Science of the Total Environment 958 (2025) 177885

Contents lists available at ScienceDirect

Science of the Total Environment

journal homepage: www.elsevier.com/locate/scitotenv

Review

A comprehensive review of approaches, systems, and materials used in adsorption-based atmospheric water harvesting

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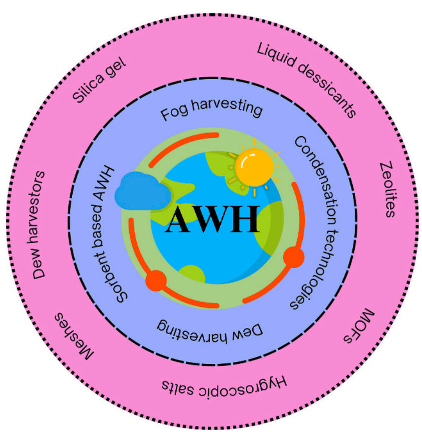
HIGHLIGHTS

- AWH addresses water scarcity, aiding 4.3B people lacking clean water access.
- The atmosphere holds 13,000 T liters of water vapor, a vast AWH resource.
- SBAWH is effective in arid and humid areas using advanced adsorbent materials.
- MOFs excel in water adsorption, surpassing traditional AWH materials.
- Continued AWH research is key to improving global water collection efficiency.

GRAPHICAL ABSTRACT



ARTICLE INFO

Editor: Damià Barceló

Keywords
Wastewater
Atmospheric water harvesting
Drinking water
Sustainability, water scarcity

ABSTRACT

Atmospheric water harvesting (AWH) is one of the most efficient, sustainable, cost-effective, and promising techniques for addressing world's water scarcity. Over 4.3 billion people around the world struggle to access clean, abundant, and safe drinking water. Additionally, >3.3 million people die each year due to drinking poor quality water. Meanwhile, our atmosphere contains approximately 13,000 trillion liters of water in the form of vapor. Therefore, AWH offers a viable solution to meet the demand for drinking water, even in arid or high humidity regions. AWH can be achieved through methods such as fog harvesting, dew harvesting and sorption-based atmospheric water harvesting (SBAWH). The main aim of this manuscript is to explore the potential of Sorption-Based Atmospheric Water Harvesting (SBAWH) as a solution to the global water scarcity crisis. The study focuses on evaluating the adsorption capacities and performance of various sorbent materials, systems, and devices used in SBAWH. Notably, materials such as silica gel, zeolite, hygroscopic salts, and metal-organic frameworks (MOFs) are highlighted, with MOFs and their composites being recognized as some of the most efficient options for atmospheric water harvesting. This review emphasizes the critical role of AWH techniques in addressing the pressing issue of global water shortages.

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https://doi.org/10.1016/j.scitotenv.2024.177885
Received 25 September 2024; Received in revised form 29 November 2024; Accepted 1 December 2024
Available online 10 December 2024

1. Introduction

Water is essential for life. Water is used across multiple sectors: domestically for daily needs, in industry for various purposes, in agriculture for growing crops, and as a resource for generating electricity. Earth is often referred to as the blue planet because >70 % of its surface is covered with water (Nandakumar et al., 2019).

According to a survey by the World Health Organization (WHO), 97.5 % of the water on Earth is salty, while only 2.5 % is freshwater. Of this 2.5 % approximately 70 % is frozen in ice caps, while 30 % is found in lakes and underground aquifers. According to all these calculations, it is estimated that <1 % of Earth's freshwater is available for direct human use (El-Ghonemy, 2012).

Water scarcity is an alarming situation for countries worldwide (Liu et al., 2017). One third of the global population lacks access to quality drinking water (Organization, 2019). Over 4.3 billion people struggle to find clean, abundant, and safe drinking water (Mekonnen and Hoekstra, 2016).

According to the literature, nearly 3 billion people worldwide lack access to adequate water resources. Additionally, approximately 3.3 million deaths occur each year due to the consumption of water that is unsafe for health (Macedonio et al., 2012). Meeting the global demand for safe, high quality drinking water remains a significant challenge. Projections suggest that by 2050, the world's population will reach 9.7 billion, exacerbating the issue of water scarcity (Shafeian et al., 2022).

Water scarcity is expected to worsen annually due to factors such as population growth, unsustainable water consumption, overexploitation of water resources, climate change and economic development. Consequently, researchers are focused on developing innovative methods and techniques to address the growing demand for fresh drinking water. Various approaches, including wastewater treatment (Fortunato et al., 2020), desalination and atmospheric water harvesting (AWH) have been proposed to ensure access to safe drinking water (Das et al., 2023). One method is wastewater treatment, where toxic pollutants like Cr(IV), Co(II), Cu(II), As(III), and Pb(II) are removed from water through chemical precipitation (Huang et al., 2012) (Das and Poater, 2021), ion exchange (Li et al., 2016), and by adsorption process (Han et al., 2023). In most cases the adsorption method is used because of its simplicity, fast separation, low cost, and easy recyclability of adsorbents (Kaur et al., 2023),(Rani et al., 2020). Even though there are lots of disadvantages associated with wastewater treatment, the cost of installing the filters and pipes is high. Even water filtration plants require frequent replacement of filters and pipes every few months, which increases the overall cost of the process. Additionally, water purifiers consume a significant amount of energy, making them expensive to operate. On the other hand, desalination is another method used to obtain freshwater, but it has notable disadvantages. The disposal of salts is challenging, and excessive salt in the soil can harm plants, vegetables, and wildlife. Furthermore, the reverse osmosis process used in desalination removes essential minerals from saline water. According to the literature, desalinated seawater can cost up to $5.80 per 1000 gal. Finally, another method that has gained increasing popularity in recent years is AWH. It is estimated that approximately 13,000 trillion liters of water are present in the atmosphere in the form of vapor, which exceeds the total amount of water stored in Earth's lakes, rivers, seas, and groundwater combined.

There are numerous bacteria, toxic gases, dust particles, and pollutants, including nano/microplastics, in the atmosphere. A crucial question arises: is water obtained through Atmospheric Water Harvesting (AWH) techniques safe for drinking? Yao et al. (Yao et al., 2020) proposed a hybrid system based on a porous sodium polyacrylate/graphene framework (PGF), which has a high affinity for adsorbing water vapor, even in contaminated environments. This material demonstrates a high water uptake of 5.2 g/g at a relative humidity of 100 % and can remove up to 96 % of harmful particles from drinking water produced through the AWH process. Kaplan et al. (Kaplan et al., 2024) designed a strategy to examine the effects of various pollutants—such as metal ions, anions, volatile organic compounds (VOCs), polyaromatic hydrocarbons, polychlorinated biphenyls, ammonia, total organic carbon, and coliforms—in an industrial area on water produced by the AWH process. Their study found only trace amounts of pollutants, with ammonia being an exception. Kinder et al. (Kinder et al., 2017) suggested that air quality should be assessed prior to AWH operations.

This review focuses on the various adsorbent materials, methods, and systems used in AWH techniques. It raises key questions, such as: Why is one technique superior to another? What are the pros and cons of each approach? Is the water produced through AWH safe for drinking? What are the economic costs associated with AWH techniques? And why is SBAWH preferable to other methods? We also present mechanisms for systems that may be employed in the future to address water scarcity challenges.

1.1. *Causes of water shortage*

Water is crucial, yet it remains insufficient in many parts of the world. Globally, more than two billion people lack access to safe water for consumption, and over four billion experience water shortages for at least one month each year. The causes of water scarcity are diverse (Fig. 1), ranging from natural factors to human-induced issues (Tarrass and Benjelloun, 2011).

