

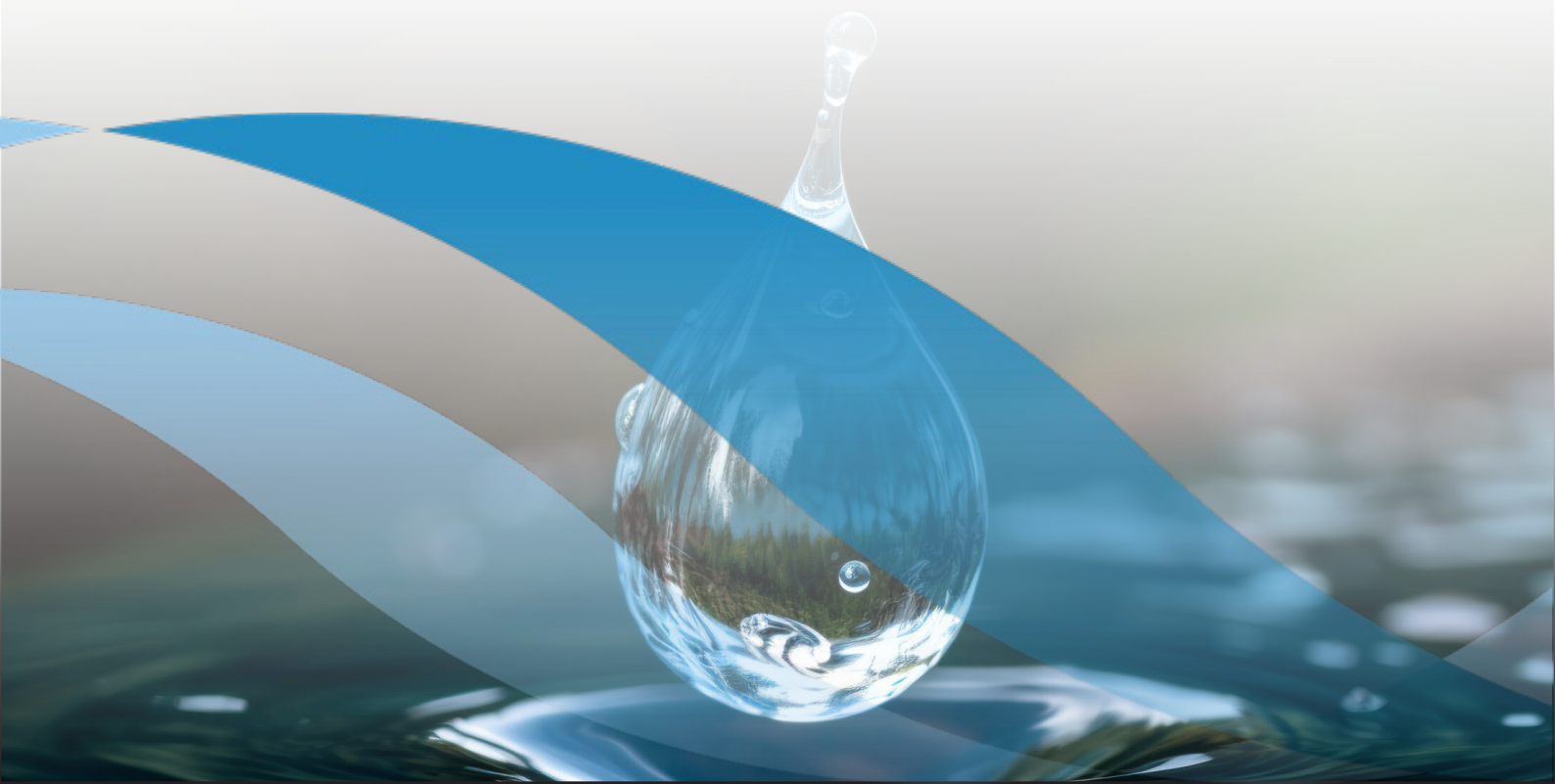


Promethean **Particles**[®]

UNLOCKING ATMOSPHERIC WATER

THE TRANSFORMATIVE ROLE OF
METAL-ORGANIC FRAMEWORKS (MOFs)
IN ENABLING THE NEXT GENERATION
OF ATMOSPHERIC WATER HARVESTING

September 2025



CONTENTS

3	Executive Summary
4	The Challenge of Water Scarcity
6	Atmospheric Water Harvesting (AWH) Technologies
8	About Metal-organic Frameworks
11	About Promethean Particles
12	Glossary
13	References

“ Water is life, yet more than a billion people do not have access to clean drinking water.

