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Atmospheric water harvesting: technologies, materials, and pathways toward scalable and sustainable deployment

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ABSTRACT

The scarcity of freshwater resources resulting from climate change, environmental pollution, and rapid population growth poses a severe threat to human life. To overcome these global problem numerous studies have been conducted on the techniques of water harvesting from atmospheric air. Thus, atmospheric water harvesting systems emerged as a promising solution towards supplementing freshwater by directly extracting water vapor from the atmosphere. However, extracting fresh water from the atmosphere is challenged by large-scale deployment, cost-effectiveness, and water quality issues. This review analyzes the recent advancements of atmospheric water harvesting technologies, with a focus on material innovation, energy consumption, performance metrics, techno-economic considerations, water quality and practical deployment potential from peer-reviewed papers between 2000 and 2026 using databases of Web of Science, Scopus, ScienceDirect, and IEEE Xplore assessing trends across sorbent-based, radiative cooling, condensation, and hybrid systems. The review highlights significant progress in the development of hygroscopic materials, represented by advanced metal–organic frameworks and composite salt-polymer sorbents, which achieve as high as 5.5 kg/m^2/day of water under low-humidity conditions, as well as 16.9 kg/m^2/day in higher humidities. Hybrid systems with passive cooling and sorption have been able to reduce energy consumption down to 0.2 kWh/L. Future studies should emphasize system integration, life-cycle analysis, and optimization in arid climates for sustainability and decentralized potable water extraction. This review has provided a thorough summary of the advancements in atmospheric water harvesting and has laid the groundwork for the development of next-generation water harvesting technologies.

Introduction

Water scarcity is the most pressing global challenge. A recent report from the World Resources Institute's Aqueduct Water Risk Atlas highlights the critical issue of global water stress. The data reveals that a quarter of the global population faces exceptionally high water stress each year, depleting almost their entire available water supply. Additionally, around 4 billion people, or 50% of the global population, experience highly water-stressed conditions for at least one month annually, endangering lives, jobs, food, and energy security [1]. Projections indicate that this fraction will increase substantially by 2040, due to climate change, declining base flow, and sustainable groundwater extraction [2,3]. This problem is intensified by the progressive degradation of surface water quality due to salinity intrusion, industrial discharge and nutrient loading. As a result, even hydrologically resource-rich regions may face functional water shortages despite an abundance of nominal resources. The impacts are spatially severe in parts of sub-Saharan Africa and South Asia, where prolonged drought, low per capita water availability, and rapid population growth produce chronically low water security indicators [4,5].

Traditional methods of urban water supply systems, such as large storage reservoirs, inter-basin water transfers, seawater desalination, and wastewater reuse, have been used to mitigate these challenges. Of these methods, reverse osmosis desalination has seen the highest level of implementation, especially in Gulf countries and North Africa. It is limited by its high-pressure operation and significant electrical energy consumption of 0.003 to 0.004 kWh/L, even in optimally designed systems. The application of this method is site-specific due to its limitations in brine disposal, intake systems, and corrosion considerations that restrict its application to coastal areas [6–8]. Advanced wastewater treatment and reuse are other alternatives that require an energy-

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Nomenclature

AWH	Atmospheric water harvesting
WHO	World health organization
LCOW	Levelized cost of water
UV	Ultraviolet
PH	Potential of hydrogen
COP	Coefficient of performance
SEC	Specific energy consumption
TDS	Total dissolved solids
MOF	Metal-organic framework
SAWH	Sorption atmospheric water harvesting
RO	Reverse osmosis
LCA	Life cycle assessment
WRI	World resources institute
RH	Relative humidity
TRL	Technology readiness level
DES	Deep eutectic sorbent

intensive tertiary treatment step and often face societal acceptance problems.

Atmospheric water harvesting has recently been considered as a potential water source, consisting of about 12,900 km^3 of water vapor, equivalent to 0.04% of total freshwater (Table 1) [6,9]. The operation is done by continuously extracting using the methods of evaporation and atmospheric circulation. Because atmospheric moisture spans diverse climatic zones from coastal fog belts to humid regions, it provides a theoretically ubiquitous resource base independent of surface hydrology [10].

However, the principal technical limit in atmospheric water harvesting is the energy required to drive condensation or sorption and desorption cycles, mostly when the relative humidity drops below 40%. At low humidity the latent heat load dominates by pushing system-level specific energy consumption above that of using a desalination process [11,12]. Current improvements in sorbent chemistry, such as metal-organic frameworks [13], hydrogels [14], composite aerogels [15], MXene-LiCl hybrids, and bio-inspired microstructured surfaces can enhance water uptake kinetics, cycling durability, and operating relative humidity thresholds. For instance, alginate-based hydrogels and MXene-LiCl composited exhibit super-hygroscopic behavior with enhanced uptake capacity enabling continuous harvesting under lower humidity conditions [16]. Furthermore, integrated systems combining sorption beds with solar thermal regeneration, radiative cooling, or dual stage harvesting systems have demonstrated improved thermal utilization and move toward continuous operation [17–19]. But the transfer of lab-scale devices into field-based systems faces unresolved challenges. To address such a gap, this review covers a climate resolved methods that evaluate fog collection, radiative cooling, condensation and sorption techniques with respect to relative humidity and temperature ranges. This comparison combines specific energy consumption, coefficient of performance, work capacity, system coupling, and material families from silica gels and zeolites to metal-organic frameworks, hydrogels, and even new nanocomposites. This review also examines this system in relation to desalination through energy intensity, carbon footprint, economic feasibility, output variability, and scalability constraints. Water quality and safety concerns are reviewed through WHO guidelines, modes of contamination, and treatment strategies that focus on climate-specific optimal zones, scalability constraints, and new strategies for future investigation.

Finally, the review will provide a consolidated technical basis for evaluating atmospheric water harvesting techniques and identify critical research directions required for high performance and large-scale deployment. (see Figs. 1 and 2).

Table 1
Global water distribution [9].

Water source	Water volume (km^3)	Amount of freshwater (%)
Oceans, Seas, and Bays	1,338,000,000	–-
Ice caps, Glaciers, and Permanent Snow	24,064,000	68.7
Groundwater	23,400,000	–-
Fresh	*10,530,000*	*30.1*
Saline	*12,870,000*	–-
Soil Moisture	16,500	0.05
Ground Ice and Permafrost	300,000	0.86
Lakes	176,400	–-
Fresh	*91,000*	*0.26*
Saline	*85,400*	–-
Atmosphere	12,900	0.04
Swamp Water	11,470	0.03
Rivers	2,120	0.006
Biological Water	1,120	0.003

Methodology of Review

In this review article, a comprehensive climate-resolved framework has been used to evaluate the development of atmospheric water harvesting technology. The data related to water harvesting technology from 2000 to 2026 has been identified through various online databases such as Web of Science, Scopus, ScienceDirect, and IEEE Xplore. The literature has been considered based on its relevance to the performance of water harvesting technology, material design for water harvesting technology, and techno-economic evaluation of water harvesting technology. The major information obtained from literature related to water harvesting technology has included technology type, material design, water yield capacity, energy consumption, scalability, economic evaluation, life cycle assessment, and water quality standards.

Energy Requirements of Atmospheric Water Harvesting System

Energy requirements in atmospheric water harvesting systems remain highly climate-dependent, and continued advancements in sorbent materials, heat recovery, and system integration are essential to approach thermodynamic limits and enhance large-scale deployment feasibility. However, realizing all-weather and efficient water harvesting from air across diverse climatic regions remains a long-standing formidable challenge for AWH. Systematic investigations of the water-energy nexus of various AWHs are highly desirable to facilitate efficient water harvesting from air [20].