1.1.1. *Natural causes*

Natural contributors to water scarcity include global warming, severe storms, and deforestation. In some regions, water supply has decreased due to increased evaporation caused by rising global temperatures. Another factor is drought, which involves extended periods of minimal rainfall, often leading to crop failure, food shortages, and financial loss (Talpur, 2001). Flooding, though seemingly abundant in water, can also disrupt access to clean water. Additionally, deforestation—the removal of trees for industrial or agricultural purposes—further exacerbates water shortages. Forests play a critical role in the water cycle, and their destruction can reduce the availability of water in affected areas (Qiu, 2010).

1.1.2. *Human-made causes*

Human-induced causes of water shortages include population growth, development, overuse of water resources, pollution, and ineffective water management practices. Expanding populations and increasing urbanization have heightened the demand for water in domestic, industrial, and agricultural sectors. These pressures strain water resources, leading to overuse and depletion (Di Baldassarre et al., 2018).

Water contamination is a significant factor contributing to shortages. Major sources of contamination include industrial waste, agricultural chemical runoff, and domestic sewage, which pollute water supplies and make them unsuitable for agriculture or human consumption. However, we cannot forget the increase in waste from consumed drugs as well as pharmaceutical substances (Hernando et al., 2006) (Postigo and Barceló, 2015). Additionally, inefficient water management—such as leaking pipes—can lead to the wastage of valuable water resources (Wan et al., 2019).

1.2. *Methods for obtaining fresh water*

Diversified strategies are essential to tackle the issue of water scarcity. Educational initiatives can raise awareness about the importance of water conservation, spreading knowledge about the effects of water shortages and promoting effective water management techniques in schools and institutions to influence behavior. Governments play a crucial role in addressing water shortages by implementing pricing systems for water, offering subsidies for adopting water-efficient technologies, and enforcing regulations to prevent water pollution. Potential solutions to water scarcity include groundwater extraction, desalination, wastewater treatment, and AWH.

1.2.1. Groundwater extraction

Groundwater is water that infiltrates reservoirs and accumulates underground in cracks, crevices, gravel, and soil (Patil and Desai). 97 % of the planet's usable drinking water is found within the Earth's crust, while the remaining 4 % is in surface water sources such as rivers and streams (Council et al., 1994). According to the United States Geological Survey, groundwater can be located near the surface or at depths of up to 9000 m (Bartolino and Cole, 2002). One of the advantages of groundwater is that it often requires less treatment than surface water, reducing pressure on existing surface water sources. It also provides an additional source of water in regions where surface water is scarce, offering a reliable supply of clean, uncontaminated water.

However, excessive extraction and overuse, especially in recent decades, threaten the sustainability of groundwater (Fig. 2). It is primarily used for drinking, residential purposes, agriculture, and electricity generation. In addition to the rapid depletion of aquifers, water quality is deteriorating, and groundwater supplies are diminishing.

Some regions, such as northwestern India, China, the Middle East, and the western United States, are already experiencing the effects of groundwater depletion. These areas are often dry or semi-arid, with unreliable surface water sources, making groundwater the only viable freshwater option (Vandenbohede et al., 2009). China, India, America, and Pakistan together extract around 325 km^3 of groundwater annually (Zhu et al., 2007). The methods of extraction depend on factors such as the depth at which water is found, its purity, and its intended use. As shallow reservoirs dry up, deeper wells are required, leading to higher pumping costs. Deeper wells demand more energy and expensive technologies to bring water to the surface.

1.2.2. Wastewater treatment

As the global population continues to rise, the demand for industries such as textiles and paper manufacturing also increases. These industries often release toxic and organic pollutants directly onto the ground or into bodies of water, such as lakes, rivers, and seas. These pollutants have detrimental effects on marine life and aquatic plants, and when polluted water is consumed by humans, it can lead to waterborne diseases.

1.2.3. Adsorption of heavy metal ions

Industries like electroplating, oil refineries, mining, and battery manufacturing release large quantities of toxic and carcinogenic ions into water, including Cr(IV), Co(II), Cu(II), As(III), and Pb(II). Exposure to these pollutants can cause serious health issues in humans, including mental retardation, anemia, cancer, and damage to the nervous system (Ghorai et al., 2012).The heart, bones, kidneys, and nervous system are particularly vulnerable to excess Pb(II) intake, while excessive Cu(II) can cause stomach cramps, nausea, diarrhea, and vomiting (Mittal et al., 2015). Researchers have developed various methods to adsorb these heavy metal ions from water (Table 1). For instance, a hydrogel composed of carboxymethyl cellulose (CMC) and polyethyleneimine (PEI) has been shown to remove Cr(VI) ions (Song et al., 2019). Cu(II) and Pb(II) ions can be removed from water using a hydrogel composed of Gum Ghatti-grafted with Poly (acrylamide-*co*-acrylonitrile) (Mittal et al., 2015). Meanwhile, L-Histidine immobilized montmorillonite has been used to adsorb As(III), with an adsorption capacity of 87.7 mg/g (Batool et al., 2022).

1.2.4. Removal of organic pollutants

The primary sources of organic pollutants include detergents, petroleum hydrocarbons, plastics, organic solvents, and pesticides (Geetha and Nagarajan, 2021). Various methods can be employed to remove these organic pollutants from water such as ultrasonic degradation methods (Ji et al., 2021) and adsorption methods (Lee et al., 2018). Hydrogels are particularly effective in absorbing and degrading organic substances due to their porous structure and functional surface groups. A research group successfully degraded organic pollutants using a polyacrylic acid-based hydrogel composed of cobalt hydroxide and graphene oxide (Yi et al., 2020).

1.2.5. Desalination process

Desalination is the process of removing excess salts and other dissolved chemicals from seawater (Darre and Toor, 2018). According to the International Desalination Association (IDA), by 2019, over 17,000 desalination plants were operating worldwide, producing 95 million m^3 of fresh water daily (Soliman et al., 2021). The average salinity of seawater is approximately 35,000 mg per liter (Shahzad et al., 2017). Desalination is achieved through two main systems: thermal-based and membrane-based systems.

1.2.5.1. Thermal-based system. In thermal-based desalination technology, heat is applied to evaporate saline water, and the resulting water vapor is condensed to yield fresh water. The humidification-dehumidification (HDH) system consists of humidifiers, dehumidifiers, and heaters (Fig. 3a).

The humidifier has three sections: seawater is sprayed from the top, passes through a packing bed for mass and heat transfer with a carrier gas, and brine is collected at the bottom. The inlet air is humidified by contact with salty water. In the dehumidifier, hot, humid air contacts

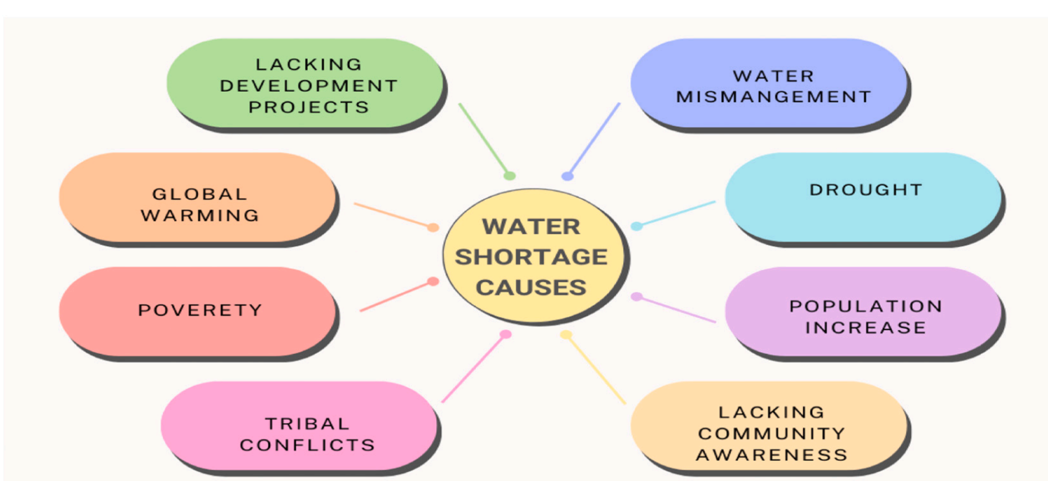


Fig. 1. Causes of water shortage.

