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Fresh water from thin air

Strategies for collecting water from the atmosphere using minimal energy could fill a crucial gap in sustaining communities that have limited access to water.

By Michael Eisenstein

Illustration: Sam Falconer

In late summer, Death Valley National Park earns its name. The heat in this region of California and Nevada is relentless. Record temperatures are set, and the air is often bone dry. The 22 August 2022 was no exception, with an average temperature during daytime of 51.6 °C and humidity of just 14% in the location aptly known as Furnace Creek.

Despite the heat and aridity, there was a slow but steady drip of water into the collection vial of Omar Yaghi's device, an assembly of components loosely resembling a telescope. By the end of the day, this system had collected only a few millilitres of water — barely enough for a refreshing sip. But these results, published in July[1], nevertheless represent a landmark in the field of atmospheric water harvesting (AWH).

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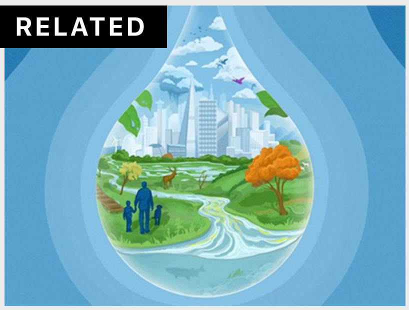


Nature Outlook: Water

Given the extremity of the testing conditions, the results suggest that the key ingredient in this device — a water-absorbing compound called MOF-303 — has the potential to deliver life-sustaining volumes of clean water to regions that currently struggle to access it. "The vision there is to have something like a village-scale device," says Yaghi, a chemist at the University of California, Berkeley. "If you've got a tonne of MOF-303, you could deliver about 500 litres of water a day, every day for five to six years."

By current estimates, roughly two billion people lack access to clean drinking water. Desalinated seawater can meet some of this need, but the technology required remains costly and is limited to communities with coastal access. This explains the growing enthusiasm for alternative solutions that extract clean water from the air. The US Geological Survey estimates that Earth's atmosphere contains nearly 13,000 cubic kilometres of water — more than six times the volume of the world's rivers. "You cannot deplete it — it's always replenished by natural evaporation from a larger water body," says Tian Li, a materials scientist at Purdue University in West Lafayette, Indiana. And although many of the most promising AWH technologies are still at the stage of lab demonstrations or proof-of-concept devices, the field is quickly building momentum towards real-world systems that produce plentiful amounts of water at low cost.

Searching for suitable sorbents

There are already several commercially available AWH systems. In mountainous, foggy regions, it is possible to literally cast a net to collect water from ever-shifting cloud masses. Such installations are producing water from the air in South America, India and parts of Africa, according to Thomas Schutzius, a mechanical engineer at the University of California, Berkeley. There are also systems for collecting the water that accumulates overnight as dew. But both fog and dew harvesting are limited to high-humidity areas. And for dew, only modest volumes of water can be produced even under optimal conditions.

Dry (left) super-moisture-absorbent gels swell as they absorb atmospheric water (right). Credit: Guihua Yu, University of Texas at Austin

Systems that condense water from ambient air offer a more generally useful solution. Several companies have already developed electrically powered 'active' AWH machines for this purpose. In most cases, these use fans to draw warm, moisture-bearing air into an apparatus that directly cools the air and collects the resulting water condensate; in some cases, this water is also subject to filtration and additional treatment. These systems can produce considerable volumes. The Maximus system from the firm SkyH2O in Irvine, California, for example, can produce more than 10,000 litres of purified water per day. But this system is complex and massive — weighing around 13 tonnes — and requires continuous external power to run. It is also priced at a costly US$395,000. Such systems could be a solution in wealthy water-deprived regions — the southwestern United States, for example, or Saudi Arabia — but they are a non-starter in locations with limited budgets or unreliable electrical infrastructure.

The need for more affordable options has spurred interest in 'passive' AWH systems that use moisture-hungry sorbent compounds to collect water. The small amounts of power that such systems require could, ideally, be supplied by the Sun. Typically, these sorbents are exposed to the air overnight, when temperatures are cooler and moisture is more abundant. They collect the airborne moisture as liquid in a process known as adsorption. When day breaks, the sorbents are transferred to a device that uses solar energy to drive the release of water. This water is then condensed and collected. These passive systems are tricky, however, because they require sorbents that bind water strongly — but not so strongly that they refuse to yield their bounty without a fight. "That's an energy penalty that you need to pay," says Guihua Yu, a materials scientist at the University of Texas at Austin.