Reference	Technology Type	Climate condition	Energy consumption (kWh/L)	Test type
[21]	Condensation-based AWH (active refrigeration)	22 °C and 63 RH	2.25	Field
[22,23]	Adsorption/MOF-based systems	15-35 °C and 10-80% RH	1.67-7	Field
[24]	Hybrid systems (solar + radiative cooling)	27 °C and 60% RH	0.676-0.855	Field

Table 1 highlights that AWH system requires significant energy inputs compared to the minimum required thermodynamic work for the separation of water from the air. In the case of condensation-based AWH technologies, the energy requirements exceed the required thermodynamic minimum for the separation of water from air. This is largely because of the inefficiencies in the compressor, heat transfer losses, and the power required for fans in condensation-based water harvesting mechanism. The energy requirements of AWH system increase even further in conditions of low relative humidity because of the significant increase in latent heat load per unit volume of water separation. Even in

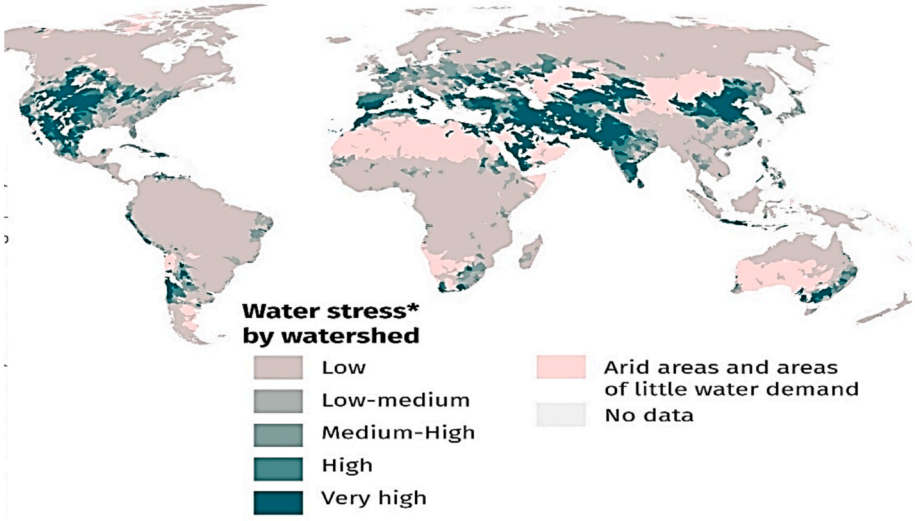


Fig. 1. Survey report on global water stress by the World Resources Institute.

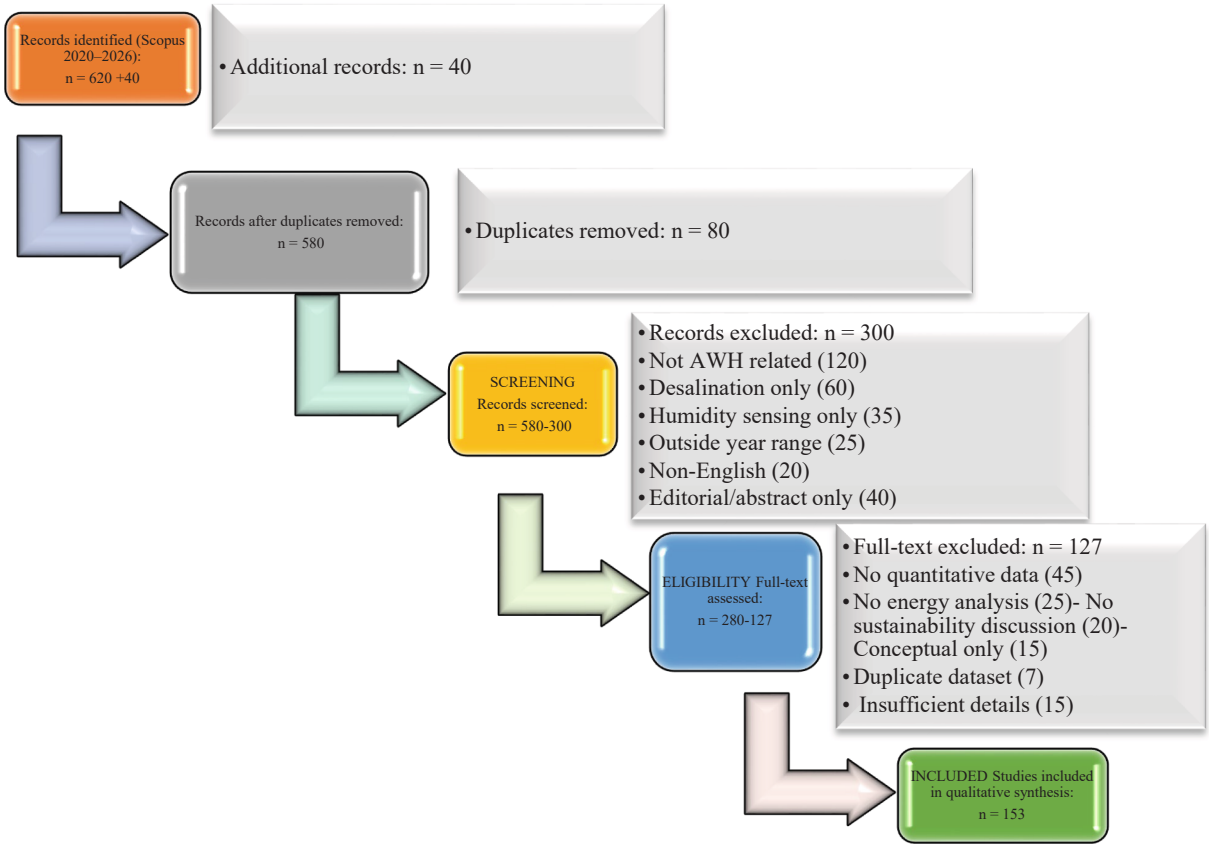


Fig. 2. Methodology of the review.

the case of adsorption/MOF-based energy requirements, the AWH system's energy requirements increase significantly under low relative humidity. Similarly, solar power and radiative cooling, which demonstrate better performance than AWH technologies based on other principles for separating water from the atmosphere, require significantly more energy than the thermodynamic minimum for separating water from air in conventional large-scale desalination plants under optimal conditions.

Fundamental Thermodynamics and Metrics

Minimum Work of Separation

The fundamental challenge in atmospheric water harvesting is the thermodynamic requirement of extracting water vapor from ambient air. The theoretical minimum energy required for this process is governed by the Gibbs free energy difference between moist and dry air at a given temperature and humidity, expressed as [12,25]:

$$W = m_w R_v T_a \ln\frac{1}{\varphi} \quad (1)$$

where (W) is the work required, (m_w) is the mass of extracted water, (R_v) is the gas constant of water vapor, (T_a) is the ambient temperature, and (φ) is the relative humidity. Under typical arid conditions (15%-20% RH), the theoretical minimum work required to condense one liter of water is approximately 0.07 kWh L^{-1} (Fig. 3) [11,26]. However, actual systems have a varying magnitude above this thermodynamic limit due to inefficiencies in heat transfer, vapor flow, and energy processing and conversion. Among actual systems, fog collectors are remarkable for their simplicity and intercept pre-condensed precipitation since no phase transition occurs. But, geographically limited to fog prone areas close to coasts or mountains and could not exceed 10-15 L m^{-2} day^{-1} [27]. Active condensers, like vapor-compression refrigeration, have a significantly high energy consumption of up to 0.5-1.2 kWh L^{-1} under dry environments [28]. Even more compact and scalable thermoelectric coolers are normally less efficient and consume energy of 1.5-2.0 kWh L^{-1} because of low coefficients of performance of heat pumps (Fig. 3) [29]. By comparison with these thermodynamic boundaries, actual systems remain below efficiencies of 10-15% of the theoretical potential. Beyond this hybrid methods like sorption enabled condensers and radiative coolers combined to merge fog collectors and condensers into more efficient methods and techniques.