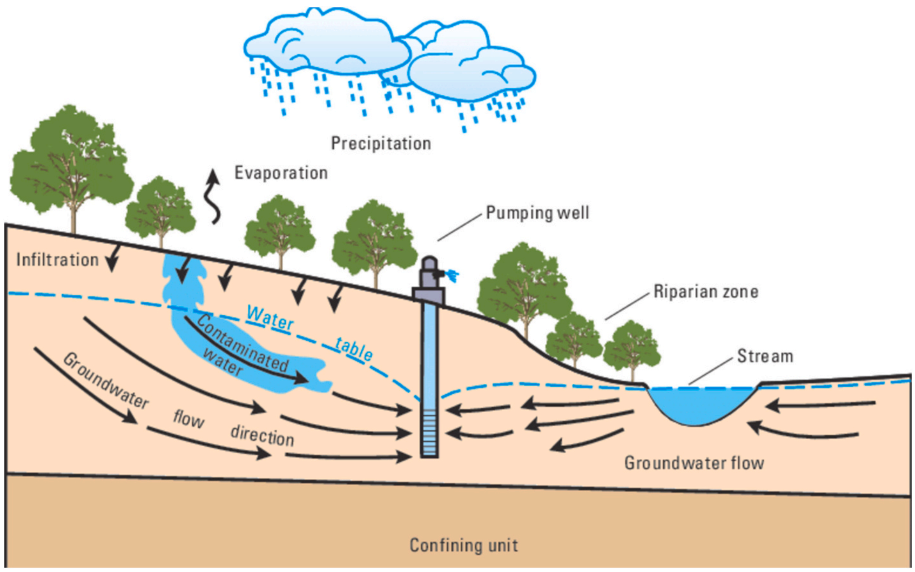


Fig. 2. Extraction of groundwater (Domagalski and Johnson, 2012).

Table 1
Different types of Sorbents used for metal ion adsorption from water.

Sr. No	Hydrogels	Metal ions	Adsorption capacity(mg/g)	pH	References
1.	Chitosan Chitin cellulose	Cu^{+2} Pb^{+2} Cd^{+2}	192.31 393.28 289.97	4.2 3.0 3.0	(Liao and Huang, 2019) (Zhao et al., 2019) (Zhao et al., 2019)
2.	Glucan /Chitosan	Co^{+2}	332.2	7.0	(Jiang et al., 2019)
3.	Chitosan alginate	Cr^{+6}	148.1	3.0	(Mei et al., 2019)
4.	L-Histidine immobilized montmorillonite	As^{3+}	87.7	6.0	(Batool et al., 2022)

cold saline water containing condensing coils, where condensation occurs, producing fresh water (Mohamed et al., 2021).

1.2.5.2. Membrane-based system. Another common method for desalination is the reverse osmosis (RO) membrane-based technique (Fig. 3b). This method operates on the principle of reverse osmosis, where saline water is forced through a semipermeable membrane by applying external pressure.

This applied pressure must exceed the osmotic pressure for the process to occur. The semipermeable membrane allows water molecules to pass through while blocking salt and other pollutants (Saleem and Zaidi, 2020).

1.3. Challenges related to desalination

The average cost of desalinating one cubic meter of seawater ranges between $0.70 and $0.90 (Elsaie et al., 2022). The brine discharged from desalination plants contains 80–90 % dissolved salts and other solid substances, with approximately 70,000 ppm of dissolved salts in the brine (Ahmad and Williams, 2011). Global brine production from

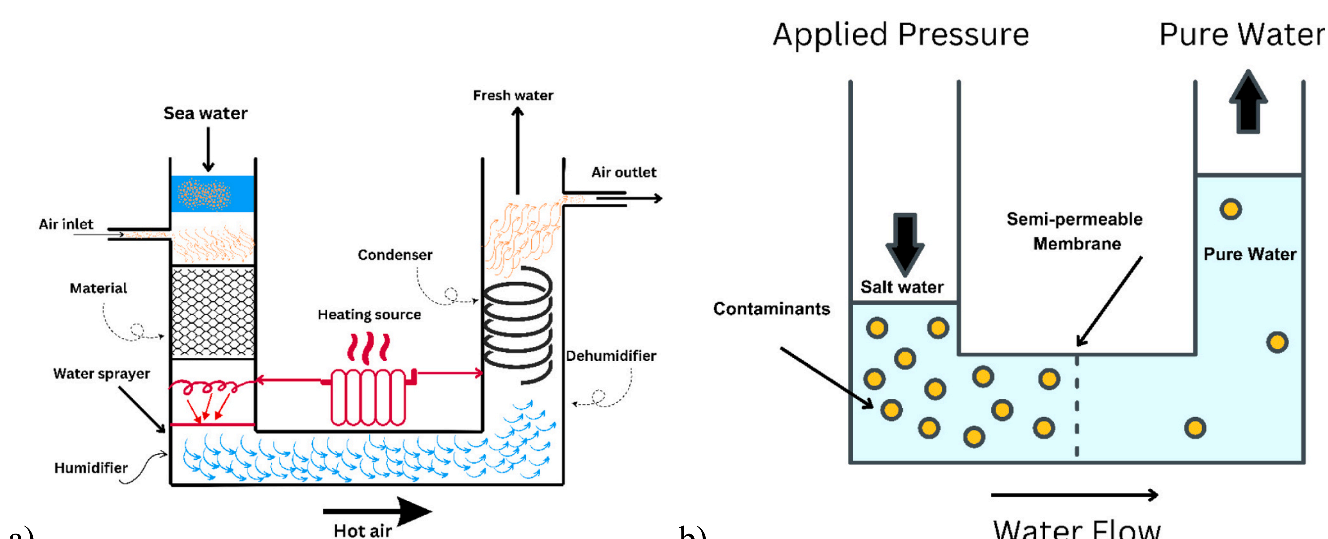


Fig. 3. a) Thermal based system and b) Membrane based system.

desalination plants exceeds 142 million cubic meters per day (Jones et al., 2019). Despite its benefits, desalination has several drawbacks, including high energy consumption and the challenge of salt disposal. Many industries discharge brine directly into seas and rivers, negatively impacting aquatic life and humans. Increased salt levels in the environment can harm plants, wildlife, and agriculture (Aziz and Hanafiah, 2021).

2. Atmospheric water harvesting (AWH)

An increasing population drives higher water demand. Atmospheric water, a renewable resource, offers a potential solution. Research shows that the atmosphere contains around 13 trillion liters of water, equivalent to 10 % of the Earth's total freshwater supply found in rivers and lakes (Li et al., 2018). This water exists as vapor and droplets (Zhou et al., 2020).

