-100(Fe); c) Thin film form of MIL-100(Fe);d) Comparison of water uptake capacities of the three forms after 8 hours of exposure (20℃, RH 80%).

although slightly lower in uptake, offer structural stability and straightforward immobilization within a device. This trade-off between kinetics and throughput suggests that bead-shaped sorbents can shorten cycle times for multi-daily operation, and the optimal MOF form should balance adsorption efficiency with processability for system-level applications.

Design and performance evaluation of the prototype device

From the above experiments, the concept was proved that depressurization using a vacuum pump and increasing the exposure area of MOFs using another porous material is effective for water harvesting. Based on these results, a new water harvesting device was designed as follows (Figure 7).

This new water harvesting device has a container with a removable lid, such as screw-type and snapware-type, that can withstand and maintain reduced pressure. This device has a vacuum pump connection unit on the side of the device so that the internal pressure of the device can be reduced by vacuum pump. The bottom of this device is equipped with a water valve that allows the water harvested from this device to be drained. The MOFs are either in the form of beads or dispersed by three-dimensional embedding of the MOFs in a porous medium such as a sponge to increase the air contact area of the MOFs and prevent the MOF powder from drifting away (the porous material can be a material with larger pores than the MOFs but with a lower water adsorption rate, e.g., zeolite, carbon nanotube sponge, etc.). The MOFs are encapsulated with a filter membrane. The filter membrane is a material that allows air and water vapor to pass through freely, but not the MOFs. The encapsulated MOF unit is coupled to the removable lid of the device. The lid can be removed from the water harvesting device to maximize contact with airborne moisture during water adsorption, while being attached to the water harvesting device to maintain vacuum pressure during water harvesting. The metal plate for easily heating and storing the sunlight heat is attached to the outside of the removable lid. During water harvesting, the top of the container is exposed to the sun light while the bottom of the container is immersed in cold sea or river water to maximize the temperature difference.

To verify the effectiveness of the thermal gradient, a prototype was tested by exposing the removable lid containing the MOF to a 50 W halogen lamp while the lower part of the container was buried in 20 °C soil. Temperature sensors were attached to the MOF-containing lid and the inner chamber to monitor heat accumulation. As shown in Figure 8, the lid temperature increased from 20 °C to 56 °C within 1 hour, while the lower part remained near 20 °C. This confirmed that the device can create and maintain a temperature differential sufficient for desorption under passive conditions.

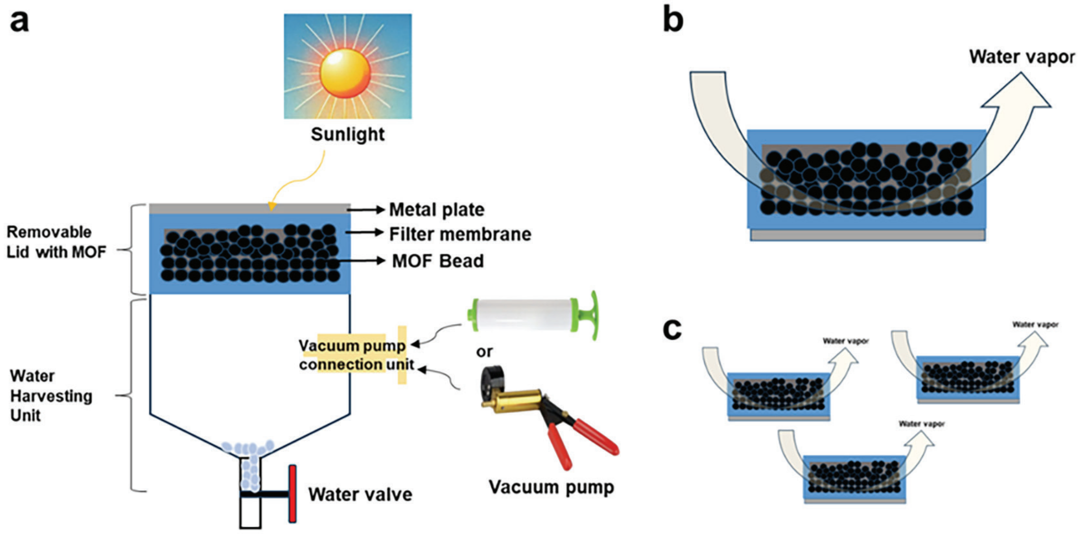

Figure 7. Development of new water harvesting device. a) Schematic diagram of new water harvesting device having removable lid with MOF. b) removable lid with MOF during water adsorption. c) multiple lids for multiple cycles.

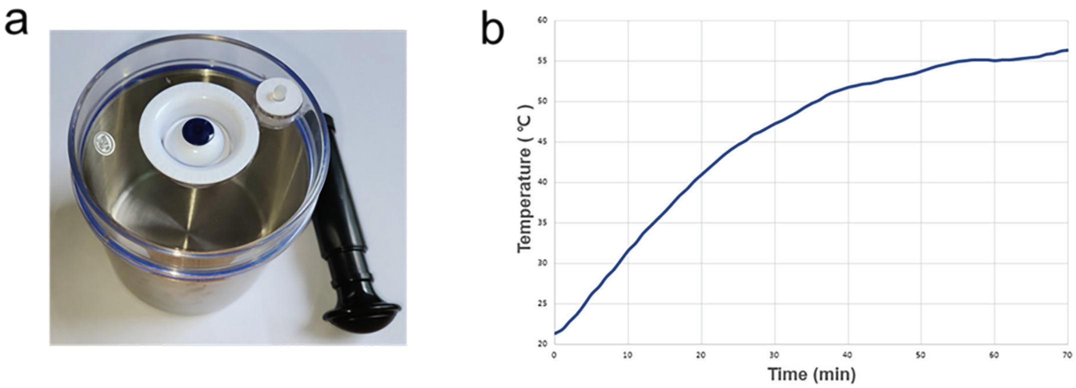

Figure 8. Thermal gradient generation in the prototype device. a) Photograph of the prototype; b) Temperature profiles of the MOF-containing lid and internal chamber under 50 W halogen light exposure over 1 h.