Specific Energy Consumption

The specific energy consumption is the single most important parameter used to determine the performance of water capturing process from the atmosphere, given by the formula.

$$SEC = \frac{E_{total}}{m_w} \quad (2)$$

where, SEC, specific energy consumption (kWh/kg or kWh/L), E_{total} total energy input (kWh), mass of water produced (kg). The total energy input to the AWH system includes: compressor power, fan power, regeneration heat (desiccant systems) and auxiliary systems

When compressor and fan power are considered, the equation is

$$SEC = \frac{W_{comp} + W_{pump}}{\dot{m}_w} \quad (3)$$

$$\dot{m}_w = \dot{m}_a(\omega_{in} - \omega_{out}) \quad (4)$$

where, W_{comp} and W_{pump} work of the compressor and pump, respectively (kW), $\dot{m}_w$ and $\dot{m}_a$ mass flow rate of the water and air (kg/s), ω_{in} and ω_{out} specific humidity of (kg_{vapor}/kg_{air})

A dehumidifier-based system consumed energy of 1.02 kWh/L in warm, humid air with temperatures of 30°C, 62% RH to 6.23 kWh/L in cold, humid air with temperatures of 6 °C, 80% RH [30]. A solar-powered, active desiccant cycle integrated with an efficient heater has demonstrated better efficiency of 1.19 kWh/L [31]. Thermoelectric cooling systems, while capable of producing approximately 1.15 kg/day of water, typically operate at higher SEC levels of 1.7-1.98 kWh/L [21,32]. In tropical climates, desiccant based systems have been reported to consume energy of 3 kWh/L with 400 L monthly production [33]. These studies highlight the importance of system configuration and operational optimization in reducing energy consumption and improving overall performance [24,34]. The study by Aurangzaib et al. [35] presented an average SEC value ranging from 0.02 to 3.64 kWh/L for refrigeration-based atmospheric water generators, whereas solar-driven sorption systems demonstrate higher SEC values of 3.19-5.29 kWh/L which indicates a growing emphasis on renewable energy utilization rather than energy density alone. Furthermore, the study conducted by Li et al. [36] investigated the efficiency of the material-dependent technology, requiring 1-10 kWh/L, depending on material properties, design, and system optimization, improving the scalability barriers faced by desiccants. Table 2 summarizes that energy efficiency of atmospheric water harvesting is highly dependent on environmental conditions and system design, and careful consideration of local climate and technology type is essential for optimizing water production in outdoor applications.

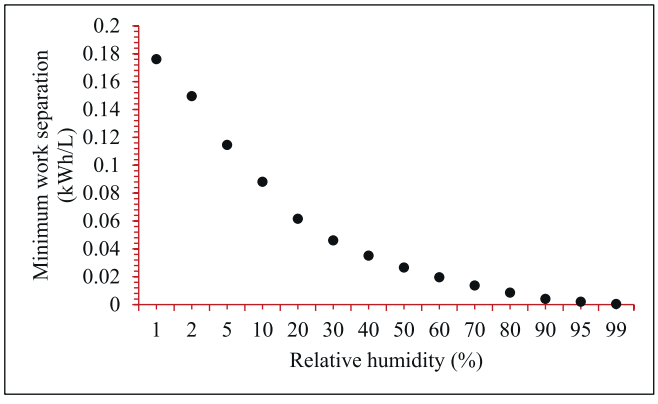


Fig. 3. Minimum work separation of atmospheric water harvesting system.

Coefficient of Performance

The coefficient of performance is an essential metric that quantifies the magnitude of latent heat removal from water vapor relative to the energy input. In simpler terms, COP measures how effectively a system converts energy into heating or cooling, providing insight into its operational efficiency.

$$COP = \frac{Desiredoutput}{Requiredinput} = \frac{Q_L}{W_{in}} \quad (5)$$

$$Q_L = \dot{m}_w h_{fg} + \dot{m}_a C_{pa}(T_{in} - T_{dew}) \quad (6)$$

If fan work is considered equation will be

$$COP = \frac{Q_L}{W_{compressor} + W_{fan}} \quad (7)$$

where, Q_L, W_{in}, represents total heat removal and energy power input required (kW), respectively. $\dot{m}_w$, water production rate (kg/s), h_{fg} latent heat of vaporization (kJ/kg), $\dot{m}_a$ dry air mass flow rate (kg/s), C_{pa} specific heat of air (kJ/kg·K), T_{in} inlet air temperature (K or °C) and T_{dew} dew point temperature.

A COP above 3.6 is an efficient long-term performance in vapor compression refrigeration systems [38]. Composite desiccant-coated heat exchangers (DCHE) show up to 107 % higher moisture removal rates compared to conventional designs, with advanced systems achieving COPs of up to 10.7 [39]. Munsin et al. [40] conducted studies on DC-AWH systems and reported average system performances of COP 4.0, indicating that optimal system efficiencies can be achieved through efficient energy consumption rate, especially in tropical and high-humidity environments. Shan et al. [41] estimated COP of 2.0-4.4 which indicates a twofold improvement in contrast to the conventional coated heat pump. Similarly, Sabbar et al. [42] investigated intelligent automation and hybrid-based cooling methods and obtained the COP of 4.0 (Fig. 4). Rostami et al. [43] investigated a COP of 2.5 by using subsurface cooling and solar-powered underground coil system.

Table 2
Specific energy consumption of AWH in outdoor conditions.

Reference	Temperature (°C)	Relative humidity (%)	Specific energy consumption (kWh/L)	Test type
[21]	22–37	45–64	0.84–1.98	Field
[21]	10–40	50–90	0.97–1.89	Field
[24]	27	60	0.676–0.855	Field
[37]	27	70	1.71	Field

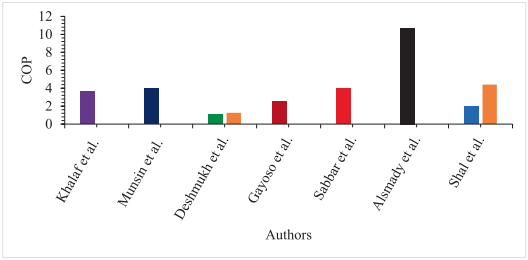


Fig. 4. Summary of COP of atmospheric water harvesting technologies.

More integrated systems [44,45], had relatively low system efficiencies as indicated by low COP of 1.05-1.26 while multifaceted systems enhance system functionality, which could pose potential system inefficiencies and increased compression work due to added components and system resistance.

Regeneration Temperature

Increasing the regeneration temperature beyond 120 °C can significantly enhance system performance, although this potential remains underexplored in efforts to maximize desiccant effectiveness. At lower regeneration temperatures (below 50-60 °C), low-grade energy sources are sufficient. But desiccants with higher water binding capacities require temperatures in the range of 90-200 °C, leading to increased energy consumption [46] (Table 3). In general, excessively low temperatures are inadequate for complete water desorption, whereas very high temperatures can reduce desiccant efficiency due to the difficulty of removing strongly bound water.