Addressing the global water crisis is not a choice – it is a necessity. ”

Ban Ki-moon¹

Former UN Secretary-General

EXECUTIVE SUMMARY

Unlocking the Atmosphere as a Water Source

Water scarcity is a growing global crisis, driven by climate change, population growth, and expanding industrial demand.

Traditional water infrastructure, reliant on large-scale reservoirs, pipelines, and energy-intensive purification, struggles to meet the needs of an increasingly water-stressed world. Innovative, decentralised, and off-grid solutions are urgently needed.

This white paper explores atmospheric water harvesting (AWH) as a scalable and sustainable solution.

Among various AWH technologies being developed around the world, metal-organic frameworks (MOFs) stand out for their unmatched efficiency in capturing water across a wide range of climatic conditions while requiring minimal energy input.

Once seen as a futuristic concept, high-quality MOFs are now becoming commercially viable at an industrial scale due to the breakthrough in manufacturing processes developed by Promethean Particles.

THE WATER SCARCITY CHALLENGE

Climate change and rapid population growth are intensifying the global water crisis. Today, more than 2.3 billion people, nearly one-third of the world's population, live in water-stressed countries².

Demand for decentralised, off-grid water solutions is accelerating

Many communities rely on surface water from rivers and lakes or draw from groundwater reserves. But these sources are under increasing pressure from overuse and depletion. Climate change compounds the issue, disrupting rainfall patterns and driving more regions into prolonged drought.

Emerging industrial processes to tackle climate change, including battery manufacturing, hydrogen production, and some carbon capture technologies, are increasing water demand and intensifying the challenge of water scarcity.

It is estimated that water scarcity may contribute to the displacement of over 700 million people by 2030^{3,4} and that more than 900 million people could be living in water-stressed regions by 2050⁵.

Rethinking water infrastructure with innovative solutions

Traditional water systems depend on large-scale infrastructure. Reservoirs, pipelines, treatment plants, and maintenance all require significant investment and resources.

As global water challenges grow, there is a pressing need for alternative methods of water capture and purification.

Desalination offers a potential solution to freshwater scarcity, but its widespread and sustainable use is constrained by the high energy demands and extensive infrastructure required for reverse osmosis and thermal technologies.

One promising opportunity lies in the atmosphere which holds an estimated 12,900 km³ of fresh water⁶, 7% more than Lake Superior, the world's largest freshwater lake. Accessing this abundant, untapped resource efficiently calls for new technological approaches.



Atmospheric Water Harvesting offers a promising path forward

AWH offers a decentralised way to produce drinking water in remote, arid, or disaster stricken areas; and of providing water independence for communities.

Many different AWH systems, each suited to different geographic and climate conditions, are now being developed, tested, and deployed. Examples include:

- Condensation cooling
- Fog-harvesting
- Solar stills
- Traditional adsorbents
- Metal-organic frameworks

One of the challenges system developers face is that many AWH systems are highly energy intensive and do not function at low levels of relative humidity (RH) or high ambient temperatures.

Metal-organic frameworks represent a cutting-edge solution for AWH system developers due to their ability to operate efficiently in even the driest climates. Their ability to work across a wide range of relative humidity conditions makes them stand out from alternative technologies. MOFs can be designed into self-contained AWH systems, making them particularly well-suited for use in decentralised and remote installations across a wide range of climatic conditions.

Looking ahead

The aim of unlocking water from the atmosphere is increasingly moving from the realm of sci-fi speculation to a practical reality.

As AWH technology matures and scales, it will follow the trend seen with solar panels and become more affordable, making it a mainstream component in ensuring global water security.

WATER SCARCITY FAST FACTS:

1 in 4



people globally were without access to safe drinking water in 2023⁷

(UNICEF)



50%

of the world's population live in regions which experience water stress in 2025^{8,9}

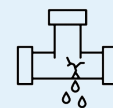
(UNICEF, United Nations)

70%



of all fresh water is used for agriculture, the largest consumer of water globally¹⁰

(FAO)



40%

of water is lost to leaks and inefficient infrastructure before reaching end users¹¹

(World Bank)

2050



Urban demand for water is expected to increase by 80%, placing immense pressure on supply systems¹²

(OECD)

ATMOSPHERIC WATER HARVESTING TECHNOLOGIES

Driven by the need for more resilient water sources, investment in AWH systems, which has been growing at 10% to 15% annually, is forecast to double by 2030^{13,14}. Here we compare some of the established and emerging water harvesting technologies.