Various AWH techniques are categorized into active and passive cooling methods (Fig. 4). Passive cooling techniques require no external energy, while active techniques rely on energy input (Raveesh et al., 2021). These methods are influenced by geographical location, relative humidity and energy demands. Among all other techniques, sorption-based atmospheric water harvesting (SBAWH) has attracted significant attention due to its high efficiency, good adsorption capacity, and low energy consumption. One of the major advantages of SBAWH is that this system can function in arid regions with relative humidity below 20 % and without electricity (Kim et al., 2017). The psychrometric properties of atmospheric air, such as relative humidity and dew point temperature, determine the most suitable AWH technology for a given location (Salehi et al., 2020).

2.1. Active refrigeration

The principle of active refrigeration is that the atmospheric air is cooled below its dew point to generate water droplets. The term 'active' indicates that the process consumes energy. In this process, both the temperature and pressure of the system must be reduced to convert water into liquid. The basic components of active refrigeration include condensers, evaporators, compressors, and valves. This method can produce significant amounts of liquid water, with an average production of around 1000 m^3/day. However, it requires a substantial amount of energy, making it energy-intensive.

2.2. Vapor compression system

The vapor compression system operates between hot and cold reservoirs. Its essential components included in Fig. 5a are compressors, evaporators, expansion valves, and condensers. In this system, the refrigerant adsorbs heat from warm air passing through the evaporator, turning it into vapor.

These refrigerant vapors are then compressed to increase temperature and pressure. The vapors are finally passed through condenser coils, cooling them back into a liquid state. The temperature and pressure of the liquid are further reduced using expansion valves, ultimately yielding liquid water (Al-Farayedhi et al., 2014).

Active refrigeration and vapor compression systems are energy-intensive processes. In addition to high energy requirements, both processes use CFCs, which contribute to ozone depletion. Moreover, these techniques are ineffective in arid regions where the dew point temperature is below 15 °C (Wang et al., 2018).

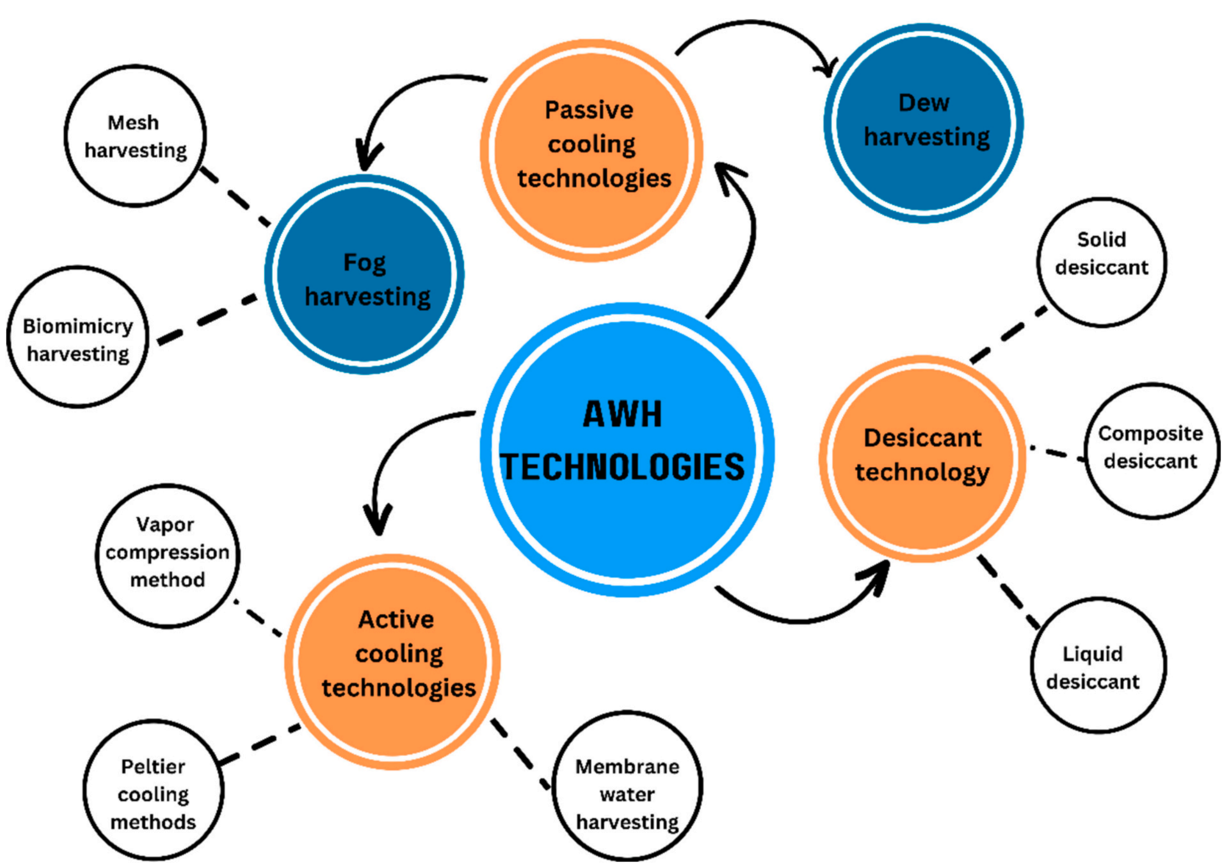


Fig. 4. Atmospheric water harvesting.

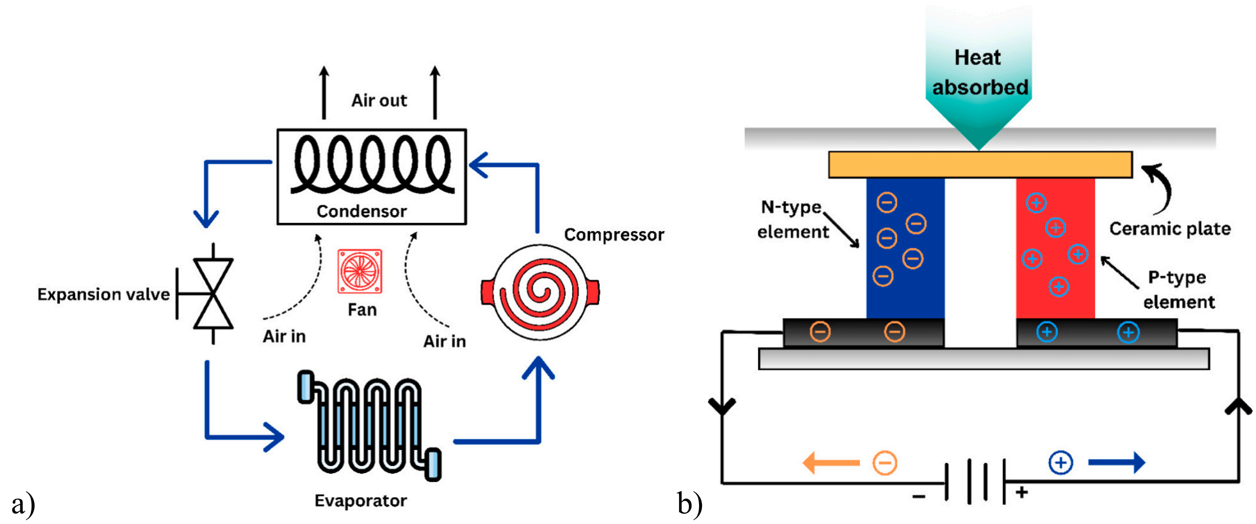


Fig. 5. a) Vapor compression system and b) Thermoelectric cooling system.