As shown in Table 3 and Fig. 5, the regeneration temperature is a critical parameter affecting the energy demand and implementation of sorbent-based AWH systems. Materials like MOF-303, MOF-801, silica gel, and LiCl operate under relatively low regeneration temperatures, which are highly suitable for AWH systems in terms of their compatibility with solar-thermal technologies and low-grade energy sources. These materials are well-established technologies with economic viability, while metal-organic frameworks are known for their tunability and water uptake capacity, although their implementation might face economic barriers. On the other hand, zeolites are known to operate under substantially higher regeneration temperatures (250-300°C) incompatible with solar-based technologies for AWH systems. Desiccant wheels and beaded desiccants are widely used in industrial dehumidification systems, which are incompatible with passive AWH systems due to their moderate to high regeneration temperatures. Materials with regeneration temperatures less than 100°C are highly favorable for AWH systems driven under sustainable and renewable sources, while those with regeneration temperatures greater than 100°C might require a high penalty in terms of their implementation with solar-based technologies.

Table 3
Regeneration temperature of various sorbent materials.

Reference	Materials	Regeneration temperature (°C)	Suitable for
[47]	MOF-303	75–85 °C	Solar-thermal or waste-heat-driven AWH
[48]	MOF-801	90 °C	Solar-thermal or waste-heat-driven AWH
[49]	Silica gel	60–90 °C	Solar-thermal or waste-heat-driven AWH
[50]	Zeolites	250–300 °C	
[46,51]	Desiccant wheel	126 °C	Industrial dehumidification systems.
[52]	Beaded desiccant	95–110 °C	Industrial dehumidification systems.
[53]	LiCl	80 °C	Solar-thermal or waste-heat-driven AWH
[54]	LiCl	78.8 °C	Solar-thermal or waste-heat-driven AWH

Climate Dependence

The performance of atmospheric water harvesting systems is highly affected by climatic conditions, which can optimize every system for a specific climate in various zones, like fog, condensation, and sorption (Fig. 6). For instance, systems that have low water harvesting rates operate better in arid environments. However, systems that use high-capacity condensers work well in more humid or tropical environments. This dependency on climatic conditions also makes it clear that AWH is not a universally applicable solution in every water-stressed location. The applicability of AWH systems is possible by using parameters such as relative humidity, air temperature, and other psychrometric analysis variables.Fig. 7.Fig. 8.

Since climatic parameters influence mass transfer potential and thermodynamic efficiency, the subsequent section evaluates how different atmospheric water harvesting technologies are designed to operate under these environmental constraints.

Technologies of Atmospheric Water Harvesting

Fog Collection

Fog harvesting is a beneficial source of water, but it is limited by the availability of fog. Fog collectors consist of a small mesh that captures water droplets from the atmospheric air, and gravity causes fall to the ground [55,56]. Structural modifications such as cylindrical and 3D meshes have demonstrated higher capturing efficiencies compared to traditional 2D nets, while biomimetic designs mimicking cactus spines or Licuala leaves have improved both droplet capture and drainage behavior [57]. Aside from other mechanical designs, more recent improvements focus on surface engineering and electrostatic promotion. Surface coatings made of Si-Cu composites have improved adhesive and fusion rates of droplets, while folded or micro-engineered surfaces facilitate continuous drainage and suppressed re-evaporation [58]. Also, efficiencies of more than 90% have been reported for droplet sizes larger than 5 μm [59]. Additionally, corona and plasma-enabled designs have positively provided high water collection and low power consumption, indicating potential hybrid applications of electrical forces and micro- or nano-engineered surfaces.

Based on the electrostatic fog harvesting mechanism, an efficient corona-discharge type collector adopted multi-mesh electrodes for drop collection [60]. Further enhancements were also implemented by combining plasma and micro and nano-structured materials, resulting in a remarkable collection efficiency of 93% and low power consumption, thereby emphasizing its feasibility and potential applications [61]. But some scalability issues remain for fog harvesting technology based on natural variations, low occurrence of fog, and high maintenance costs of large mesh or electrostatic elements. However, combining efficient materials, geometric adaptability, and sustainable energy resources can be a practical way towards scalable and sustainable fog harvesting technology for use as a decentralized water resource in water-limited areas.

Dew and Radiative Cooling

Dew harvesting performs best at relative humidity above 40%, while fog collection benefits from supersaturated conditions [11]. Combination of high infrared emissivity with wetting gradients or superhydrophilic patches outperforms conventional flat plates or meshes enables earlier condensation onset and higher collection rates [62]. Radiative cooling has emerged as a transformative enhancement, allowing surfaces to achieve sub-ambient temperatures by radiating heat through the atmospheric infrared window (8-13 μm) while reflecting solar radiation (Fig. 9) [63]. Photonic coatings and bio-derived fabrics

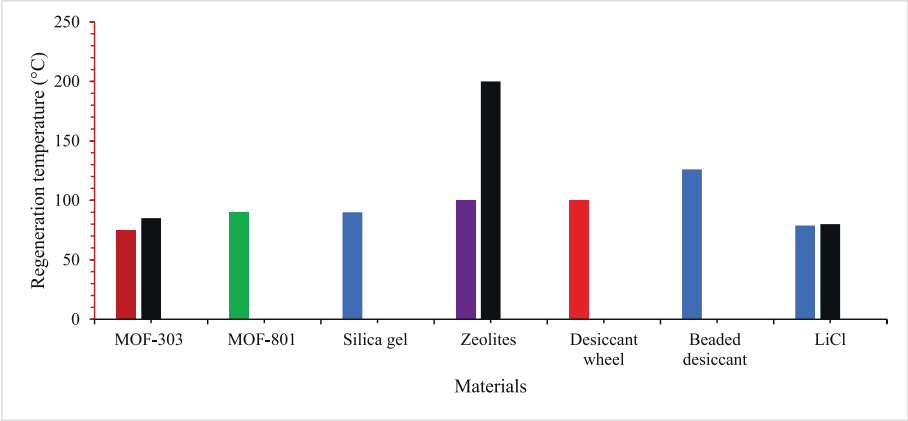


Fig. 5. Summary of regeneration temperature of different materials.

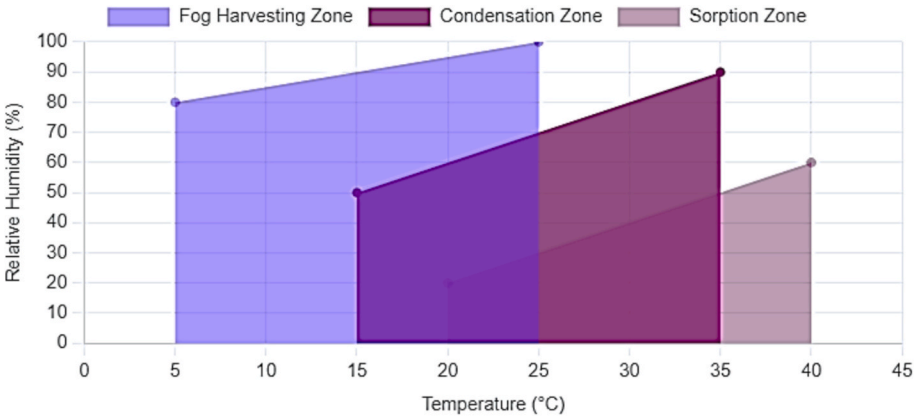


Fig. 6. Climate dependency of different zones for AWH.

