



ADSORPTION BASED ATMOSPHERIC WATER HARVESTING

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Abstract: Water scarcity is a critical global challenge, particularly in arid and semi-arid regions where conventional water resources are inadequate to meet growing demands. Atmospheric Water Harvesting (AWH) has emerged as a promising alternative water source by extracting moisture directly from ambient air. Among various AWH techniques, adsorption-based atmospheric water harvesting has gained increasing attention due to its ability to operate under low relative humidity conditions and its potential for energy-efficient operation. This paper presents a comprehensive review of adsorption-based atmospheric water harvesting systems with a focus on working principles, adsorbent materials, system configurations, and performance parameters. Various solid adsorbents such as silica gel, zeolites, metal-organic frameworks (MOFs), and composite materials are discussed with respect to water uptake capacity, regeneration temperature, and operational feasibility in arid climates. The advantages and limitations of adsorption-based systems are critically analyzed and compared with conventional condensation-based water harvesting methods. In addition, recent advancements, sustainability aspects, and challenges related to material cost, regeneration energy, and system scalability are highlighted. The study identifies key research gaps and emphasizes the need for low-cost, environmentally friendly adsorbents and passive or solar-driven regeneration techniques. This review aims to provide a consolidated understanding of adsorption-based AWH systems and serve as a reference for future research and practical implementation in water-stressed regions.

Keywords - Atmospheric Water Harvesting, Adsorption Technology, Arid Regions, Water Scarcity, Adsorbent Materials, Sustainable Water Resources.

1. INTRODUCTION

Water scarcity has emerged as one of the most pressing environmental challenges of modern times, particularly in arid and semi-arid regions where natural freshwater resources are limited. Rapid urbanization, population growth, and climate change have intensified the global water crisis, leaving millions without reliable access to clean water. In many dry regions, conventional water sources such as surface water and groundwater are either non-existent or over-exploited.

Several factors contribute to the growing severity of water scarcity worldwide. One of the primary causes is the uneven geographical distribution of freshwater resources, with some regions naturally receiving very limited rainfall. Rapid population growth, particularly in urban areas, has significantly increased the demand for water, placing immense pressure on available supplies. Agricultural activities, which consume the largest share of freshwater globally, further exacerbate the problem through inefficient irrigation practices and over-extraction of groundwater. Climate change is another major driver, altering precipitation patterns, increasing

the frequency and severity of droughts, and accelerating the melting of glaciers, which are key sources of freshwater for many regions. Additionally, pollution from industrial, agricultural, and domestic sources contaminates surface water and groundwater, reducing the availability of clean water for consumption and other uses. Together, these factors create complex, interrelated challenges that make sustainable water management increasingly difficult in many parts of the world.

Consequently, there is a growing need for innovative and sustainable solutions that can address water scarcity effectively, especially in areas where traditional methods such as desalination or groundwater extraction are either impractical or energy-intensive.

The atmosphere holds a vast, untapped reservoir of water vapor, which exists even in some of the driest regions on Earth. Atmospheric water harvesting (AWH) technologies aim to capture this moisture from the air and convert it into usable liquid water. Among the various AWH methods, adsorption-based systems have gained significant attention due to their ability to operate in low-humidity conditions, which are common in arid climates. This approach leverages the unique properties of advanced adsorbent materials that can effectively capture water molecules from the atmosphere, even at relative humidity levels as low as 10–20%. Adsorption-based atmospheric water harvesting relies on specialized sorbent materials, typically metal-organic frameworks (MOFs), silica gels, zeolites, or other porous compounds, which possess high surface areas and exceptional water affinity. These materials can adsorb water vapor from the air during cooler nighttime conditions when humidity levels tend to rise. Upon exposure to solar heat or low-grade thermal energy during the daytime, the adsorbed water is released through desorption and condensed into liquid form. This cyclic process of adsorption and desorption enables continuous water production without relying on external energy-intensive cooling mechanisms.

One notable advancement in this field has been demonstrated through the development of MOF-801, a zirconium-based metal-organic framework known for its high-water adsorption capacity and stability under harsh environmental conditions. A breakthrough study led by researchers at the Massachusetts Institute of Technology (MIT) and the University of California, Berkeley, successfully demonstrated the use of MOF-801 for water harvesting in desert conditions. The field trial, conducted in Tempe, Arizona, USA, involved a prototype device that was able to harvest clean, drinkable water from the air with zero electricity input, relying solely on sunlight for regeneration. The system operated under extremely low relative humidity levels of around 10–32%, conditions that are typical in many arid regions around the world.

In addition to MOF-801, other materials and hybrid systems are also being investigated to improve water yield, reduce cycle times, and enhance the scalability of adsorption-based water harvesting technologies. Efforts are being made to optimize the structural properties of sorbent materials, such as pore size, hydrophilicity, and thermal conductivity, to maximize water uptake and minimize energy requirements for regeneration. Furthermore, innovative device designs incorporating heat exchangers, insulation layers, and efficient condensers are being explored to improve overall system performance.

The ability to harvest atmospheric water using adsorption processes presents a transformative opportunity for enhancing water security in arid and drought-prone regions. These systems offer multiple advantages, including low energy consumption, minimal maintenance, and the capability to function in environments with limited infrastructure. By utilizing abundant materials and renewable energy sources like solar heat, adsorption-based atmospheric water harvesting holds promise as a sustainable, decentralized solution to water scarcity challenges.

As advancements in sorbent materials and device engineering continue, adsorption-based water harvesting is poised to play an increasingly significant role in the future of water resource management, particularly in areas where conventional approaches remain ineffective or economically unfeasible.

2. CONVENTIONAL WATER HARVESTING SYSTEMS

Conventional water harvesting systems have long been employed to address freshwater demands across agricultural, industrial, and domestic sectors. Common methods such as groundwater extraction, wastewater treatment, and desalination have played a significant role in supplying water in many regions. However, despite their widespread use, these systems often face limitations related to energy consumption, operational

complexity, environmental impacts, and long-term sustainability, particularly in arid and water-scarce regions. A clear understanding of these traditional approaches is essential to assess their effectiveness and to identify the need for more innovative and sustainable water harvesting technologies.