2.3. *Thermoelectric cooling system*

The thermoelectric cooling system utilizes the principle of the Peltier effect to extract water from the atmosphere. In this process in Fig. 5b, an electric current flows through a thermocouple made of two semi-conductor materials, absorbing heat on one side and releasing it on the other (Drebushchak, 2008). The region where heat is absorbed becomes the cooling region, which is used to condense water vapor from the atmosphere into liquid form (Tu and Hwang, 2020).

2.4. *Passive cooling*

The term "passive" refers to the collection of water through natural phenomena, such as coalescence, without requiring energy input. This concept can be applied in refrigeration for harvesting.

2.4.1. *Dew harvesting*

The term Dew refers to small droplets of water that form on a surface when the temperature drops. Dew formation depends on several factors like relative humidity and temperature of the environment. Dew harvesting involves using specialized devices, known as dew harvesters. Research shows that the geometry of the collector impacts the yield, with hollow structures outperforming planar ones due to atmospheric pressure and wind resistance factors (Beyssens et al., 2013).

2.4.2. *Fog AWH*

Fog harvesting extracts water from fog particles, which range from 1 to 30 μm in diameter (Schemenauer and Cereceda, 1992). Some organisms like the Namib desert beetle (Xu et al., 2018), spider silk, and cactus spines, have surface features that enable them to capture water from fog (Xu et al., 2018). This technique, while location-dependent, can be implemented using meshes and screens. Fog particles condense on these surfaces to form water droplets. The efficiency of fog AWH is influenced by fog density and the size and shape of the nets, making it a simple, cost-effective method for collecting water (Abdul-Wahab and Lea, 2008).

2.4.3. *Water vapor concentration*

In refrigeration-based AWG systems, significant energy is used to cool incoming air, which contains water vapor mixed with non-condensing gases. The vapor concentration method offers a more energy-efficient approach by concentrating water vapor using sorption techniques or selective membranes. The efficiency of sorption-based systems is evaluated by measuring the water production relative to the mass of sorbent material used.

2.4.4. *Sorption-based atmospheric water harvesting (SBAWH)*

In recent years, many scientific institutions worldwide have shown growing interest in exploring adsorption technology for capturing water from atmospheric humidity. Unlike other methods, SBAWH systems excel at producing water in low humidity conditions, making them versatile for various climates, from deserts to tropical areas. However, SBAWH systems require more energy to generate water as humidity decreases, since the thermal conductivity of both the desiccant and the body of the devices remains constant.

In the context of SBAWH the adsorption process can increase the pressure of water droplets within the system through an open and periodic cycle. The basic principle involves exposing the adsorbent to ambient air, where it absorbs moisture due to its hydrophilic properties. Once the material has absorbed sufficient moisture, the system is closed, and the adsorbent is heated, reducing its ability to retain water. This heating causes the release (desorption) of water vapor, which increases the pressure within the system. The water vapor then condenses, forming droplets that can be collected (Saeed-Ul-Hassan et al., 2024). Once the system is sealed, the adsorbent material undergoes thermal treatment. As the temperature of the desiccant rises, its hydrophilic properties decrease, causing water molecules to desorb. This release of water vapor increases the partial pressure within the system. The vapor then condenses as it comes into contact with a colder surface, forming water droplets. Once these droplets grow large enough, gravity pulls them down into the collection tank.

Moisture harvesters in AWH systems employ either absorption or adsorption mechanisms to capture water molecules from the air, making them key to efficient water collection (Cao et al., 2012; Ehtisham et al., 2024). Absorption and adsorption are processes involving the attachment of water molecules to materials, either physically or chemically. Absorption occurs when water molecules penetrate a substance, altering its composition and size, and may involve either chemical bonds or physical interactions (Butt et al., 2013).

The extent of chemical absorption depends on the concentration and interaction components, whereas physical absorption is typically influenced by capillary effects. Hygroscopic materials, often used in moisture harvesters, utilize both mechanisms through hydration (Kallenberger and Fröba, 2018).

Adsorption, on the other hand, is a surface phenomenon where molecules adhere to material exteriors through chemisorption (strong chemical bonds) or physical adsorption (weaker forces) (LaPotin et al., 2019). Chemisorption involves strong binding sites, such as hydrogen bonding or electrostatic forces, with a significant energy barrier (80–400 kJ/mol), typically irreversible without an external energy source. Understanding the thermodynamics of adsorption is crucial for enhancing moisture-harvesting materials (Canivet et al., 2014).

Shukla et al. (Shukla et al., 2024) designed an AWH system based on the principle of active cooling condensation, which is effective for water harvesting in extremely dry and hot environments (temperature = 49 °C, RH = 12 %). This system achieved a 70 % increase in water harvesting performance under such conditions, raising the water harvesting rate from 0.3 to 0.5 L/h by humidifying the air at a relative humidity of 50–60 %. Tao et al. (Tao et al., 2024) proposed a sandwich-like structure that combines a thermoelectric cooler (TEC) with two layers of MIL-101(Cr), which performs well in arid regions with low temperature and low relative humidity. When a DC voltage is applied to the TEC, heat transfers from one end of the MOF to the other: the cold side captures water, while the hot side releases it. This system demonstrated an increased water adsorption capacity of 3.7 L/kg·day at 30 % RH and 25 °C. Weng et al. (Weng et al., 2024) introduced a continuous, multi-cycle sorption-based water harvester suitable for arid environments, achieving a high water adsorption capacity of 8.07 L/day (temperature = 15 °C, RH = 25 %). Hanikel, et al. (Hanikel et al., 2019) synthesized an aluminum-based MOF effective in arid environments, producing 1.3 L/kg·day of water in an indoor arid environment (RH = 32 %) and 0.7 L/kg·day in desert conditions (RH = 10 %).

2.5. Essential properties of material for AWH

Key properties of effective moisture-capturing materials include high moisture-capture capacity, low energy consumption, efficient sorption and desorption dynamics, and strong cycling stability. Materials with high water affinity, large surface area and high porosity can significantly enhance water uptake, facilitating vapor liquefaction and water collection. Rapid adsorption and efficient water release are also crucial for maximizing water production. Since AWH is time-intensive, the materials should maintain performance over long-term use without degradation. By carefully selecting and modifying these materials, it is possible to achieve high water uptake, minimal energy for regeneration, fast sorption/desorption cycles, and stable performance. A major advantage of this technique is its ability to capture water vapor across a broad range of temperature and humidity levels (Jarimi et al., 2020).

2.5.1. Liquid desiccants

Liquid desiccants are materials with a high capacity to adsorb water vapor, commonly including salts like NaCl, LiCl, $CaCl_2$, and $MgCl_2$ (Bilal et al., 2022), as depicted in Fig. 6. These salts, known as hygroscopic due to their strong affinity for water vapor, absorb water through the hydration process. However, a key challenge with liquid desiccants is their tendency to dissolve in water, exhibiting deliquescence (Lu et al., 2022). Their water adsorption capacity is 5 to 6 times greater than that of solid desiccants (Bilal et al., 2022). Despite their efficiency, liquid desiccants are not suitable for atmospheric water harvesting (AWH) due to the complexity of handling and system design required for their use (Hu et al., 2021).

2.5.2. Solid desiccants

Solid desiccant materials, such as activated carbon, metal-organic frameworks (MOFs), silica gel, mesoporous silicate, natural rocks, and zeolites, are used for water adsorption even at low humidity levels (Abd Elwadood et al., 2022).