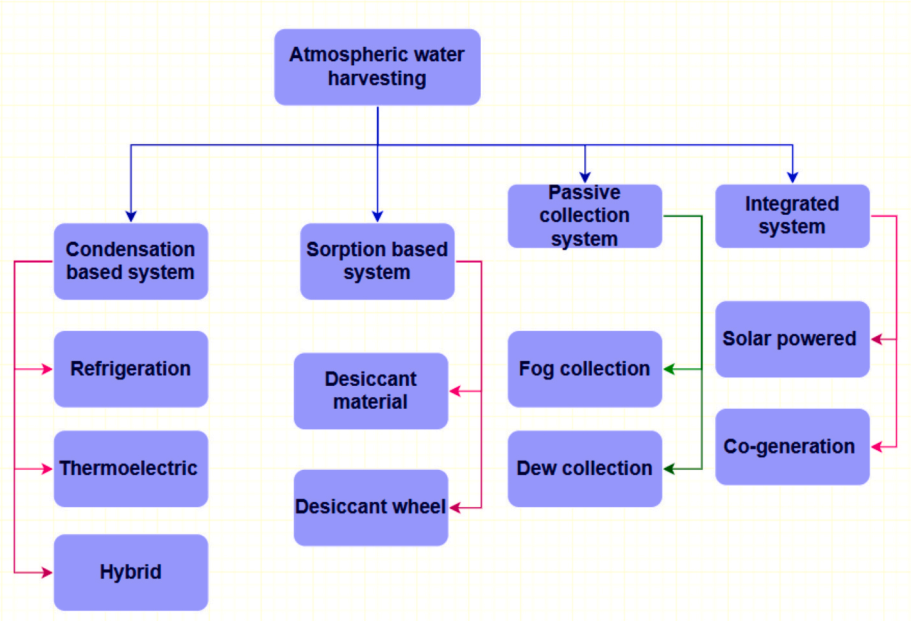


Fig. 7. Classification of atmospheric water harvesting mechanisms.

have achieved 5-10 °C reductions below ambient, even under sunlight. Studies demonstrated that a cellulose-based fabric can maintain 7.5 °C below ambient and absorb 1.29 kg of water per kg of material at 80% relative humidity [64].

Fig. 10 indicates the spectral selectivity of radiative cooling materials for atmospheric water harvesting. High emittance within the 8-13 μm

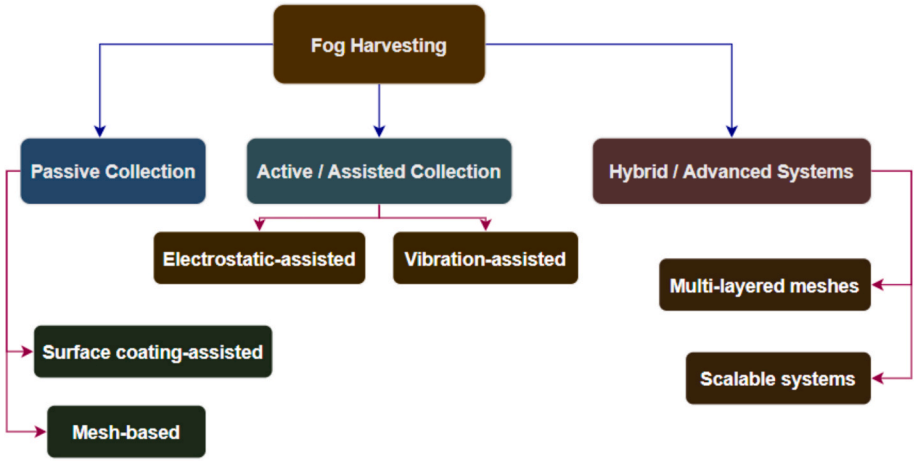


Fig. 8. Classification of fog harvesting mechanisms.

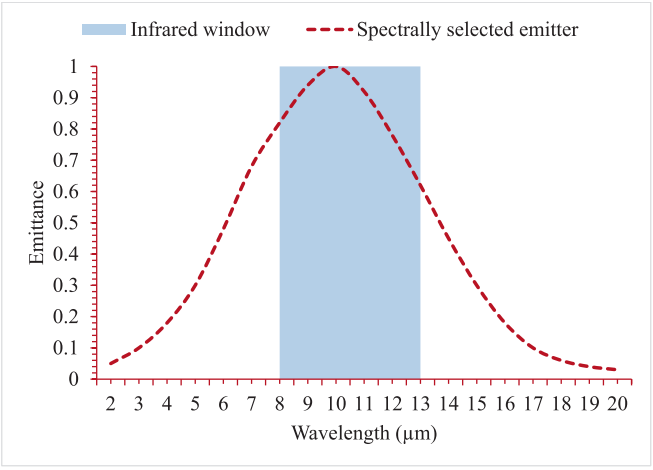


Fig. 9. Spectral selectivity of radiative cooling.

window enables efficient thermal radiation through the infrared atmospheric window, while low emittance outside this range minimizes heat absorption. The water absorption property of hygroscopic salts, hydrogels, or MOFs is possible in lower humidity but needs energy for desorption [65]. The integration of these sorbent materials with radiative cooling or solar regeneration has shown promising productivity. The integrating effect of these sorbent materials with radiative cooling decreases the desorption energy requirement, making the system more environmentally friendly to harvest water from the atmosphere.

Daytime photonic radiators

Daytime photonic radiators have revealed a revolution in atmospheric water harvesting, making sub-ambient cooling possible even under direct sun exposure. The high solar reflectance values, combined with high thermal emission within the atmospheric infrared window (8-13μm wavelength range), enable these substances to radiate heat outward while blocking the sun's rays, thereby achieving net radiative heat loss even during the daytime (Fig. 9). This capability extends passive water-harvesting techniques beyond nighttime, opening new opportunities for hybrid AWH systems [64]. The design of these radiators precisely suppresses absorption across the solar spectrum (0.3-2.5 μm) while maximizing emissivity in the IR window [66].

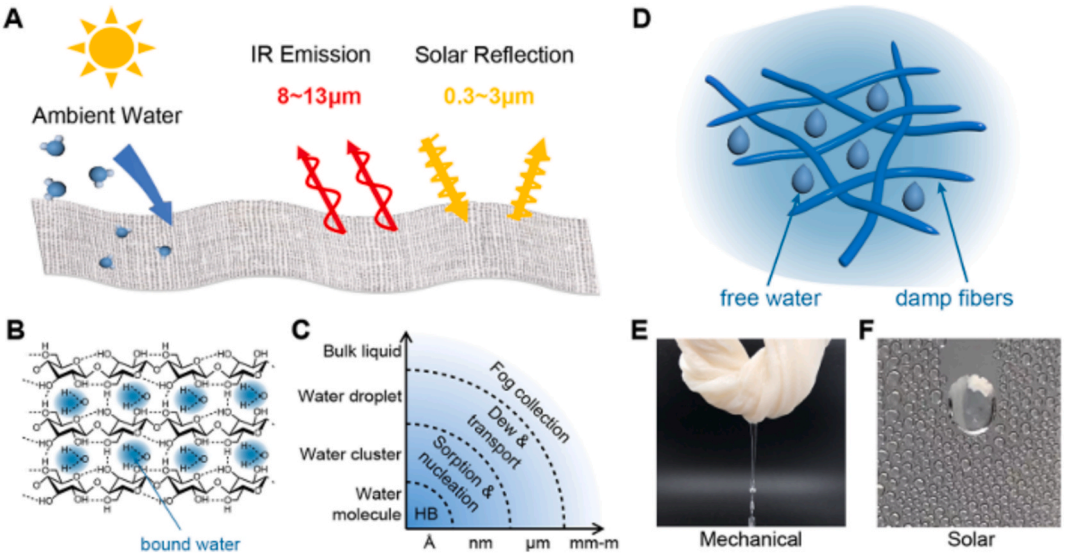


Fig. 10. Energy-efficient atmospheric water adsorption and extraction with radiative cooling cellulose [64].

Wettability-patterned and superhydrophobic surfaces

Surfaces with contrasting wettability, integrating hydrophilic and hydrophobic regions, used capillary forces and surface energy differences to control the movement of water droplets. Biphilic surfaces, which aggregate and guide droplets toward designated collection areas to improve water harvesting from both fog and dew [67]. Based on this, subsequent studies investigated superhydrophobic surfaces with micro and nanoscale topographies, demonstrating enhanced harvesting efficiency by providing a rapid droplet removal and reducing thermal limitations [68] . In addition, analyses of Janus meshes with varying pore sizes incorporating unblocked superhydrophilic regions can enhance overall collection efficiency [69].