The field got a big boost in 2017 when Yaghi, along with engineer Evelyn Wang at the Massachusetts Institute of Technology in Cambridge and their colleagues, described a solar-powered system that could extract nearly 3 litres of water per day per kilogram of sorbent — an unprecedented feat at the time[2]. "I was inspired by that paper," says Peng Wang, an environmental scientist at Sun Yat-sen University in Guangzhou, China. "This is how I got into this field."

The leap in performance was thanks to the use of a different kind of sorbent — a metal–organic framework or MOF. These porous compounds, developed in Yaghi's lab, offer a vast surface area for water to bind to, and can be readily chemically modified to further enhance their capacity and water affinity. "It takes up water even at as little as 5% relative humidity," says Yaghi about his current sorbent of choice, MOF-303. Equally important is that little heat is needed to drive the water back out, with temperatures of 40–45 °C typically proving sufficient. Moreover, Yaghi says, MOFs remain stable throughout years of continuous use.

Other promising sorbents are also emerging. Polymers known as hydrogels are a low-cost and highly customizable class of materials that can potentially achieve even greater capacity for moisture capture than MOFs. This is especially true if these gels are loaded with water-absorbing salts such as lithium chloride. Hydrogel-based AWH systems are not yet as efficient as their MOF-based counterparts at capturing and releasing water — particularly under ultra-dry conditions — but they are steadily improving. In September, Yu's team described a microgel formulation that offers a much larger water-binding surface area than other hydrogel designs, and incorporates a heat-sensitive component to induce water release at lower temperatures[3]. This allows water to be cleared from the gel in about 20–30 minutes — three to four times faster than previous iterations of his team's hydrogel-based system, Yu says. This is still about ten times slower than the release from MOF-303, however.

Even simpler materials are also being explored. Li and her colleagues have been developing specialized fabrics based on cellulose, a plant-derived fibrous molecule that can absorb water[4]. In addition to being abundant and inexpensive, says Li, cellulose "has the nanoscale features already there without you doing anything". Her group is exploring ways to extend the capabilities of cellulose. Impregnating the fabric with lithium salts, for example, has been shown to boost its water-harvesting capacity by more than five-fold relative to the salt-free version[5].

But cellulose-based systems yield a substantial amount of water only when the relative humidity is at least 60%. By comparison, the MOF-303-based system operates effectively at relative humidity of 20% or less, as shown in the Death Valley field test. And Yu's microgels could achieve reasonably fast uptake of meaningful volumes of water at 30% relative humidity — although, of course, the water yield will always be lower in such conditions owing to the limited moisture available.

Preparing for the harvest

A good sorbent is only a starting point. Wang says that most passive AWH systems that have been described so far have the capacity for only one round of water absorption and release every 24 hours. This single-cycle operation can squander the potential output of a material that saturates quickly.

A water harvester containing MOF-303 can collect water from desert air with high efficiency and without power. Credit: Yaghi Laboratory, UC Berkeley

To address this, many researchers are using batch-process systems, which require swapping the sorbent beds between an air-exposed state for water absorption and an enclosed state for Sun-assisted water release. Most of these are active systems that require external sources of electrical power. That's not necessarily a deal breaker, however – such systems could prove cost-effective. "If you just have a battery that can open a door and close it, you can triple your delivery because now you can do more than one cycle a day," says Yaghi. In a 2019 study, his group demonstrated a compact device[6] that used batteries to power multiple cycles of atmospheric water collection throughout the day. These batteries could be fully recharged by solar power during daylight hours, allowing the system to function off grid.

Cost is a crucial consideration, especially given that passive AWH will — at least initially — be targeted at resource-limited populations. Fortunately, many of the sorbents now under development should be affordable. Yaghi says that MOF manufacture is already being done at an industrial scale, and that the cost is largely determined by the metal involved. For MOF-303, that means aluminium, which he says costs just $1–2 per kilogram. Some hydrogel polymers can be expensive to produce, but others can be made more cheaply. Yu's team is even exploring whether hydrogel ingredients can be directly extracted from biomass. The opportunity for low-cost production from easily accessible materials is a key asset of Li's cellulose fabrics. Her group is working on deploying its system in coastal communities in Senegal where fresh water is scarce. "The burden of getting fresh drinkable water there falls onto the teenage girls," she says. "We're trying to educate the girls, and developed a curriculum so that they can build a set-up themselves with locally available cellulose sources."