Condensation Cooling (Dew-point machines)

Condensation cooling systems use existing refrigeration and dehumidification processes to chill air below its dew point, causing water vapour in the air to condense into a liquid. Most systems use a vapour-compression refrigeration cycle or thermoelectric coolers to create a cold surface. A fan draws humid air over the cold surface, water condenses and is collected. The water usually requires filtration and UV sterilisation to ensure potable quality.

While the technical simplicity of condensation cooling is an advantage, significant energy is required to cool air below its dew point and its efficiency falls when the relative humidity is below 50%, or ambient temperatures are high¹⁵. These factors limit the regions where it can be considered as a viable option.

ADVANTAGES

- ✓ High water yield in humid areas
- ✓ Mature technology
- ✓ Modular and scalable systems
- ✓ Commercially available

DISADVANTAGES

- ✗ Very high energy consumption
- ✗ Inefficient below 50% RH
- ✗ Not suitable for arid climates
- ✗ Require cooling below dew-point
- ✗ Require refrigerants

Traditional Adsorbents

Desiccant-based systems rely on hygroscopic materials (desiccants) that naturally absorb water vapour from the air instead of dew formation. The captured water can then be released by heating.

A wide range of materials have been explored including solid porous sorbents (e.g., silica gel, zeolites) as well as liquid or salt-based absorbents (e.g., lithium chloride or calcium chloride brines). They can operate at lower relative humidity (10-30%)¹⁵ and outperform condensation cooling in deserts and high-temperature zones. However, their effectiveness reduces as relative humidity falls and the heating cycle can be energy intensive. Desiccant based systems are promising for a wide range of climates, especially arid regions where condensation-based methods struggle.

ADVANTAGES

- ✓ Works at lower relative humidity
- ✓ Can store water for later release
- ✓ Adaptable to semi-arid regions

DISADVANTAGES

- ✗ Medium to high energy consumption
- ✗ Slow water release
- ✗ Require a heat source for regeneration
- ✗ Can degrade over time

Fog Harvesting

Not all atmospheric water is vapour. In certain regions, large quantities of liquid water exists as fog and mist - water droplets suspended in air. Fog harvesting is a passive technique that captures those droplets using mesh nets. When wind-blown fog passes through the nets water droplets collide with the fibres of the mesh

ADVANTAGES

- ✓ No external energy input required
- ✓ Low maintenance
- ✓ Simple and low-cost set up

and form larger droplets that coalesce and are collected in tanks. The water produced through fog-harvesting is generally high quality and may only require basic filtration.

Fog-harvesting nets require no external energy, driven entirely by wind and gravity. Whilst relatively simple to build and maintain, they require the consistent presence of fog which limits its use to specific geographies (e.g., coastal deserts). As a low-tech, low-cost AWH method, fog-harvesting can be transformative in the regions where it could be used.

Solar Stills

Solar stills harness energy from the sun to produce high purity water from the atmosphere through evaporation and condensation. They have been extensively used to desalinate water and to produce clean water from non-potable water sources. The same principles are being applied to condense fresh water from moist air.

By using the sun's heat to evaporate water, they are passive systems requiring no external energy. To increase efficiency, some designs incorporate reflectors to concentrate the solar energy and increase evaporation. However, they require a large surface area due to their low yield potential and their performance is weather dependant. Solar stills are best suited for use in hot, sunny areas that also experience cool nights (e.g. Middle East and North Africa).

Metal-organic Frameworks (MOFs)

MOFs have been shown to operate over a wider RH range than other AWH technologies. They can work effectively down to 10% RH and outperform condensation cooling in deserts and high-temperature zones.

Their fast kinetics for adsorption and desorption enable them to capture water vapour faster and they require less energy to release the captured water. This makes them well suited for areas where access to energy infrastructure is limited. When coupled with local energy production, e.g., solar, they are able to operate in completely off-grid systems.

With industrial scale manufacturing now available, MOFs are becoming a leading solution for new AWH systems.