According to Table 4, the extremely wettable surfaces (hydrophilic) have a maximum rate of 144 L/m^2/day at 25 °C and 90% RH. This is because if the surface is extremely wettable, the spreading rate of the droplets is very high along with film wise condensation to drain the water continuously. However, superhydrophobic surfaces have the least rate of 140 L/m^2/day at 33 °C and 80% RH. This is because superhydrophobicity helps in the higher mobility of droplets along with quick dropping off. At the same time, the lower nucleation site density restricts the net condensate mass from being condensed. Thus, the rate is comparable but lower than the superhydrophilic surface. Superhydrophilic surfaces display varying rates in the range 91.2- 312 L/m^2/day at 20 °C and 80% RH. This is because the superhydrophilic surfaces possess extremely high surface energies. The hydrophobic surfaces provide the least rate of 72 L/m^2/day at 25 °C and 92% RH.

Active system

Vapor Compression Refrigeration

Condensation based atmospheric water generators extract water by cooling ambient air below its dew point using vapor-compression refrigeration cycles (Fig. 11) [71] and it can operate under various climate conditions, including arid, urban, and tropical regions with an average harvesting rate of 22.9, 55.3, and 80.7 kg/day, respectively [72]. Long-term evaluations in arid regions reveal a stable water production of 15-30 L/day with a specific energy consumption of 0.5-1.2 kWh/L, even under harsh desert conditions [38]. Similarly, VCR-based atmospheric water generators yielded water harvesting rates of 0.23-1.45 kg/h and unit performance coefficients ranging from 1.0 to 4.65 kWh/kg [73]. However, the practical deployment is constrained by high energy demand and associated operating costs.

Thermoelectric Cooling

Thermoelectric coolers use the Peltier effect to provide compact energy-efficient temperature control by cooling one side while dissipating heat from the other without moving parts (Fig. 12). The temperature of the semiconductor material ranges from 0°C to 90°C makes suitable for atmospheric water harvesting, where sub-ambient cooling is required to reach the dew point [74]. Integrating TECs with solar panels and batteries enables the production of fully off-grid freshwater for remote areas. John et al. [29] demonstrated a system capable of producing 2 L of water in 12 hours at 30 °C and 80% RH, using heat sinks to enhance condensation and thermal management. Pontious et al. [75] further tested the TEC-based atmospheric water generator that can yield 0.5-1.0 L/day under laboratory conditions of 25 °C and 70% RH, highlighting the importance of energy efficiency and condensation surface optimization. Portable systems were later explored by He et al. [76] and Liu et al. [77] indicates the water production rates of 0.3-0.8 L/day under typical indoor conditions, which makes the progress of TECs toward scalable, compact, and practical solutions.

Table 5, summarizes the performance characteristics of different atmospheric water harvesting mechanisms under varying climatic conditions. Vapor-compression refrigeration systems generally operate over a temperature range of 25-38 °C and relative humidity 15-70 %, with water production rates ranging from 5.52 to 80.7 L/day. The corresponding specific energy consumption for VCRS varies widely between 0.26 and 4.65 kWh/L, reflecting differences in operating conditions, system design, and ambient humidity, while the coefficient of performance ranges from 1 to 4.65. Thermoelectric cooler systems, operating at a temperature of 25-30 °C but often under higher humidity 70-80 %, shows considerably lower water production 0.5-2 L/day and higher SEC values 0.97-2.3 kWh/L, accompanied by lower COPs 0.3-0.8. These data collectively indicate that VCRS systems are generally more efficient and capable of higher water yields, particularly under moderate temperatures and elevated humidity, whereas TEC-based systems are limited by both water output and energy efficiency.

Traditional Sorbents

Traditional sorbents remain important because of low cost, commercial availability and well-known behavior, but recent studies have focused on overcoming three recurring limitations: (a) low usable uptake at low relative humidity, (b) slow sorption/desorption kinetics, and (c) stability/salt-leakage (for deliquescent salts) during cycles [78]. Silica gels are a long-term desiccant in AWH due to their high surface area, thermal stability, and accessibility. Recent research has demonstrated three things: (i) silica gels possess relatively low desorption capacity at low relative humidity and require higher relative humidity to attain high desorption capacity [79], (ii) silica gels can be integrated into structured desiccants that enhance heat/mass transfer in practice [80], and (iii) can be combined with photo- or hygroscopic agents to increase actual desorption efficiency in practice [81]. Reviews and comparative studies still classify silica as robust and cyclable, but less attractive for arid (very low RH) locations without hybridization [78].

Rapid kinetic response and good thermal stability are characteristics of zeolites. Low-silica zeolites are also able to adsorb water from moderate relative humidity levels. Recent modeling and experimental results: (a) investigated zeolite isotherms and cyclic heat requirements [82,83], (b) compared zeolites to advanced MOFs and salt composites in device simulations [84,85], and (c) suggested zeolites are promising, where fast cycling under moderate RH and higher regeneration temperatures are acceptable [86,87]. However, their usable uptake per mass at very low RH is generally lower than top MOFs or engineered salt composites, limiting their standalone appeal in hyper-arid climates [88]. Salts ($CaCl_2$, LiCl, and related deliquescent hygroscopic salts) have shown the most dramatic recent gains for AWH because of very high gravimetric uptake and strong vapor affinity at low RH, but salt deliquescence has limited practical use [89]. Additionally, Yang et al. [90] highlighted that salt-based composite sorbents, composed of hygroscopic salts and porous matrices, can achieve high water sorption

Table 4
Wettability-patterned and superhydrophobic surfaces of different sorbent materials.

Reference	Wettability	Temperature (°C)	Relative humidity (%)	Rate of water collection (L/m^2/day)	Test type
[67]	hydrophilic	25	90	144	Lab
[58]	Superhydrophobic	33	80	140	Lab
[69]	Superhydrophilic	20	80	91.2/312	Lab
[70]	hydrophobic	25	92	72	Lab

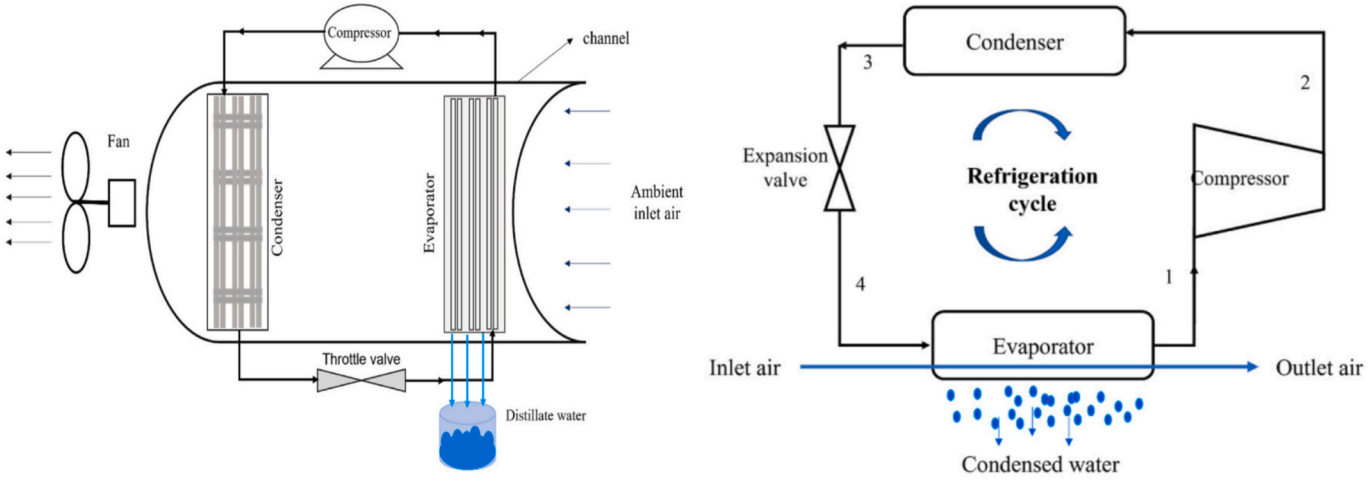


Fig. 11. Schematic diagram of vapor compression refrigeration cycle [56].