In prototype trials, 10 g of MIL-101(Cr) produced approximately 7 g of water in 1 hour under vacuum-assisted conditions and 5 g in 3.5 hours without vacuum assistance (i.e., 7 g/10 g/1 h and 5 g/10 g/3.5 h, respectively). Based on these yields, the system achieved a specific water productivity of approximately 16.8 L kg^{-1} day^{-1} with vacuum and 3.43 L kg^{-1} day^{-1} without vacuum, assuming ideal continuous operation over 24 hours. However, it is important to note that the 16.8 L kg^{-1} day^{-1} productivity was achieved using a 50 W halogen lamp, which induces a rapid and sustained temperature increase not fully representative of passive atmospheric water harvesting (AWH) conditions. While this setup effectively simulates high-intensity solar input, such consistent heating is unlikely to be sustained throughout the day under natural sunlight. If we conservatively assume that a comparable thermal gradient can be passively maintained for only 6 hours per day in high-solar-radiation environments, the adjusted productivity under vacuum-assisted conditions would be approximately 4.2 L kg^{-1} day^{-1}. Under the same assumption, the non-vacuum condition corresponds to approximately 0.86 L kg^{-1} day^{-1}, which still falls within the range of previously reported passive AWH systems (typically 0.1–2.6 L kg^{-1} day^{-1}). The clear difference in water yield between vacuum-assisted and non-assisted conditions under identical thermal assumptions highlights the significant role of vacuum in enhancing desorption efficiency. These results demonstrate that, even without external electricity, the system can enable multiple harvesting cycles per day, and that the incorporation of a simple, hand-operated vacuum pump can substantially boost performance. This reinforces the system's potential as a practical off-grid water harvesting solution in resource-limited settings.

CONCLUSION

This study demonstrates the feasibility of a decentralized, electricity-free water harvesting device by leveraging the intrinsic adsorption–desorption behavior of MOFs under solar-driven thermal gradients. Rather than relying solely on numerical yield, the device's effectiveness can be mechanistically understood through adsorption kinetics and vapor–pressure differentials.

Under ambient conditions, MOFs such as MIL-101(Cr) rapidly adsorb water vapor due to their large pore volume and high surface area. Upon heating, the vapor pressure inside the pores increases significantly, promoting desorption once the partial pressure exceeds the equilibrium threshold with ambient air. The integration of hand-operated vacuum pump further amplifies the desorption driving force by reducing external pressure, thereby lowering the vapor pressure needed for water release and accelerating the overall mass transfer rate. In contrast, in vacuum-free mode, desorption is governed primarily by passive thermal gradients, which remain effective but proceed at a slower rate due to limited vapor-pressure differential.

The use of a removable lid exposed to solar radiation creates a localized heating zone, while the buried lower chamber maintains a relatively cool environment, forming a vertical thermal gradient conducive to directional vapor flow. This configuration not only supports repeated adsorption–desorption cycling within a single day but also reflects a thermodynamically favorable pathway for passive water harvesting. The enhancement observed with MOF-sponge composites is attributed to improved airflow and vapor accessibility, which increases the effective contact area and facilitates faster adsorption kinetics.

Despite the promising results demonstrated in this study, several limitations remain that highlight opportunities for further development. The total water yield under field-relevant conditions is currently modest, due in part to non-optimized sorbent selection, thermal losses, and vacuum leakage. In particular, the efficiency of vacuum-assisted desorption is highly sensitive to sealing performance; even minor leakage can diminish the pressure differential and significantly reduce water recovery. Future device iterations should therefore incorporate improved sealing strategies, such as the use of high-performance gasket materials or integrated one-way valve systems.

The MOFs employed in this study, namely MIL-100(Fe) and MIL-101(Cr), were selected for their representative humidity response profiles. However, they do not constitute fully optimized choices for all environmental conditions. For example, MOF-801 offers higher uptake at low relative humidity and may be more suitable for arid climates, while MIL-100(Fe) provides broad stability across varying humidity levels. Therefore, the selection of MOFs should be strategically aligned with site-specific climatic conditions and targeted operational parameters, such as desired cycle frequency, to achieve optimal performance.

Further improvements in thermal management are also warranted. Integrating solar-selective absorbers, thermally insulating materials, or phase-change elements into the lid could enhance desorption efficiency by sustaining higher localized temperatures without external energy input. In addition, modular multi-lid architectures may enable staggered adsorption–desorption phases, thereby facilitating near-continuous operation. For certain applications where limited external energy is available, optional integration of solar-powered air blowers or electric vacuum pumps may further extend system versatility, while the core design remains fully off-grid.

The long-term durability and scalability of the system also require additional investigation. While prior studies have shown that MOFs such as MIL-101(Cr) can maintain performance over multiple cycles, the present work did not experimentally evaluate cycle stability under repeated thermal and mechanical stress. Future studies will focus on quantifying long-term sorbent performance, mechanical robustness, and potential fouling in order to validate the system's suitability for extended deployment in real-world, resource-limited environments.

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CONFLICT OF INTEREST

The author declares that there are no conflicts of interests related to this work.

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