DISADVANTAGES

- ✗ Only works in fog-prone areas
- ✗ Water yield highly weather-dependent
- ✗ Require a large surfact area
- ✗ Ineffective in dry air

ADVANTAGES

- ✓ Uses renewable solar energy
- ✓ Simple and robust design
- ✓ Suitable for remote or desert areas
- ✓ Simple technology
- ✓ Easy to construct

DISADVANTAGES

- ✗ Low daily water output
- ✗ Needs brine or moisture source
- ✗ Slow collection process
- ✗ Ineffective in dry air

ADVANTAGES

- ✓ Operate at very low relative humidity
- ✓ Low energy intensity
- ✓ Modular and scalable
- ✓ Do not require the use of refrigerants

DISADVANTAGES

- ✗ Limited number of systems in use
- ✗ Unproven long-term durability

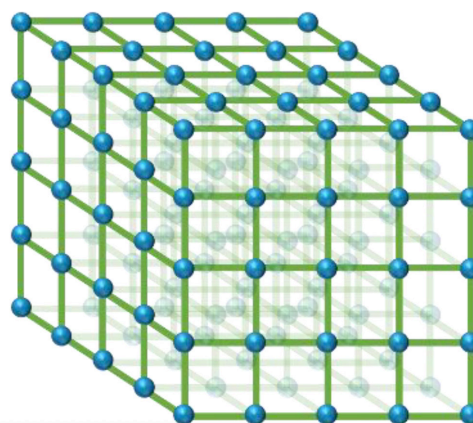
ABOUT METAL-ORGANIC FRAMEWORKS

MOFs represent a cutting-edge class of sorbent materials. Their fast adsorption and desorption kinetics makes them one of the most promising materials for atmospheric water harvesting.

A new class of incredible materials

MOFs are a relatively new family of compounds which were first discovered in 1965 as by-product from other chemical processes. They first came to prominence in mid 1990s, with academic interest ramping in the mid-2000s.

The first permanently porous metal-organic framework was discovered by Omar Yaghi et al. in 1999¹⁶ when the term metal-organic framework was also coined¹⁷. More than 100,000 MOFs have been recorded in the Cambridge Structural Database (CSD) as of 2025¹⁸, although very few have been made at any industrially significant scale — until now.



A three-dimensional representation of a MOF structure comprised of metal clusters and organic linkers

What makes a MOF special?

MOFs are highly porous, crystalline frameworks comprised of metal ions and organic linkers (ligands). They exhibit a 'cage' like structure, which can be a two- or three-dimensional lattice, which has an incredibly high surface area that acts as a 'sieve' to selectively trap (adsorb) specific molecules (adsorbate). The trapped adsorbate can then be released (desorbed) to regenerate the MOF and this cycle can be repeated many times.

A MOF's surface area can be 10 to 100 times that of other 'high surface area' materials like activated carbons and zeolites. BET surface areas of up to 2,000 m²/g can be achieved for MOFs¹⁹ and this can be as high as 7,000 m²/g.

The choice of metal ion and organic linker is almost limitless, allowing for the tuning of the MOFs' pore size and volume for different applications.

Key attributes of MOFs:

- ✓ Incredibly high surface areas
- ✓ Tunable selectivity
- ✓ Low energy of desorption
- ✓ High thermal and chemical stability
- ✓ Recyclability

DID YOU KNOW?

7,839 m²/g

The highest reported surface area²⁰ for a MOF is 7,839m²/g.

That's equal to the average size of an entire football pitch.

(Angewandte Chemie International)

Assessing the Suitability of MOFs for AWH

The assessment of a MOF's capability for water capture is conducted on a lab-scale by generating a water isotherm (shown in figure 1). This isotherm, or adsorption curve, is a measure of the uptake of water by a MOF as pressure is increased. A desorption curve can also be plotted by reversing the process.

During this experiment, the MOF sample (A) is first dried completely to activate it and the dry weight recorded. The sample is then dosed with a known amount of water vapour at a constant temperature but at varying relative pressures (p/p_0). Data points are plotted as this continues until the sample is fully saturated (when $p/p_0 = 1$).

The last point on the graph is the total water uptake of the sample and recorded in mmol/g or wt%. The higher this value is the more water the MOF is able to adsorb.

Kinetic information can also be obtained from this isotherm and this data informs the suitability of the MOF in either high or low relative humidity environments.