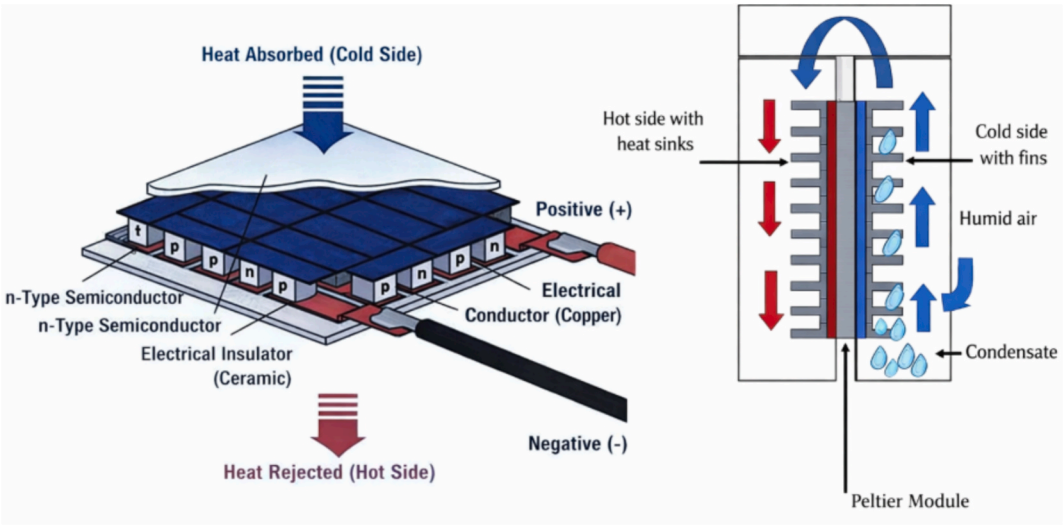


Fig. 12. Schematic diagram of a thermoelectric cooler system.

Table 5
Comparison of water uptake capacity and specific energy consumption of VCRS and TEC based on the climate conditions.

Reference	System type	Temperature (°C)	Relative humidity (%)	Water uptake (L/day)	SEC (kWh/L)	COP
[72]	VCRS	25–35	20–70	22.9–80.7	0.26–1	1–1.5
[38]	VCRS	32–38	15–25	15–30	0.5–1.2	1–1.5
[73]	VCRS	25–35	20–30	5.52–34.8	1–4.65	1–4.65
[29]	TEC	30	80	2	1–2.3	0.3–0.8
[75]	TEC	25	70	0.5–1	0.97–2.27	0.3–0.7

capacities across a wide range of RH. However, also noted that deliquescence can lead to the formation of a passivation layer, causing sluggish sorption kinetics and potential salt leakage, which affects cycling stability. Recent studies have shown that salt immobilization strategies can suppress leakage and sustain more than 100 cycles with retained capacity, while also improving heat transfer for desorption [89].

Advanced Sorbents

Comparison of the performance of MOF-801 prepared using green synthesis and solvothermal synthesis revealed that the green-synthesized material had better adsorption performance due to its greater specific surface area and smaller crystallite size. [48]. Enhancements in the water sorption capacity of MOF-303 have been achieved by modifying its structure to improve performance in atmospheric water harvesting systems [91] Moreover, by incorporating a vinyl substituent into the existing structure of MOF-303, a new structure was synthesized and labeled as MOF-LA2-1. This change in structure was reflected in the increase in volume and water uptake capacity under low relative humidity conditions. Studies by Solovyeva et al. [92] revealed that MIL-160 can achieve a maximum water uptake of 0.31-0.33 g_{H2O}/g_{ads} per cycle under specific conditions, indicating its potential for efficient AWH (Table 6). Additionally, integrating hydrogels with hygroscopic salts to improve their performance in AWH systems [93] and similarly, a combination of MXenes with hydrogels to create composites

Table 6
The performance of sorbents based on different measuring criteria.

Sorbent Type	Typical Water Uptake (g_{H2O}/g)	Regeneration Temperature (°C)	Cycling Stability	Estimated Production Cost	Test type	References
MIL-160	0.31–0.33	80—100	High, stable over multiple cycles	Medium to high	Lab	[95]
MOF-801	0.25–2.8	50–70	High, stable over multiple cycles	Medium to high	Lab	[96]
MXenes	1.69	40–80	Exceed 100 cycles in composites	Medium	Lab	[16]
$CaCl_2$, LiCl	2.1–2.685	<80	>100 cycles	Low to medium	Lab	[97,98]
Zeolites (13X)	0.14–0.27	80–120	High, robust under repeated cycling	Medium	–	[99]

that enhance water uptake and retention [94].

Table 6 summarizes the comparative overview of various sorbent materials employed in atmospheric water harvesting, highlighting their water uptake capacities, regeneration conditions, cycling stability, and estimated production costs. MIL-160 demonstrates moderate water uptake of 0.31-0.33 g_{H2O}/g and requires relatively high regeneration temperature 80-100 °C, while maintaining high stability over multiple adsorption–desorption cycles, with medium to high production costs. MOF-801 reveals a broad water uptake range 0.25-2.8 g_{H2O}/g under lower regeneration temperature of 50-70 °C, also enabling high cycling stability at medium to high cost. MXenes stand out for their high water uptake (1.69 g_{H2O}/g) and relatively low regeneration temperature of 40-80 °C, attaining over 100 cycles in composite systems at medium production costs. Conventional salts such as $CaCl_2$ and LiCl reach the highest water uptake of 2.1-2.685 g_{H2O}/g at regeneration temperatures below 80 °C, with better cycling performance and low to medium costs. Zeolites (13X) present lower water uptake of 0.14-0.27 g_{H2O}/g and require higher regeneration temperature 80-120 °C, but are highly stable under repeated cycling, with medium cost implications.

The water uptake capacity of various sorbents based on relative humidity levels has been depicted in Fig. 13 and Table 7 noted that under low relative humidity levels of 30%, the water uptake capacity of polyzwitterionic hydrogels is 0.62 g_{H2O}/g, while hydrogel microspheres have shown a water uptake capacity of 1.132 g_{H2O}/g. The enhanced water uptake capacity of hydrogel microspheres compared to hydrogels has been attributed to an increase in surface area and porosity. In metal-organic frameworks, MOF-801 has shown limited water adsorption capacity under 30-40% RH. In contrast, MOF-303 has shown a water uptake capacity of 1.3 g_{H2O}/g under 30% RH levels. The enhanced water uptake capacity of MOF-303 has been attributed to hydrophilicity. In salt-impregnated sorbents such as PCLG and SA-MXene@LiCl composite materials, water uptake capacity is 2.55 g_{H2O}/g and 1.69 g_{H2O}/g under 40-45% RH. The enhanced water uptake capacity of PCLG has been attributed to the hygroscopic nature of salt. In addition to salt-impregnated sorbents, radiative cooling has also shown enhanced water uptake capacity through reduced surface temperature. In LiCl-cellulose composite materials, water uptake capacity is 2.5 g_{H2O}/g under 60% RH levels. Cellulose fabric has also shown enhanced water uptake capacity of 1.29 g_{H2O}/g under 80% RH. In BHA aerogel materials, water uptake capacity is 3.18 g_{H2O}/g under 80% RH. In dual-network hydrogel microspheres under 90% RH levels, water uptake

Table 7
Water uptake capacity of sorbents.