2.1 Groundwater Extraction

Groundwater extraction is one of the most widely practiced methods of obtaining freshwater for agricultural, industrial, and domestic purposes. It involves tapping underground aquifers, which are natural formations of permeable rock, sand, or gravel that hold water beneath the earth's surface. Water is withdrawn from these aquifers through structures such as wells, boreholes, and tube wells, depending on the depth and type of the aquifer.

The common methods of groundwater extraction include the use of hand pumps, which are simple and manually operated systems suitable for shallow wells. In deeper aquifers, motorized pumps are frequently employed, providing higher discharge rates and meeting larger water demands. Deep tube wells, equipped with submersible pumps, are also widely used in agricultural regions where large quantities of water are needed for irrigation.

One of the primary advantages of groundwater extraction is its availability in many regions, often providing a reliable and continuous source of water. In areas where surface water resources are scarce, groundwater serves as an essential lifeline for both rural and urban populations. Additionally, the initial cost of accessing groundwater can be relatively low, particularly for shallow wells using simple pumping mechanisms. Due to its ease of access, groundwater extraction remains a commonly practiced water supply method in various parts of the world.

However, groundwater extraction comes with several limitations:

- Over-extraction leads to depletion of aquifers and reduction in water table levels.
- Causes land subsidence in some cases.
- Quality deterioration due to contamination by salts, heavy metals, or pollutants.
- Limited recharge rates, especially in arid regions with low rainfall.
- Excessive groundwater withdrawal disrupts ecosystems and reduces surface water flows.

2.2 Wastewater Treatment

Wastewater treatment plays a crucial role in conserving and recycling water, especially in regions facing water stress. This process involves the removal of contaminants from domestic sewage or industrial effluents to produce water that is safe for discharge into the environment or for reuse in various applications.

Wastewater treatment is typically carried out in three main stages. In the primary treatment stage, large solids, grit, and suspended particles are removed through physical processes such as screening and sedimentation. This stage mainly targets the removal of easily separable materials. The secondary treatment stage involves biological processes where microorganisms are used to break down organic matter present in the wastewater. Systems such as activated sludge processes, biofilters, and trickling filters are commonly employed at this stage to reduce biochemical oxygen demand (BOD) and remove organic pollutants. The tertiary treatment stage is an advanced step aimed at removing remaining dissolved substances, nutrients, and pathogens. Techniques such as membrane filtration, chemical coagulation, UV disinfection, and reverse osmosis are utilized to achieve high-quality treated water.

Treated wastewater has a wide range of applications. It can be reused for agricultural irrigation, reducing the demand on freshwater sources for farming activities. Industries often use treated wastewater for cooling and process operations, while some advanced treatment plants produce water of potable quality that can be reintroduced into the drinking water supply or groundwater recharge systems. This method of water reclamation is becoming increasingly vital for sustainable water management in many urban regions.

Wastewater treatment offers several advantages, such as reducing pollution in rivers, lakes, and oceans by minimizing the release of untreated wastewater. It also contributes to the conservation of water resources and enhances the overall resilience of water supply systems.

Nevertheless, this approach faces certain limitations:

- High capital and operational costs.
- Requires skilled operation and regular maintenance.
- Energy-intensive, especially in advanced treatment stages.
- Limited public acceptance for potable reuse in many regions.

2.3 Desalination Process

Desalination is an advanced water purification method designed to remove dissolved salts, minerals, and other impurities from saline water sources, such as seawater or brackish water. It is increasingly being adopted in coastal regions and water-scarce countries to supplement freshwater supplies.

Two main technologies dominate the desalination industry. Reverse osmosis (RO) is the most widely used method, involving the use of semi-permeable membranes to separate salt and impurities from water. High pressure is applied to force water through the membrane, leaving salts and contaminants behind. The second widely used method is thermal desalination, which includes processes such as Multi-Stage Flash Distillation (MSF) and Multi-Effect Distillation (MED). In these methods, water is heated to produce steam, which is then condensed to obtain freshwater, leaving the dissolved salts behind in the concentrated brine.

Desalination provides a reliable and consistent source of drinking water, especially for coastal regions where seawater is abundant. It plays a crucial role in regions where freshwater sources are either limited or over-exploited. Many countries in the Middle East, as well as island nations, rely heavily on desalinated water for their daily needs.

However, despite its advantages, desalination faces several challenges and limitations:

- Very high energy consumption, making it costly and carbon-intensive.
- High operational and maintenance costs.
- Produces concentrated brine, which requires safe disposal and can harm marine ecosystems.
- Not suitable for inland areas without nearby saline water sources.

3. ATMOSPHERIC WATER HARVESTING

3.1 Introduction

Atmospheric water harvesting (AWH) is an innovative and emerging technique that enables the extraction of water directly from air by utilizing the moisture content in the atmosphere. This method presents a promising solution for arid and drought-prone regions where traditional water sources such as groundwater, rivers, and lakes are either limited, heavily depleted, or unavailable. The atmosphere acts as an enormous reservoir of water vapor, containing nearly 13,000 billion cubic meters of water at any given time, which significantly surpasses the volume of freshwater stored in rivers and lakes combined.

Unlike conventional water supply systems, atmospheric water harvesting does not rely on rainfall, making it an attractive decentralized water source. The key advantage of AWH lies in its ability to function under varying environmental conditions, including regions with low relative humidity. By leveraging physical processes such as condensation, adsorption, or absorption, atmospheric water harvesting systems can convert water vapor into liquid water, which can then be collected for domestic, agricultural, or industrial use.