2.5.2.1. Silica gel. Silica gel is a hydrophilic, porous material with a high surface area, thin and granular structure, and good affinity for water molecules (Thu et al., 2013). It is made from sodium silicate and consists of siloxane (≡Si–O–Si≡) and silanol (≡Si-OH) groups (Hamza et al., 2017). Advantages include low cost, commercial availability, and low regeneration temperature. However, it has limitations like slow adsorption kinetics, lower water adsorption capacity, and poor thermal stability (Shi et al., 2022).

Sleiti et al. (Sleiti et al., 2021) designed a small water harvesting plant and used silica gel as a desiccant, achieving an adsorption capacity of 159 g/kg over a cycle of 12 h. In contrast, Zheng et al. (Zheng et al., 2023) reported a significantly higher adsorption capacity of 3.5 kg/kg/d using a composite material made of porous activated carbon fiber felt (ACFF), silica sol, and LiCl. This demonstrates the potential for improved water harvesting performance when using composite materials compared to traditional silica gel.

2.5.2.2. Zeolite. Zeolites are naturally occurring crystalline substances (Golomeova and Zendelska, 2016), formed during volcanic eruptions when lava interacts with seawater and salts (de'Gennaro et al., 2000). This reaction creates a structure composed of an aluminosilicate framework with a tetrahedral arrangement of SiO_4 and AlO_4 molecules (Fig. 7). The substitution of some Si^{4+} ions with Al^{3+} ions results in a net negative charge, balanced by alkali or alkaline earth metal ions. Water molecules must be absorbed in the cavities of zeolites. The general chemical formula for zeolites is $[(Li, Na, K)_a(Mg, Ca, Sr, Ba)_e(Al_{(a+2e)}Si_{n-(a+2e)}O_{2n}]\cdot mH_2O$ (Moshoeshoe et al., 2017). In terms of water uptake, Solmuş et al. (Solmuş et al., 2010) reported a range of 0.02–0.12 kg/kg.

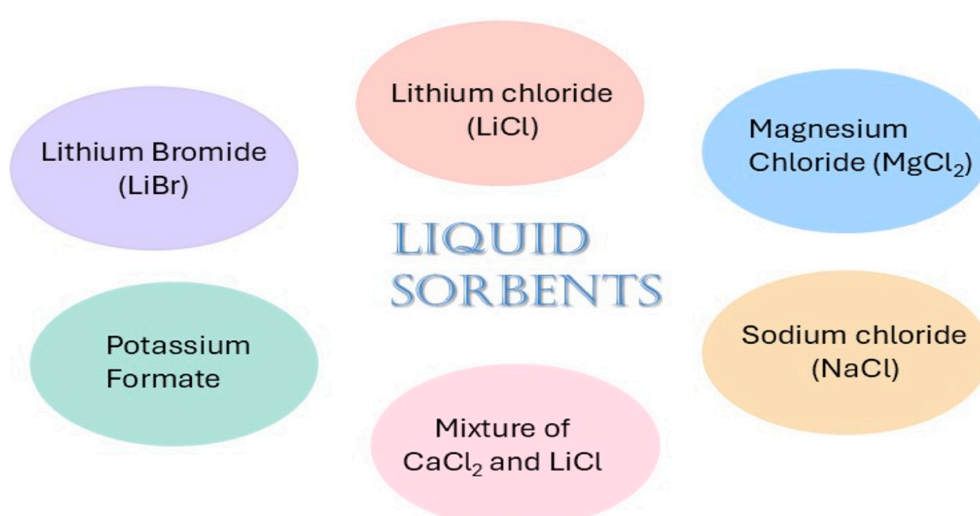


Fig. 6. Liquid desiccant materials.

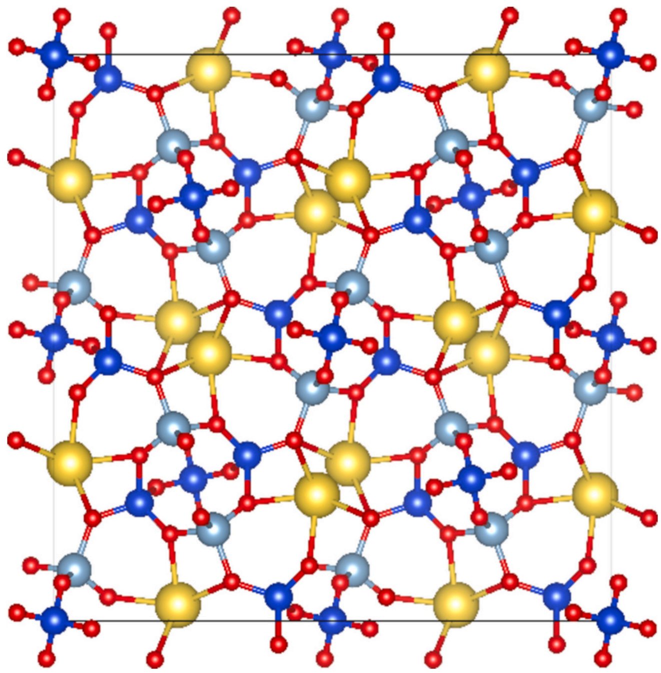


Fig. 7. Crystal structure of zeolite.

Zhao et al. (Zhao et al., 2024) achieved a water adsorption capacity of 0.29 g/g using aluminophosphate zeotypes (AlPO-18) at 13 % relative humidity, with full regeneration below 70 °C and thermal stability up to 900 °C. Mittal et al. (Mittal et al., 2022) enhanced water adsorption to 0.80, 0.84, and 0.91 g/g by reinforcing a super-porous hydrogel polymer matrix (methacrylamide and acrylic acid) with iron, silicon, and aluminophosphate zeolites. Additionally, Zhao et al. (Zhao et al., 2020) reported a water adsorption capacity of 1.1 g/g by impregnating zeolite 13× with hygroscopic salts like LiCl and $CaCl_2$. These studies highlight the potential of zeolites for atmospheric water harvesting applications.

2.5.2.3. Metal-organic framework (MOFs). Metal-organic framework (MOF) are a class of compounds characterized by metal ions coordinated by organic ligands to form extensive 3D structures. MOFs are ideal adsorbents for AWH due to their porous structures, thermal stability, high water uptake, structural diversity, and low regeneration temperatures. They are particularly advantageous for low-humidity environments where other adsorbents may be less effective. These studies underscore the potential of MOFs to enhance water harvesting technologies in various humidity conditions.

Recent research in Table 2 highlights the water vapor adsorption capabilities of various MOFs:

- He et al. (He et al., 2023) synthesized MOF-801 and improved its water uptake performance by 1.2 times compared to conventional MOF-801.
- Sharma et al. (Sharma et al., 2023) developed a composite material incorporating MOF-808 with $CaCl_2$ and Fe_3O_4, achieving a high-water uptake performance of 1.02 g/g at 75 % relative humidity.
- Yu et al. (Yu et al., 2024) created a composite with UiO-66-NH_2, carbon black, nanofibers, and LiCl, achieving a water adsorption capacity of 1.16 g/g.
- Su et al. (Su et al., 2024) designed a core-shell material by combining UiO-66 and MIL-101(Cr). This innovative structure demonstrates high water uptake performance across a broad range of humidity levels. Specifically, the outer layer of the core-shell material excels in water adsorption under low humidity conditions, while the inner layer performs optimally at higher humidity levels. Overall, the material achieved a water adsorption capacity of 1.336 kg/m^2/day, showcasing its versatility and effectiveness in diverse atmospheric conditions.
- Tao et al. (Tao et al., 2023) fabricated porous carbon strips embedded in tubular MOF membranes, reaching high water uptake capacities of 6.2 and 8.6 L_{H2O}/kg_{TMM}/day at 20 % and 60 % relative humidity respectively.
- Luo et al. (Luo et al., 2023) synthesized a monolithic adsorbent using a layer-by-layer assembly of chitosan/polydopamine layers with MIL-160(Al) and MOF-303, achieving an adsorption capacity of 0.94 g/g per day.
- Shao et al. (Shao et al., 2023) developed Ni_2Cl_2(BTDD) and attained a water adsorption capacity of 840.5 g/m^2 per 0.1 g of adsorbent in a 7 h cycle.
- Zhu et al. (Zhu et al., 2024) created a vertically aligned nanocomposite sorbent incorporating MOF-801 within a sodium alginate-tannic acid matrix via directional freezing, reaching high water adsorption capacities of 1.40 L/kg at 20 % relative humidity and 5.57 L/kg at 80 % relative humidity, respectively.
- Tan et al. (Tan et al., 2023) produced a sandwich-like adsorbent comprising Cu_xS, Al-Fumarate, and Cu sheet, which demonstrated an adsorption capacity of 2.14 g/cycle in their AWH device.