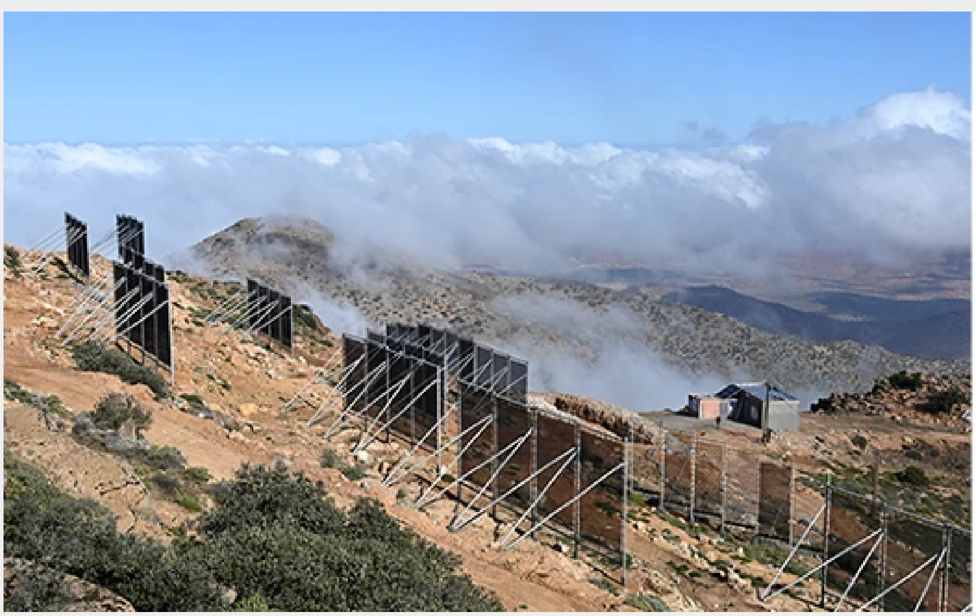
Li's system simply requires a textile drape that can be wrung out by hand. Other sorbent-based systems depend on more sophisticated apparatus for the harvesting process — but even those do not need to be expensive. For example, Wang recalls a prototype hydrogel-sorbent-based device that he developed about five years ago[7]. Apart from the sorbent itself, Wang says, all the materials for the system were purchased from a local supermarket. For just $3.20, Wang and his colleagues estimated that they could construct a device that would supply roughly 3 litres — the minimum amount of water needed daily by a typical adult.

Of course, there is also the issue of ensuring that the water pulled from the air is free of dangerous substances. Yaghi says that his experiences in field testing in US deserts have been reassuring. "We tested the water for metal and organics, and it was like the purest water you could find," he says. But this is not a certainty in every environment, particularly near sources of industrial pollution. Careful assessments will be needed to ensure that collected water is separated efficiently from contaminants.

Pollution has been a particular concern when harvesting fog, Schutzius says. In August, his group described a fog-harvesting net enhanced with a titanium dioxide coating, which efficiently breaks down organic pollutants such as diesel after being activated by ultraviolet light from the Sun[8]. He thinks that researchers should take similar considerations into account for other domains of AWH. "The whole point of adsorption is you can concentrate a lot of stuff that's otherwise dilute," he says.

Opening the tap

Some passive AWH systems are already moving into commercial development. Yaghi's lab, for example, has spun off a start-up firm in Irvine, California, called Atoco, which aims to roll out first-generation MOF-based harvesters in the next year or so. Different water-harvesting technologies will find different applications. The robust performance of MOFs in extremely arid conditions will make them a versatile choice, whereas systems based on cellulose or hydrogels might be restricted to more humid environments.



A fog-collector park (left) in the mountains of Morocco traps water vapour on nets (right). Credit: aqualonis.com

These technologies are unlikely to fully replace existing systems such as seawater desalination, which has a proven track record of high-volume water production. But AWH could greatly reduce dependency on centralized water processing, making it accessible at the village or even single-household scale. Yaghi sees a future in which any house with electricity could reliably address its drinking-water needs with an appliance roughly the size of a microwave oven.

And there are abundant opportunities beyond simply producing drinking water. For example, Wang's group has described a harvesting system that piggybacks on existing photovoltaic solar panels, using the waste heat and energy from these panels to power water production[9]; the resulting water helps to cool the panels and therefore improves their efficiency. Similar approaches have been described for managing — and exploiting — waste heat in industrial settings. AWH also has agricultural applications; Yu's group, for example, is working on using hydrogel-based materials to produce self-watering soils that directly draw moisture from the air[10].

It is indisputable that, as the ongoing climate catastrophe worsens, society will need to leverage every solution at its disposal to meet the planet's water needs. "I worked in Saudi Arabia, and people there say water security is national security — that's 100% true," says Wang. "It's getting more serious, and we need to do things more effectively."

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