In recent years, AWH technologies have gained considerable research attention due to their potential in addressing water scarcity challenges, particularly in off-grid locations and rural communities. Advanced materials such as metal-organic frameworks (MOFs) and biomimetic surface designs inspired by organisms like the Namib Desert beetle have further enhanced the efficiency of these systems, enabling water collection even at low humidity levels. Given their adaptability, sustainability, and minimal dependence on external infrastructure, atmospheric water harvesting technologies are increasingly being viewed as a viable long-term solution for securing water in vulnerable regions.

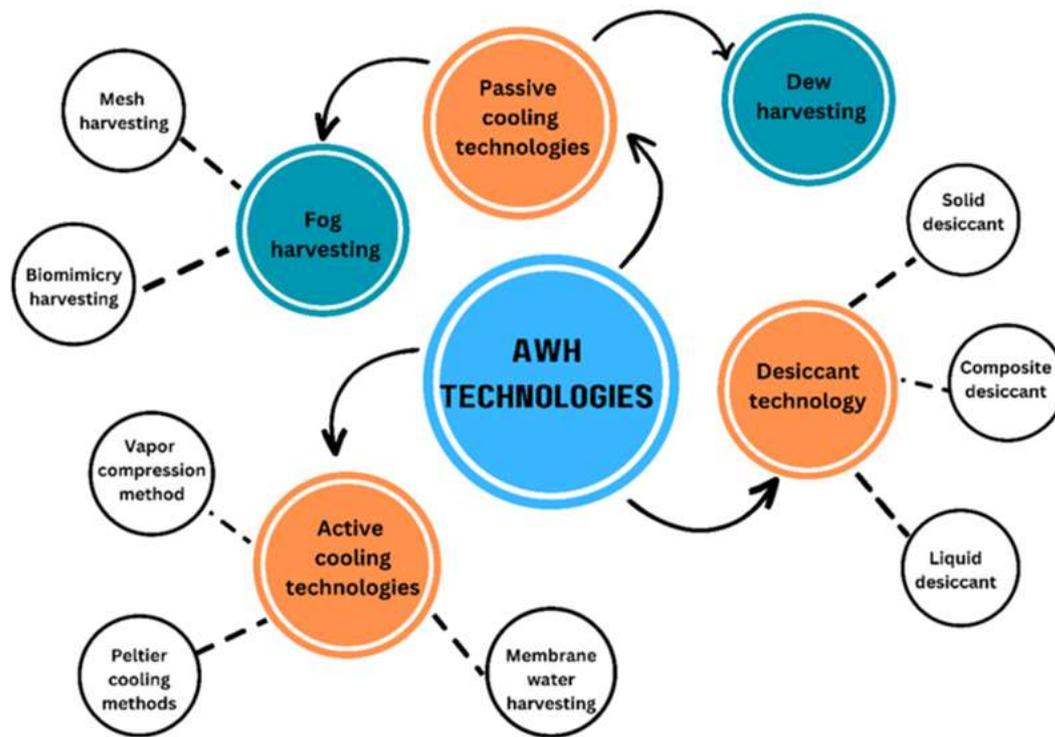


Fig 1. Atmospheric Water Harvesting

3.2 Types of AWH

3.2.1 Condensation-Based AWH

Condensation-based atmospheric water harvesting techniques work on the principle of cooling air below its dew point, leading to the condensation of water vapor into liquid water. This category includes fog harvesting, dew harvesting, and active mechanical condensation systems.

3.2.1.1 Fog Harvesting

Fog harvesting utilizes specialized mesh structures to capture water droplets suspended in fog-laden air. As the fog passes through these mesh materials, droplets accumulate on the surface, coalesce, and are then collected by gravity into storage tanks. This method is highly effective in regions where fog occurs frequently, such as coastal or mountainous areas.

An iconic example from nature is the Namib Desert beetle (*Stenocara gracilipes*), which survives in one of the driest places on Earth by harvesting fog water. The beetle's back is covered with hydrophilic bumps and hydrophobic troughs, allowing it to collect and direct condensed water droplets toward its mouthparts. This natural mechanism has inspired the development of engineered fog-harvesting surfaces that mimic the beetle's shell structure, improving the efficiency of artificial fog collectors.



Fig 2. Namib Desert Insect

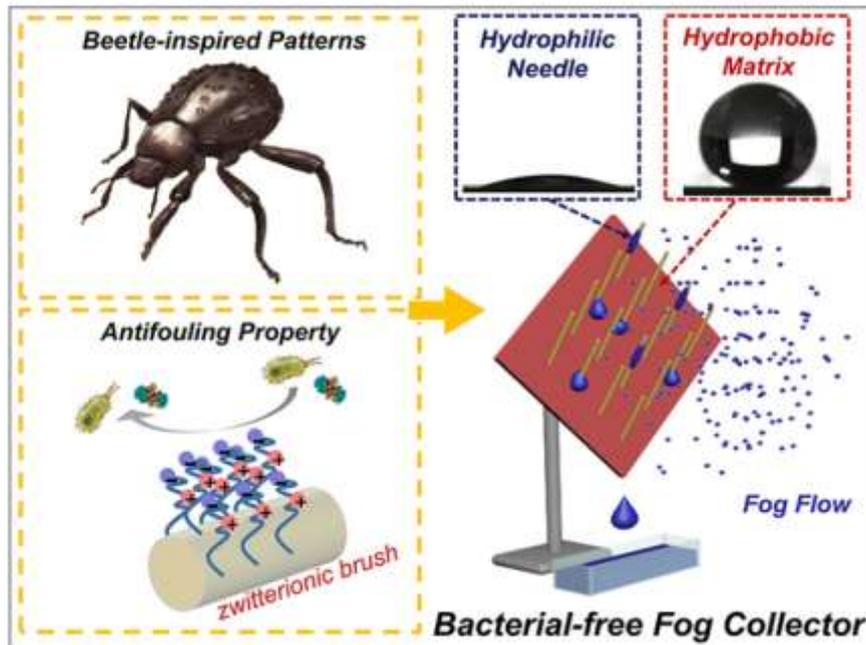


Fig 3. Beetle Inspired Fog Collector

Fog harvesting can yield 2 to 10 Liters of water per square meter of mesh per day under favourable conditions. It is a passive, low-energy method suitable for remote communities but depends heavily on the presence of consistent fog.