There are three main mechanisms through which adsorption occurs on MOFs: (i) chemical bonding at open metal sites, (ii) physical forces, and (iii) condensation (Kalmutzki et al., 2018).

An ideal MOF for AWH should exhibit the following characteristics: (i) significant water uptake at lower temperatures and high relative humidity, (ii) minimal toxicity, (iii) adequate lifecycle stability, (iv) morphological diversity, and (v) high adsorption kinetics.

To optimize AWH, it is essential to design MOF-based harvesters with these desired features in mind. The efficiency of water collection is influenced by the MOFs' durability, hydrophilicity, and pore size (Fig. 8).

Adjusting the hydrophilic nature, pore diameter, and morphology of MOFs can enhance their sorption/desorption properties (Table 3). Functional groups can be added to metal nodes and organic ligands to tailor the hydrophilic properties of MOFs, which shifts adsorption isotherms to lower relative pressures as hydrophilicity increases (Kalmutzki et al., 2018). The size of the pores is a key factor in water retention, with larger pores (achieved by extending organic linkers)

Table 2
Water vapor adsorption uptake and BET surface area for various MOFs (Gado et al., 2022).

MOF	BET surface area (m^2/g)	Water uptake (cm^3/g)
UiO-66(Zr)	1473	217
UiO-66(Zr)-NH_2	1286	210
UiO-66(Zr)-OH	858	78
UiO-66(Zr)-$(OH)_2$	510	41
MIL-101(Cr)	3250	88
MIL-100(Fe)	1948	333
MIL-100(Cr)	1842	277
MIL-100(Al)	1786	358

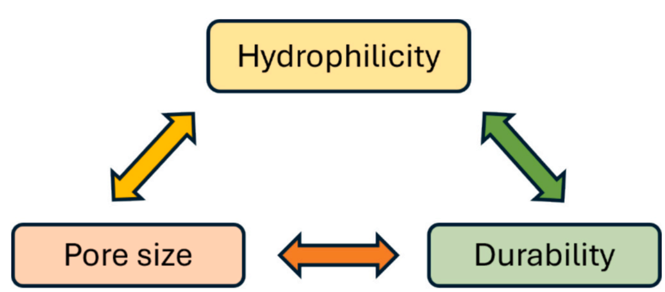


Fig. 8. Factors impact on the water collection efficiency of MOFs.

Table 3
Comparison between characteristics and water uptake performance of various adsorbents (Xu and Hu, 2023).

Materials	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

providing greater sorption capacity. Additionally, the geometry of MOFs also impacts their water adsorption capabilities (Cmarik et al., 2012).

3. Systems used in AWH

In Fig. 9, Kumar and Yadav (Kumar and Yadav, 2015) designed and constructed three distinct types of boxes for capturing water vapor from the air. These boxes were made from fiber-reinforced materials and featured 3 mm thick glass for glazing and condensation purposes. Inside the containers, steel wire mesh was used to hold the adsorbent material. Silica gel was employed as the adsorbent. In this setup, the maximum adsorption capacity achieved by the silica gel was 200 mL/kg. On the other hand, Kim et al. (Kim et al., 2018) developed a solar-assisted desorption/water production setup designed to operate even at low relative humidity levels (20–40 %). This system features two compartments: one for the adsorbent material, in this case, MOF, and an air-cooled condenser enclosed within the setup. The back side of the adsorbent layer functions as a solar absorber. During nighttime, the walls of the setup are opened to allow the adsorbent layer to become saturated with water vapor. During the day, the setup is closed, and the back side is covered with an optically transparent thermal insulator (OTTI aerogel). Exposure to sunlight induces the release of water vapor from the adsorbent layer. The released water vapor is then condensed by the air-cooled condenser to collect fresh water. Using MOF-801 [$Zr_6O_4(OH)_4(fumarate)_6$] as the adsorbent material, the system achieved an adsorption capacity of 0.25 L/kg.

A water vapor adsorption experiment was conducted using an AWH plant designed in-house by Legrant et al. in Fig. 10a (Legrand et al., 2021). The AWH plant is a simple closed apparatus constructed from glass. It includes a humidifier to control humidity, a small fan to regulate both humidity and temperature within the closed cabin, and a bulb to increase the temperature inside the isolated chamber. The equilibrium moisture content (EMC) of $ZnFe_2O_4$ and various concentrations of cobalt-doped $ZnFe_2O_4$ was measured across different humidity levels ranging from 45 % to 95 %.

The total moisture content in the materials was determined using the standard gravimetric method. Initially, the samples were dried in an oven at 200 °C for 2 h to remove any initial water. The samples were then placed in the AWH isolated cabin at a specific humidity, and weight changes were observed every 20 min until no further adsorption occurred, indicating the saturation point. The EMC of each sample was determined at this saturation point. The procedure was repeated to confirm the results. The maximum adsorption capacity observed was 597 mg/g at 95 % relative humidity for 60 % cobalt-doped $ZnFe_2O_4$ (Ehtisham et al., 2024). This high capacity was attributed to the increased number of surface charges on the material's surface (Su et al., 2024).

4. State of art

4.1. AWH

Jin et al. (Jin and Ghaffour, 2024) developed a multi-stage device consisting of a hot feed section, air gap, hydrophobic membrane, and coolant section. In this setup, the hot feed and air gap are separated by a hydrophobic membrane made of polytetrafluoroethylene, while the air gap and coolant section are separated by a condensation plate. As hygroscopic salts move through the hot feed section, water vapor is produced, which then passes through the membrane into the air gap and condenses on the plate. This device achieved water production rates of 0.82–6.27 $kg/m^2/day$ at a relative humidity of 19–69 % and 25 °C. Luo et al. (Luo et al., 2023) designed a solar-driven, MOF-based AWH device with a backbone of MOF and polydopamine/chitosan layers combined