Not all MOFs are the Same

Performance differences in MOFs that are suitable for water harvesting can be observed in their water isotherm data (shown in figure 2).

Here MOF B (light dashed blue line) is seen to adsorb water faster than MOF A (dark blue line) at lower relative pressure and becomes fully saturated at 9.4 mmol/g. In contrast, MOF A displays slower kinetics at low relative pressure but at $p/p_0 = 0.23$ fast uptake is observed until an overall uptake of 23.6 mmol/g is recorded at saturation point.

Figure 1. A water isotherm for a water harvesting MOF manufactured by Promethean Particles

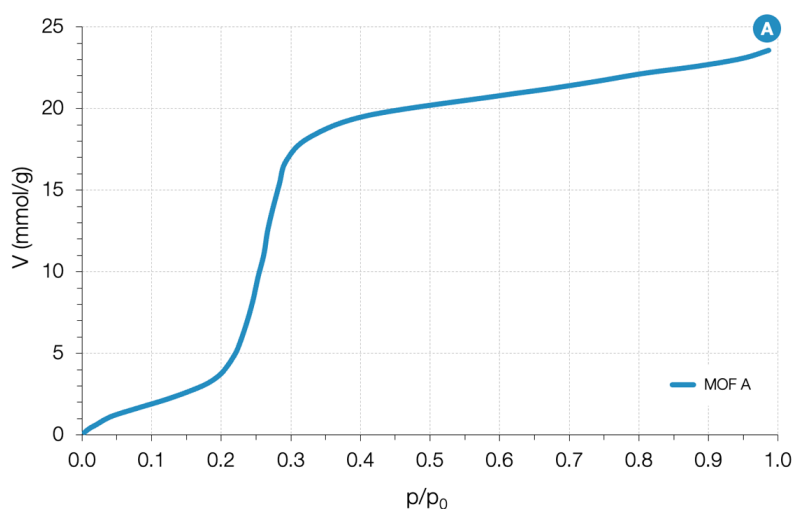
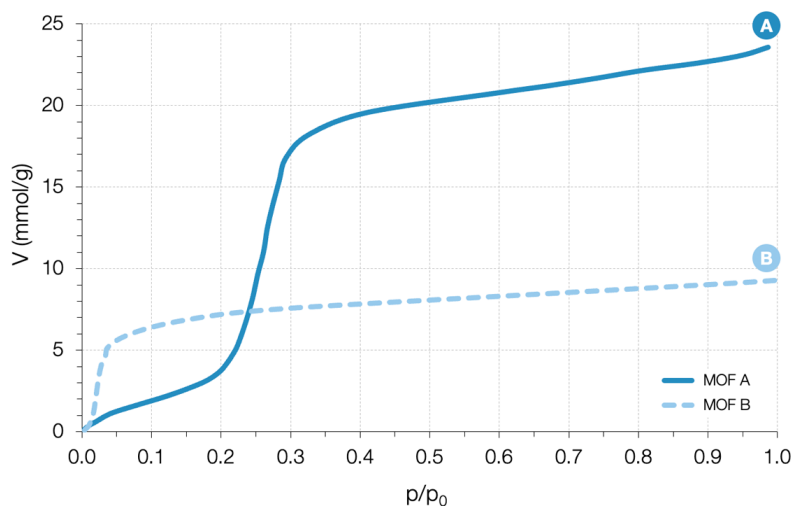


Figure 2. A comparison of water isotherms for two different MOF structures



These differences in the rate of adsorption and total water uptake capacity provide valuable insight into the suitability of a specific MOF for a particular application.

In this example, MOF B would be an ideal candidate for AWH in low relative humidity environments, although a greater volume of this MOF may be required depending on the amount of water required to be adsorbed. MOF A would be suitable for AWH in higher RH environments. Depending upon the specific climatic conditions a system incorporating both MOF A and MOF B could offer distinct advantages.

For application of MOFs in an engineered system, whether on a pilot or industrial scale, it is key to shape the MOF into a suitable form. MOFs are initially produced as powders and can be shaped into pellets, granules or prills.

Shaping the MOF reduces the health and safety considerations associated with powder handling at scale. The shaping must not compromise on the overall uptake capability of the MOF as well as kinetics of the adsorption and desorption processes. The shape of the final MOF product will also depend on various physical and chemical properties of the MOF itself.