3.2.1.2 Dew Harvesting

Dew harvesting involves the use of surfaces that cool below the dew point through radiative cooling, causing water vapor to condense into liquid droplets. These droplets are then collected using sloped surfaces designed to channel the water into storage containers. Materials with high emissivity and low thermal conductivity are often selected to maximize dew collection efficiency.

While dew harvesting systems generally produce smaller amounts of water compared to fog harvesting, they can operate consistently in areas with moderate humidity during night-time cooling. The typical yield ranges from 0.1 to 0.5 Liters per square meter per night, depending on ambient temperature, humidity, and surface design.

3.2.1.3 Active Condensation Systems

Active condensation systems employ mechanical cooling techniques, such as vapor compression refrigeration or thermoelectric cooling, to reduce air temperature below the dew point and extract water. These systems can operate effectively in a wide range of environments but typically require significant energy input.

Water production rates in active systems depend on the relative humidity and air temperature, with higher yields achievable in humid conditions. However, their high energy consumption and operational costs make them less suitable for widespread use in low-income or off-grid areas.

3.2.2 Sorption-Based AWH

Sorption-based AWH systems utilize advanced materials that can capture and later release water vapor through physical or chemical interactions. These systems are particularly suitable for regions with low relative humidity.

3.2.2.1 Adsorption Systems

Adsorption systems use porous materials such as metal-organic frameworks (MOFs), silica gels, and zeolites that can adsorb water vapor onto their surfaces. One of the most promising materials is MOF-801, a zirconium-based framework known for its exceptional water adsorption capacity even under low humidity conditions.

In a field study conducted in Tempe, Arizona, MOF-801-based water harvesters were able to produce 0.25 Liters of water per kilogram of MOF per day under relative humidity levels as low as 10% to 32%. These systems typically operate in a two-phase cycle: adsorption during cool, humid night-time hours and desorption during daytime using solar heat. The desorbed water vapor is then condensed into liquid form.

3.2.2.2 Absorption Systems

Absorption systems involve hygroscopic materials, such as lithium chloride or calcium chloride, that chemically bind with water vapor. These materials absorb water directly from the air and require heating or pressure changes for water release. Although effective in capturing large amounts of water, absorption systems often demand higher regeneration energy than adsorption systems and may face material degradation issues over time.

Table 1: Comparison of Various Atmospheric Water Harvesting Techniques

AWH Method	Mechanism	Typical Water Yield	Energy Requirement	Key Applications/Regions
Fog Harvesting	Capturing fog droplets on mesh	2–10 L/m ² /day	Very Low (Passive)	Coastal, foggy, mountainous areas
Dew Harvesting	Night-time radiative cooling	0.1–0.5 L/m ² /night	Very Low (Passive)	Semi-arid regions with high night-time RH
Active Condensation	Mechanical cooling below dew point	Variable (higher in humid areas)	High (Electricity Needed)	Urban, industrial areas
Sorption (MOF-801)	Adsorption and desorption using solar heat	0.25 L/kg of MOF/day (10–32% RH)	Low (Solar or Thermal Heat)	Arid, low-humidity, remote regions
Absorption Systems	Hygroscopic chemical absorption	Moderate to High	Moderate to High (Thermal)	Specialized industrial or remote applications

3.3 Principle

Atmospheric water harvesting systems operate based on two primary principles: condensation and sorption.

3.3.1 Condensation Principle

In condensation-based systems, water vapor from humid air is cooled below its dew point, triggering the phase change from vapor to liquid water. This can occur through either passive cooling, such as radiative cooling during night-time (as in dew and fog harvesting), or active cooling methods that rely on mechanical energy. The Namib Desert beetle utilizes a biological condensation mechanism by exploiting the temperature difference between its body surface and the surrounding air. The beetle's back, with its contrasting hydrophilic and hydrophobic patterns, enables fog droplets to condense and flow toward its mouth, serving as a natural water-harvesting device. This biomimicry principle has inspired many modern fog and dew harvesting devices.

3.3.2 Sorption Principle

Sorption-based systems capture water by allowing water vapor to adhere to or chemically react with a sorbent material. During adsorption, porous materials such as MOFs attract water molecules to their internal surfaces through weak intermolecular forces. Desorption is achieved by heating, often using solar energy, which releases the water vapor for condensation.

In absorption systems, water vapor is taken up by hygroscopic materials through chemical bonding. The release process requires significant heat or pressure changes to separate water from the absorbing material.

3.4 Advantages

Atmospheric water harvesting technologies offer numerous advantages that make them suitable for addressing global water scarcity challenges:

- **Adaptability to Diverse Climates:** Certain technologies, particularly MOF-based sorption systems, can operate effectively under low relative humidity conditions, making them suitable for arid regions.
- **Decentralized Water Supply:** AWH systems can provide localized water sources independent of centralized infrastructure, making them ideal for remote or disaster-affected areas.
- **Sustainability:** Many AWH systems are powered by renewable energy sources, such as solar heat or natural cooling, reducing carbon emissions and environmental impacts.
- **Low Maintenance Requirements:** Passive systems such as fog and dew collectors require minimal maintenance and have long operational lifespans.
- **Scalability:** Systems can be designed for a variety of scales, ranging from household-level units to large community-based water harvesting installations.
- **Environmentally Friendly:** Unlike desalination or groundwater extraction, AWH has minimal adverse effects on ecosystems, offering a sustainable water sourcing method with little or no chemical discharge.

4. ADSORPTION BASED AWH

4.1 Introduction

Adsorption-based atmospheric water harvesting (AWH) is a highly promising method designed to extract water from the air, particularly under low relative humidity (RH) conditions. Unlike conventional water harvesting techniques that often depend on high ambient humidity, this method utilizes advanced sorbent materials with a strong affinity for water molecules, allowing for efficient water capture even in arid environments.