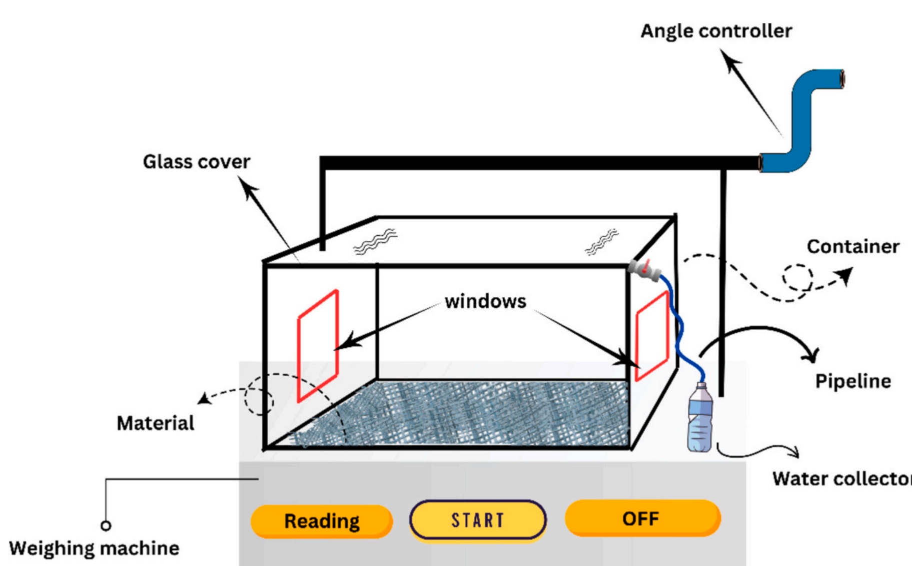
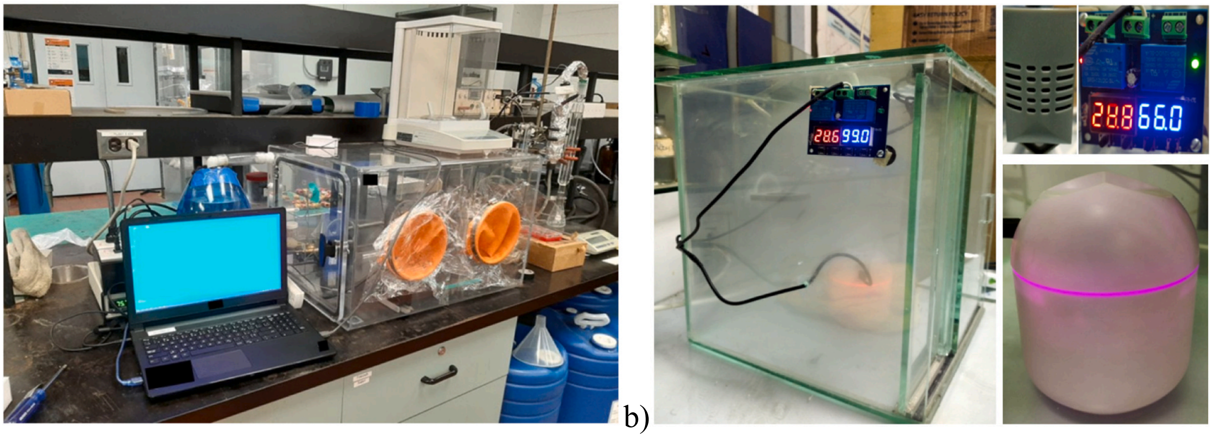


Fig. 9. Water harvesting by fiber-reinforced box setup (Reprinted with permission from (Kumar and Yadav, 2015) Copyright AIP Publishing).



a) b)

Fig. 10. Custom-made Automated Environmental Chamber (Reprinted with permission from (Legrand et al., 2021). Copyright American Chemical Society, and b) Atmospheric water harvesting plant (Ehtisham et al., 2024).

on a glass fiber substrate, demonstrating a high adsorption capacity of 0.44 g/g and 0.56 g/g at 30 % and 90 % RH, respectively. Song et al. (2022) developed a rapid-cycle water harvester by combining MOF with a porous carbonaceous material, which enabled fast desorption kinetics and a good adsorption capacity of 0.18 L/kg·h at 30 % RH. Feng, et al. (Feng et al., 2024) created a MIL-101(Cr) structure with cooling-assisted adsorption, offering high sorption, large adsorption capacity, and low desorption temperature. This device demonstrated impressive water productivity, ranging from 7.75 to 22.81 L/kg·day (RH = 20–80 %, temperature = 10–35 °C), and produced up to 990.4 mL/day even at low RH (26 %), corresponding to a productivity of 9.9 L/kg·day with an energy expenditure of 2.96 kWh per liter of water. Li et al. (Li et al., 2024) developed a composite foam made of $CaCl_2$, MIL-101, and bacterial cellulose (BC). This structure prevents salt leakage, while its micro- and macropores facilitate water capture, transport, and vapor release. The hydrophilic BC network acts as a host matrix, benefiting from multiple oxygen functionalities. This material changes to dark green upon adsorbing significant amounts of water vapor and demonstrates a water adsorption capacity of 0.78 g/g at 30 % RH.

4.2. Economic analysis

Economic analysis is crucial for determining the feasibility of a process. A small AWH setup demonstrated a water adsorption capacity of 6.75 L/kg/day at 70 % relative humidity and 21.6 °C, with a low material cost of 3.15–5.86 USD/kg (Wang et al., 2023). Ansari et al. (Ansari et al., 2024) analyzed the costs of various sorbent materials, suggesting that silica gel and $CaCl_2$ are economical options for AWH, costing approximately $0.98 and $0.25 per kilogram, respectively.

4.3. Drinkable quality water

It is essential to assess whether water obtained through AWH is safe for drinking. Zhang et al. (Zhang et al., 2023) used a hygroscopic hydrogel and LiCl as sorbent materials. They analyzed the water produced using inductively coupled plasma–mass spectrometry (ICP–MS), finding that Na^+, K^+, Ca^{2+}, and Mg^{2+} levels were well below WHO standards for water quality. Additionally, despite the presence of LiCl in the sorbent material, Li^+ levels were also low. Entezari et al. (Entezari et al., 2020) developed a complex mixture of sodium alginate with Li and Ca cations, embedding functionalized carbon nanotubes (FCNTs). They assessed water quality at temperatures of 70–80 °C and found it suitable for drinking, with calcium ions at 2.9–12.3 ppm, classifying the water as soft. Li and Cl ions were also present at low levels that met WHO standards for safe drinking water. Similarly, Lyu et al. (Lyu et al., 2024) evaluated ion concentrations (K^+, Na^+, Ca^{2+}, Mg^{2+}, Pb^{2+}, Al^{3+}) in water obtained through AWH, all of which were below WHO safety thresholds.

Water scarcity is an increasingly critical global issue. Techniques such as desalination, wastewater treatment, and AWH have been implemented to address water demands. Among these, AWH stands out as the most efficient and promising due to its sustainability, low cost, and minimal energy requirements. AWH includes fog collection, dew harvesting, and desiccant-based water harvesting. While fog and dew collection depend on geographical location, sorbent-based AWH is versatile, functioning in both arid and humid regions. This review focuses on the adsorption capacities, benefits, and limitations of materials like silica gel, zeolite, hygroscopic materials, and MOFs. Actually, MOFs and their high surface area, porous structure, high surface area, and tunability, offer superior adsorption performance compared to conventional materials. Various AWH systems and mechanisms have been analyzed, highlighting recent improvements in water production efficiency. Overall, this review underscores the importance of continued research in AWH technologies to further enhance their water collection potential.

CRediT authorship contribution statement

Muhammad Ehtisham: Writing – review & editing, Writing – original draft, Conceptualization. **Muhammad Saeed-Ul-Hassan:** Writing – review & editing, Writing – original draft, Conceptualization. **Albert Poater:** Writing – review & editing, Writing – original draft, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

A.P. is a Serra Húnter Fellow, and ICREA Academia Prize 2019, and thanks the Spanish Ministerio de Ciencia e Innovación for project PID2021-127423NB-I00 and the Generalitat de Catalunya for project 2021SGR623.

Data availability

No data was used for the research described in the article.

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