MOF Selection, Shape and Quality

There are many factors which can impact the water selectivity and suitability of each particular MOF structure for an AWH application. These include:

- the rate of adsorption and desorption
- the pressure range over which adsorption takes place
- the total adsorption capacity
- the regeneration conditions
- MOF shape and form factor

This makes the selection, tuning, and shape of a specific MOF for an application critical to maximise its effectiveness in a system.



ABOUT PROMETHEAN PARTICLES

Promethean Particles is a world-leading specialist in the synthesis and production of metal-organic frameworks. Our proprietary and patented continuous flow manufacturing process enables the industrial scale production of high-quality, cost-effective MOFs.

Founded in 2007 as a spin-out from the University of Nottingham, UK, we now operate the world's largest continuous MOF manufacturing plant at our Nottingham site.

Over the past decade, we have evolved into a global leader, delivering advanced MOF solutions for a diverse range of industrial applications.

Our team of research chemists and process engineers bring deep expertise in assessing the synthesis potential of MOF structures, both in the laboratory and at an industrial scale. We have a proven track record of developing safe, efficient, and reliable synthesis methods, successfully transitioning numerous MOFs from small-batch laboratory processes to continuous-flow manufacturing.

We partner with MOF inventors, research institutions, and engineering companies to unlock the full potential of MOFs in applications including:

- Carbon capture
- Biogas upgrading
- Atmospheric water harvesting
- Gas storage and separation
- Dehumidification

Since securing a Series A investment in July 2024, we have expanded our team and capabilities to accelerate the commercialisation of MOF-based technologies.

We are actively collaborating with organisations worldwide to test MOFs in real-world environments. Results to-date have been exciting, demonstrating that MOFs offer multiple benefits over alternative separation and capture technologies.

With the capacity, expertise, and innovation to scale, Promethean Particles is shaping the future of MOFs for a cleaner, more efficient world.



GLOSSARY

Absorption	The process by which atoms, ions, or molecules penetrate into the bulk of a solid or liquid material, becoming uniformly distributed throughout its volume. Unlike adsorption, absorption is a bulk phenomenon rather than limited to the surface
Adsorbate	The substance that accumulates on the surface of an adsorbent.
Adsorbent	A solid material that has the ability to attract and hold molecules (such as gases, liquids, or dissolved substances) on its surface through the process of adsorption.
Adsorption	The process by which atoms, ions, or molecules (adsorbate) from a gas, liquid, or dissolved solid accumulate on the surface of a solid or liquid material (adsorbent), forming a film or layer. Unlike absorption, adsorption is a surface phenomenon.
AWH	Atmospheric Water Harvesting
BET surface area	The specific surface area of a porous material, determined using the Brunauer–Emmett–Teller (BET) method, which applies gas adsorption isotherms to calculate the surface accessible to adsorbates. BET surface area is a key metric for characterizing porosity and adsorption capacity of MOFs.
Desalination	The process of removing dissolved salts and other impurities from seawater, brackish water, or wastewater to produce fresh water suitable for human consumption, agriculture, or industrial use.
Desiccant	A substance that absorbs or adsorbs moisture from the surrounding environment. Some desiccants adsorb water onto their surface (e.g. silica gel, zeolites, activated alumina) whilst others absorb water into their structure through chemical reactions (e.g. calcium chloride, sulfuric acid).
Isotherm	Graphs that describe the relationship between the amount of gas adsorbed by a porous material and the pressure of that gas at a constant temperature. Adsorption isotherms are used to evaluate pore size distribution, surface area, and adsorption capacity.
MOF	Metal-organic framework
Relative humidity	The ratio of the amount of water vapor present in air to the maximum amount the air can hold at the same temperature, expressed as a percentage. In AWH relative humidity is a critical parameter because it determines how much moisture is available in the air and influences the efficiency of different technologies.
Saturation point	The stage on an adsorption isotherm where the pores of a porous material, such as a MOF, are fully filled with adsorbate molecules (e.g., water). At this point, further increases in pressure or relative humidity do not lead to significant additional uptake, marking the maximum adsorption capacity of the material under those conditions.
Silica gel	A porous, granular form of silicon dioxide (SiO_2) made synthetically from sodium silicate. Silica gel is a strong adsorbent and is chemically inert and non-toxic.
Zeolite	A crystalline, microporous material made primarily of aluminosilicate minerals.