This technology leverages the ability of certain porous materials to adsorb water vapor during periods of higher humidity, typically at night, and subsequently release the adsorbed water as liquid through a controlled desorption process, usually driven by solar energy. One of the most notable features of adsorption-based AWH systems is their ability to operate without complex mechanical components, relying instead on temperature-driven adsorption-desorption cycles.

Recent advancements in material science, particularly the development of metal-organic frameworks (MOFs), have significantly improved the efficiency and applicability of adsorption-based AWH systems. These materials offer high surface area, tunable pore sizes, and selective adsorption characteristics, enabling water harvesting in climates where conventional methods are not feasible.

4.2 Working Principle

The working principle of adsorption-based atmospheric water harvesting revolves around the cyclic adsorption and desorption of water vapor by specially designed porous materials.

Adsorption Phase

During nighttime or periods of relatively higher humidity, the adsorbent material captures water vapor from the surrounding air. This process is typically favoured by the lower temperatures and higher humidity that prevail during night hours. The adsorbent's surface and pore structure enable it to attract and hold significant amounts of water vapor through physical or chemical interactions.

Desorption Phase

In the desorption phase, typically occurring during daytime, the adsorbed water is released by heating the material. This heating is often achieved using solar energy, making the system energy-efficient and environmentally friendly. As the material's temperature rises, it loses its affinity for water, causing the stored water to evaporate. The water vapor is then condensed on a cooled surface to collect liquid water.

Key Features of the Process:

- **Passive Operation:** Adsorption occurs without external energy input.
- **Solar Regeneration:** Desorption uses low-grade heat from sunlight.
- **Cyclic Nature:** The process repeats daily, harvesting water with each cycle.
- **Low Humidity Functionality:** Effective in environments with RH as low as 10%–30%.

This two-phase process enables continuous, renewable water production even in extreme climatic conditions.

4.3 Adsorbent Materials

The performance of adsorption-based atmospheric water harvesting systems greatly depends on the choice of adsorbent material. These materials are generally classified into solid desiccants and liquid desiccants based on their physical state and water sorption mechanisms.

4.3.1 Solid Desiccants

Solid desiccants are porous, hygroscopic materials that adsorb water vapor onto their surface or within their internal pores through physical or chemical interactions. They are widely used in adsorption-based AWH systems due to their structural stability and reusability over multiple cycles.

4.3.1.1 Metal-Organic Frameworks (MOFs)

MOFs are advanced crystalline materials composed of metal ions linked by organic ligands, forming porous structures with extremely high surface areas. They are considered among the most promising materials for atmospheric water harvesting, particularly in low-humidity environments.

One of the most extensively studied MOFs for water harvesting is MOF-801, a zirconium-based framework. It has shown exceptional water adsorption capacity even at very low relative humidity levels (as low as 10%). In a field demonstration conducted in Tempe, Arizona, MOF-801 was able to produce approximately 0.25 Liters of water per kilogram of material per day under typical desert conditions. These systems work through a solar-driven adsorption-desorption cycle, making them highly energy-efficient.

Key characteristics of MOFs include:

- High specific surface area and porosity.
- Strong water uptake even in arid climates.
- Regeneration using low-grade solar heat.
- Relatively high cost due to complex synthesis.

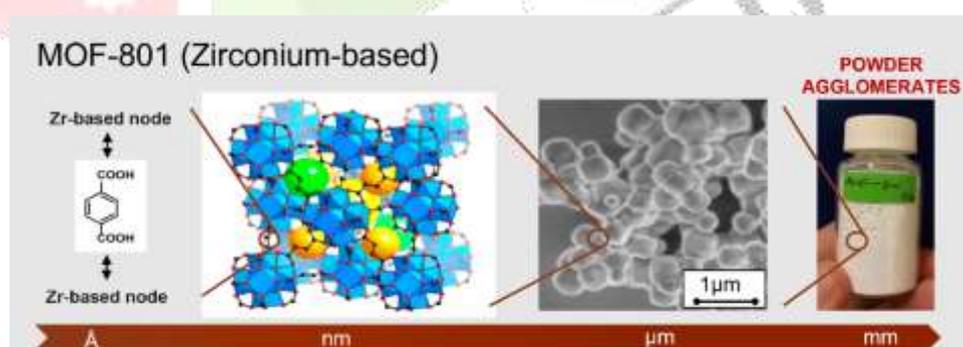


Fig 4. MOF 801

4.3.1.2 Zeolites

Zeolites are microporous aluminosilicate minerals known for their high thermal stability and strong adsorption properties. They have been traditionally used for gas separation and drying but are also suitable for AWH applications.

Zeolites offer good mechanical durability and can adsorb significant amounts of water. However, their performance under very low humidity conditions is generally lower than that of MOFs. Additionally, they require relatively high regeneration temperatures, which may increase the energy requirements of the system.

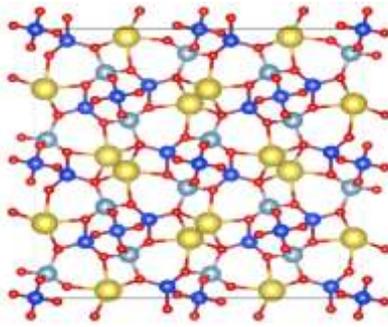


Fig 5. Crystal structure of Zeolite

4.3.1.3 Silica Gels

Silica gels are amorphous forms of silicon dioxide with a highly porous structure. They are widely available and inexpensive, making them accessible for various adsorption applications. Silica gels can adsorb moderate amounts of water vapor and can be regenerated using thermal energy, although they require higher temperatures compared to MOFs.

While they are suitable for moderate humidity environments, their performance in extremely low humidity conditions is limited. However, due to their low cost, they remain popular in less demanding applications.