REFERENCES

1. Ban Ki-moon (2010), World Water Day speech, Buenos Aires. <https://archive.upf.org/united-nations/other-reports-on-the-un/2712-celebrating-world-water-day-in-argentina>
2. UNICEF data on global water scarcity. <https://www.unicef.org/wash/water-scarcity>
3. United Nations (2024), “Water Scarcity” facts & figures page
4. UNDP (2025), “Water for Sustainable Development.” <https://www.undp.org/water>
5. The American Society of Mechanical Engineers (2023), “Hand-held Device Takes Water from the Air Using MOFs.” <https://www.asme.org/topics-resources/content/harvesting-water-from-air>
6. US Geological Survey (2019), “How much water is there on earth?” <https://www.usgs.gov/water-science-school/science/how-much-water-there-earth>
7. WHO & UNICEF (2025), “1 in 4 people globally still lack access to safe drinking water” report. <https://www.who.int/news/item/26-08-2025-1-in-4-people-globally-still-lack-access-to-safe-drinking-water---who--unicef>
8. UNICEF data on global water scarcity. <https://www.unicef.org/wash/water-scarcity>
9. United Nations Environmental Programme, UN EP (2025), “Global water shortages are looming. Here is what can be done about them.” <https://www.unep.org/news-and-stories/story/global-water-shortages-are-looming-here-what-can-be-done-about-them>
10. Food and Agriculture Organization of the United Nations, FAO (2025), “Water and One Health”, 2025. <https://www.fao.org/one-health/areas-of-work/water/en>
11. World Bank data as reported by We Are Water Foundation (2024), “Water waste: Ending water losses, a global priority.” <https://www.wearewater.org/en/insights/water-waste-ending-water-losses-a-global-priority/>
12. OECD (2012), OECD Environmental Outlook to 2050, OECD Publishing. https://www.oecd.org/content/dam/oecd/en/publications/reports/2012/03/oecd-environmental-outlook-to-2050_g1g14e69/9789264122246-en.pdf
13. Grand View Research (2023), “Atmospheric Water Generator Market Size, Share & Trends Analysis Report By Product (Cooling Condensation, Wet Desiccation), By Application (Industrial, Commercial, Resi-dential), By Region, And Segment Forecasts, 2024 – 2030” <https://www.grandviewresearch.com/industry-analysis/global>
14. Fortune Business Insights (2025), “Atmospheric Water Generator Market Size, Share & Industry Analysis, By Product Type (Cooling Condensation and Desiccant Based), By Application (Industrial, Commercial and Household), and Regional Forecast, 2024-2032” <https://www.fortunebusinessinsights.com/atmospheric-water-generator-market-103321>
15. Royal Society of Chemistry – RSC Advances (2023), “An overview of atmospheric water harvesting methods, the inevitable path of the future”, RSC Publishing
16. H. Li, M. Eddaoudi, M. O’Keeffe and O. M. Yaghi, Nature, 1999, 402, 276–279.
17. M. Yaghi and H. Li, J Am Chem Soc, 1995, 117, 10401–10402.
18. <https://www.ccdc.cam.ac.uk/free-products/csd-mof-collection/>
19. Zhijie Chen, Kent O. Kirlikovali, Peng Li, Omar K. Farha (2022), ‘Reticular Chemistry for Highly Porous Metal–Organic Frameworks: The Chemistry and Applications.’ American Chemical Society Publications. <https://pubs.acs.org/doi/10.1021/acs.accounts.1c00707>
20. M. Hönicke, I. Senkovska, V. Bon, I. A. Baburin, N. Bönisch, S. Raschke, J. D. Evans and S. Kaskel, Angewandte Chemie International Edition, 2018, 57, 13780–13783.



Promethean Particles Ltd
1-3 Genesis Park, Midland Way
Nottingham
NG7 3EF
United Kingdom

 info@proparticles.co.uk

 prometheanparticles.co.uk

 [linkedin.com/company/promethean-particles](https://www.linkedin.com/company/promethean-particles)

Copyright © 2025 Promethean Particles, Ltd. All rights reserved. Due to a policy of continued development, we reserve the right to alter or amend any published specification without notice. This document may not be copied, reproduced, transmitted, modified, or used, in whole or in part, without the prior written consent of Promethean Particles Ltd.