Fig 6. Silica Gel

4.3.2 Liquid Desiccants

Liquid desiccants are hygroscopic solutions that absorb water vapor chemically from the atmosphere. They generally involve salt solutions with strong moisture-attracting properties. Though more common in absorption-based systems, liquid desiccants are sometimes considered in hybrid AWH technologies.

4.3.2.1 Calcium Chloride (CaCl_2) Solution

Calcium chloride is one of the most widely used liquid desiccants due to its high hygroscopicity and affordability. It can absorb large amounts of water vapor from the air but also presents challenges such as corrosion risks, handling difficulties, and potential leakage of the liquid solution. Regeneration typically requires moderate heating to release the absorbed water.

4.3.2.2 Lithium Chloride (LiCl) Solution

Lithium chloride is another highly effective liquid desiccant with excellent water absorption capacity, even at low relative humidity. However, it is more expensive than calcium chloride and may require higher regeneration temperatures or vacuum-based techniques for efficient water recovery. LiCl solutions are often used in specialized or industrial-scale applications due to their superior performance but higher cost.

4.3.2.3 Other Liquid Desiccants

Other salts, such as lithium bromide or potassium formate solutions, have also been explored for water harvesting. While they can offer high water uptake, challenges such as material degradation, leakage, and operational complexity often limit their application in basic or decentralized AWH systems.

4.3.3 Material Selection Considerations:

- Water Uptake Range: Must perform under low RH.
- Energy Requirements: Low regeneration temperatures preferred.
- Durability: Should withstand repeated adsorption-desorption cycles.
- Environmental Stability: Resistant to degradation under operating conditions.

Table 2: Classification of Adsorbent Materials for Atmospheric Water Harvesting

Feature	Solid Desiccants	Liquid Desiccants
Physical State	Solid (porous or structured material)	Liquid (aqueous salt solutions)
Common Types	MOFs, Zeolites, Silica Gels	CaCl ₂ , LiCl, other salt solutions
Water Uptake Mechanism	Adsorption (surface or pore-based capture)	Absorption (chemical bonding in solution)
Regeneration Method	Heating (usually solar or thermal)	Heating or dehumidification
Water Leakage Risk	Very low	High (possible leakage/spillage)
Thermal Stability	Generally high (especially MOFs and zeolites)	Depends on solution concentration and handling
Cost	Varies; MOFs expensive, silica gels cheaper	Generally low but varies with desiccant choice
Applications in AWH	Widely used for low-humidity water harvesting (e.g., MOFs)	Mostly in industrial/hybrid systems; less common for standalone AWH

Table 3: Comparison between characteristics and water uptake performance of various adsorbents

Material	Water Uptake(g/g)	Pros	Cons
Silica Gel	0.30–0.50	Low cost, easy synthesis	Poor recyclability
Mesoporous Silica	0.50–0.90	Hydrothermal stability	High cost
Zeolites	0.20–0.45	Hydrophilic	Poor recyclability, high desorption temperature (>200°C)
Covalent Organic Frameworks (COFs)	0.30	High selectivity, reusability	High cost
Metal-Organic Frameworks (MOFs)	0.39	High selectivity, reusability, low desorption temperature	Unstable at high humidity, high cost

4.4 Advantages

Adsorption-based atmospheric water harvesting systems offer several significant advantages that make them highly suitable for deployment in water-scarce regions. One of the most notable advantages is their ability to operate effectively in arid climates with low relative humidity. Advanced adsorbent materials such as metal-

organic frameworks (MOFs) can efficiently harvest water even at relative humidity levels as low as 10%, which is far beyond the capability of most conventional water collection methods.

These systems also make use of renewable and sustainable energy sources. Specifically, they rely on solar energy for the desorption phase, reducing operational costs and minimizing environmental impact. The adsorption phase itself is entirely passive, meaning it does not require electricity or mechanical components to capture moisture from the air. This simplicity in design allows the systems to function efficiently in off-grid and remote locations, where conventional energy infrastructure is absent or unreliable.

Another key advantage of adsorption-based AWH systems is their scalability. They can be designed to suit a wide range of needs, from small household units to larger community-scale installations. The systems also offer high specific water production rates, with some advanced materials like MOF-801 demonstrating the ability to produce approximately 0.25 Liters of water per kilogram of adsorbent per day in real-world field tests under arid conditions.

Additionally, these systems generally require minimal maintenance due to the absence of complex moving parts, making them easy to operate and maintain over long periods. Their modular nature also allows integration with other renewable energy technologies, such as photovoltaic systems, for enhanced water production, making them a versatile option for water harvesting in diverse environments.

4.5 Disadvantages

Despite their promising features, adsorption-based atmospheric water harvesting systems do have certain limitations that need to be addressed before they can be widely adopted. One major drawback is the high cost of advanced adsorbent materials, particularly metal-organic frameworks. The synthesis of MOFs often involves complex chemical processes and expensive raw materials, which raises the overall cost of the system and may restrict its use in low-income regions or for large-scale applications.

Another limitation is the relatively limited long-term performance data available for these systems. While initial studies and short-term experiments have shown excellent water harvesting potential, the long-term durability and performance of these materials under continuous daily operation in real-world conditions remain areas of active research.

These systems are also heavily dependent on solar irradiation for the desorption process. In locations with frequent cloud cover or limited sunlight, their performance may be reduced, affecting daily water yields. Furthermore, although adsorption-based systems perform well in low-humidity environments, their total water output may still be lower than mechanical condensation systems in regions with high humidity.

Material degradation over time presents another concern. Certain adsorbent materials may experience a reduction in efficiency or structural breakdown after many adsorption-desorption cycles, potentially requiring replacement or reactivation. In the case of liquid desiccants, there are additional risks such as leakage, corrosion, and chemical handling challenges, which complicate system design and operation.

Finally, some systems involving liquid or salt-based adsorbents may require more complex handling and operational control to prevent environmental hazards or operational failures. These issues highlight the need for further research, material optimization, and cost reduction strategies to enable the wider adoption of adsorption-based atmospheric water harvesting technologies.

5. SYSTEM CONFIGURATIONS AND DESIGN CONSIDERATIONS

This case study is based on the research article titled "*Water harvesting from air with metal-organic frameworks powered by natural sunlight*" by Yaghi et al., published in Nature Communications in 2018. The study demonstrates an advanced adsorption-based water harvesting system specifically designed for arid climates.

5.1 Introduction

Water scarcity poses a critical challenge in arid and semi-arid regions, where conventional water supply methods such as desalination, groundwater extraction, and wastewater treatment are often impractical due to high costs, limited infrastructure, or unsuitability to local climates. The atmospheric water harvesting (AWH) technology presented in this case study offers an innovative solution for such regions, utilizing a sorbent-based process to extract water vapor from the atmosphere even at low relative humidity conditions. The device

developed in this study employs metal-organic framework (MOF)-801 as the adsorbent material, which has been proven effective in low-humidity environments.

The study was conducted in Tempe, Arizona, USA, where day-time relative humidity can drop to as low as 10% and dew points are often below zero. In such extreme climates, conventional refrigeration-based atmospheric water generators (AWGs) fail due to their high energy demands and inefficiency under low humidity. The sorbent-based AWH system described here offers an energy-efficient alternative by using solar thermal energy for the water desorption process. This technology enables water capture with minimal infrastructure, making it suitable for decentralized water production in remote and arid locations.

5.2 Device Design and Operation

The device operates based on a single daily adsorption-desorption cycle that harnesses natural humidity fluctuations between night and day. During the night, when ambient humidity is relatively higher (20%–40% RH), the MOF-801 adsorbs water vapor from the air. The device design incorporates an adsorbent layer and an air-cooled condenser housed within an insulated enclosure. The back side of the MOF layer is coated with black solar-absorbing paint to maximize heat absorption during the day.

At night, the enclosure's side walls are opened to allow the free flow of ambient air over the MOF layer. Passive radiative cooling, facilitated by exposure to the night sky, reduces the MOF's temperature below the ambient, effectively enhancing its water adsorption capability. During the day, the enclosure is sealed, and the MOF layer is covered with an optically transparent thermal insulating aerogel (OTTI aerogel) to minimize heat losses. Solar energy heats the MOF layer, causing the desorbed water vapor to move toward the condenser, where it is cooled and collected as liquid water.

The device is carefully optimized to suit the local climate. The MOF-801 layer, embedded in a porous copper foam for enhanced thermal conductivity, has a high packing porosity and specific thickness to ensure rapid water uptake during the night. The condenser is made of a copper plate coupled with a commercial air-cooled heat sink to efficiently dissipate heat during the condensation process. Experimental results demonstrated the device's ability to achieve effective adsorption within an 8-hour night cycle, followed by complete desorption during daytime, even under extremely arid conditions.

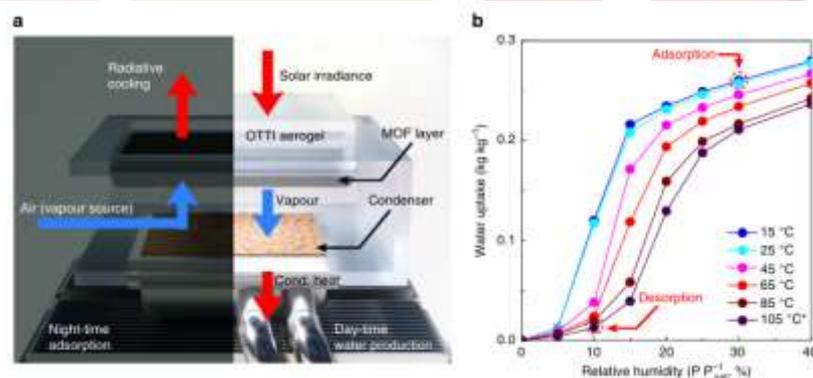


Fig 7. a) Working principle of the MOF-801-based water harvesting device b) Water adsorption isotherms of MOF-801

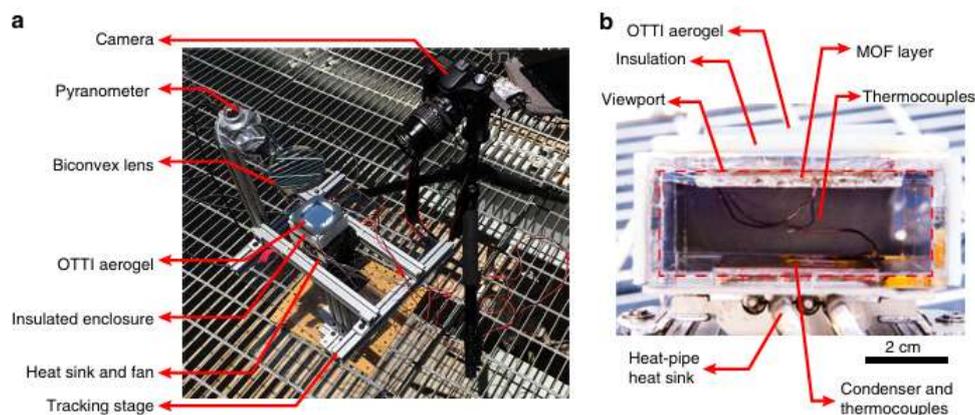


Fig 8. Water harvesting device test apparatus

5.3 Water Harvesting Experiments

Field experiments were conducted over multiple cycles between May 11 and May 18, 2017. Each cycle consisted of night-time water vapor adsorption and day-time water desorption and condensation. During night-time operation, passive radiative cooling consistently reduced the MOF layer's temperature by approximately 3°C below the ambient, effectively increasing the local relative humidity experienced by the adsorbent by about 5% to 7%. This cooling effect enhanced water uptake during the adsorption phase.

In the morning, the MOF layer was sealed inside the device before the relative humidity began to decrease. Desorption was initiated by exposing the device to solar radiation. Two experimental setups were tested: one under natural sunlight and another with an optical concentration of 1.8× using a biconvex lens. The tilted design of the device allowed for buoyancy-assisted vapor transport, which accelerated condensation.

Although the amount of water collected was too small for direct measurement due to the limited quantity of MOF used (~3 g), the researchers used computational models validated with experimental data to predict the harvested water quantity. Without optical concentration, the device achieved a predicted water yield of 0.12 Liters per kg of MOF per day, while with optical concentration, the yield increased to approximately 0.28 Liters per kg of MOF per day. The optical concentration improved thermal efficiency by nearly 5 times, reaching up to 14% thermal efficiency compared to 3% in the non-concentrated case.

5.4 Prediction of Harvested Water

High-precision computational simulations were employed to predict the water harvesting potential under varying conditions. These simulations incorporated real-time measurements of ambient temperature, solar flux, and relative humidity, providing an accurate estimate of water production. In the non-concentrated trials, the device achieved an equilibrium water uptake of 0.28 kg of water per kg of MOF-801 during night-time adsorption. After the desorption process, residual water content in the MOF was reduced to approximately 0.16 kg/kg, resulting in a net water yield of around 0.12 Liters per kg per day.

For cycles involving optical concentration, the MOF layer reached temperatures as high as 100°C, which significantly enhanced the desorption process. Under these conditions, the system achieved near-complete desorption, producing about 0.28 Liters of water per kg of MOF per cycle. The simulation results matched well with experimental observations, confirming the effectiveness of optical concentration and device tilting in enhancing water recovery.

The results also showed that the device could deliver about 0.34 Liters of water per square meter of MOF base area per cycle with concentrated solar input, highlighting its scalability for larger applications. This demonstrates that such systems can achieve meaningful water production in extremely dry climates.

5.5 Water Quality Analysis

An essential aspect of the study was to ensure the quality of the harvested water. The researchers conducted detailed chemical analyses to confirm that no harmful substances leached from the MOF-801 material during the adsorption-desorption cycles. Using inductively coupled plasma-mass spectrometry (ICP-MS) and infrared spectroscopy, the harvested water was tested for potential contaminants such as zirconium ions (from the MOF) and organic linker residues.

The analysis showed that the concentration of zirconium in the harvested water was below 1 part per billion (ppb), well within safety limits, and no traces of organic linkers were detected. This confirmed that MOF-801 remained stable throughout the cycles and that the harvested water was free from contamination, making it safe for potable or other uses.

5.6 Key Findings from the Case Study

This case study clearly demonstrates the potential of adsorption-based AWH systems for efficient water production in arid regions. By leveraging solar thermal energy and advanced adsorbent materials like MOF-801, the system provides a sustainable, low-energy solution for water harvesting in harsh climates with limited water resources. Its passive design, scalability, and clean water output make it highly promising for decentralized water supply in remote areas.

6. RECENT ADVANCEMENTS AND FUTURE DIRECTIONS

Recent research has focused on developing low-cost, high-performance adsorbent materials and improving system designs to enhance energy efficiency and water production rates. Innovations such as solar-driven MOF-based harvesters have demonstrated the feasibility of producing water in desert environments with minimal energy input.

Future research should prioritize the development of environmentally friendly and cost-effective adsorbents, as well as the integration of renewable energy sources for system operation. Additionally, efforts to improve system scalability and durability will be critical for enabling widespread deployment in water-scarce regions. The use of advanced computational modelling and machine learning techniques to optimize material properties and system configurations represents another promising avenue for future development. Furthermore, hybrid systems that combine adsorption-based AWH with other water harvesting technologies may offer enhanced performance and reliability.

7. CONCLUSION

Water scarcity remains one of the most pressing challenges of the modern world, particularly in arid and semi-arid regions where conventional freshwater sources are either severely limited or entirely absent. With growing population demands, climate change impacts, and increasing water stress, the need for alternative and sustainable methods to secure water supplies has never been more urgent. Atmospheric water harvesting, especially adsorption-based technologies, offers a promising solution to address this issue by tapping into the vast and underutilized reservoir of atmospheric moisture.

Adsorption-based atmospheric water harvesting technologies are uniquely capable of operating under low-humidity conditions, making them highly suitable for deployment in regions where traditional methods such as groundwater extraction, desalination, or fog collection are ineffective. These systems make use of advanced adsorbent materials, such as metal-organic frameworks (MOFs), which can efficiently capture and release water vapor even when relative humidity is as low as 10%. The process typically relies on solar energy for desorption, allowing water to be harvested with minimal external energy inputs, thus promoting energy efficiency and environmental sustainability.

One of the most notable advantages of adsorption-based systems is their ability to function in off-grid and decentralized settings. Their modular design enables flexibility in scale, from small, individual units to larger systems capable of serving entire communities. In addition, the passive and renewable operation of these systems significantly reduces maintenance needs and operational costs over time, making them attractive for long-term use in remote and water-scarce areas.

Field demonstrations have shown that adsorption-based atmospheric water harvesting is not only technologically feasible but also capable of delivering clean, safe drinking water without the need for complicated mechanical systems. Water quality analyses from these systems have confirmed the absence of harmful contaminants, ensuring the suitability of harvested water for consumption and other uses.

While the high initial cost of certain advanced adsorbent materials remains a challenge, ongoing research and developments in material science are expected to improve the affordability, scalability, and efficiency of these systems. Innovations aimed at reducing material costs, improving adsorption capacity, and enhancing system durability are key to expanding the practical use of this technology worldwide.

Overall, adsorption-based atmospheric water harvesting represents a significant advancement in the field of sustainable water resource management. Its ability to operate in challenging climates, reliance on renewable energy, and low environmental footprint make it a compelling solution for future water security. As water stress intensifies globally, technologies like adsorption-based atmospheric water harvesting are likely to play an increasingly vital role in ensuring access to clean, reliable, and sustainable water sources across a wide range of regions.

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