Reference	Sorbent Type	Relative humidity (%)	Water uptake capacity (g_{H2O}/$g_{sorbent}$)	Test type
[100]	Polyzwitterionic hydrogel	30	0.62	Lab
[101]	BHA aerogel	30	0.25	Lab
[102]	Dual-network hydrogel microspheres	30	1.132	Lab
[103]	MOF-801	30	0.315	Lab
	MOF-303	30	1.3	Lab
	MOF-801	40	0.41	Lab
[104]	PCLG sorbent	40	2.55	Lab
[16]	SA-MXene@LiCl composite	45	1.69	Lab
[105]	LiCl-cellulose scaffold (radiative cooling)	60	2.5	Lab
[48]	Processed MOF-801	80	0.41	Lab
[101]	BHA aerogel	80	3.18	Lab + Field
[106]	Polyzwitterionic Gel		0.97	Lab
[102]	Dual-network hydrogel microspheres	90		Lab
[105]	LiCl-cellulose scaffold (radiative cooling)	90	16	Lab
[81]	Alginate-based composite (salt + graphene)	90	6.85	Lab
[107]	Hygroscopic Mn complex and hierarchical porous PVF-PPy	90	2.12	Lab + Field

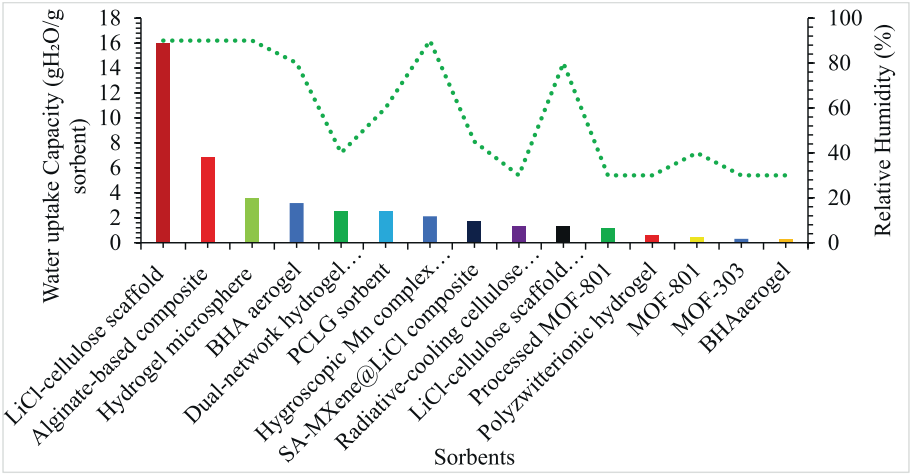


Fig. 13. Summary of the water uptake capacity of sorbents.

capacity is 3.586 g_{H2O}/g. In addition to dual-network hydrogel microspheres, alginate-based salt/graphene composite materials have also shown enhanced water uptake capacity of 6.85 g_{H2O}/g. In general, low-humidity performance is governed primarily by surface chemistry and adsorption enthalpy, whereas high-humidity performance is dominated by salt-assisted absorption, capillary condensation, and thermally optimized composite design.

Emerging Chemistries

Ionic liquids are salt substances that remain in a liquid state at normal temperatures with no vapor pressure. Ionic liquids that are responsive to temperature allowing for an efficient harvesting of water from air through the use of temperature differences [108]. These liquids are capable of absorbing solar radiation to maximize water collection from air, which is more efficient in AWH technology (Fig. 14) [109]. Deep eutectic solvents are a combination of two or more substances that have a melting point lower than that of individual substances when mixed. DESs have been shown to have low toxicities and biodegradable rates, which makes green solvents. It is also tested for its ability to absorb moisture in the air and is suitable for AWH technology [110]. Similarly, Ionogels have been developed as a combination of ionic liquids and a polymer component that have the characteristics of both materials to efficiently absorb and desorb water molecules [111].

Device Architectures

Monolithic structures have been designed to integrate hygroscopic materials in a continuous and porous form, thus improving mechanical strength as well as enhancing the efficiency of water sorption. Hierarchically structured monoliths have been designed that include metal organic framework materials to improve water harvesting. This combination provides enhanced strength and scalability compared to powdered metal organic frameworks [112], while the current mixed-MOF monoliths have also shown efficiency in harvesting as well as a higher rate of adsorption at low humidity conditions compared to conventional foam structures [113]. Coated foams have been designed that include an integration of porous foam structures with enhanced hygroscopic material-water uptake capabilities. Similar to bio-inspired foam structures based on polyvinyl alcohol designed through a supercritical carbon dioxide foam system, which have been designed to replicate scale-like structures upon a Tillandsia leaf surface to efficiently absorb or release harvested water [114]. Hygroscopic interconnectivity porous gels have been designed that possess fast kinetics of sorption and desorption, high scalability, as well as excellent adhesion strength to enhance metal organic framework harvesting systems based upon efficient sorption efficiently [90].

Rotary desiccant wheel systems make use of revolving wheels that contain hygroscopic materials in a cyclic process of adsorbing and desorbing water from air. Recent research has focused on several materials with an aim to improve rotary desiccant wheel systems' efficiencies by using a metal-organic framework, MIL-100(Fe) in desiccant wheels, which proved beneficial in enhancing water adsorption capacities and reducing regeneration temperatures [115]

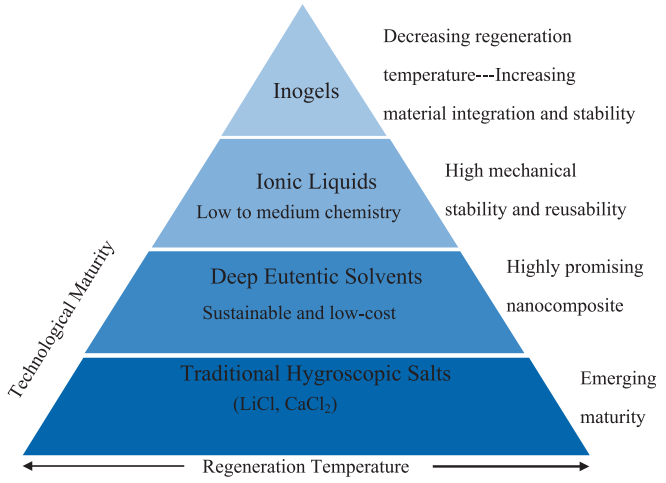


Fig. 14. Material hierarchy based on regeneration temperature.

Field Trials and Prototypes

Experimental studies conducted outdoors consistently highlight the actual performance of heat management, optimized air-sorbent contact, and reliable system integration to ensure stable and continuous operation. For instance, a study by Zhong et al. [116] indicated outdoor experiments with a dual-stage device utilizing commercial zeolite (AQSOA Z01) (Fig. 15). The system achieved a record-high water yield of 0.77 L/m^2/day, showcasing the potential of zeolite-based sorbents in actual conditions.

Gao et al. [117] developed a new AW in a completely bio-inspired manner. This designed system showed a promising harvesting rate of 5.50 kg/m^2/day in 35% humidity conditions, as well as 16.9 kg/m^2/day in higher humidities above the theoretical rate of release (Fig. 16).

Hoogendoorn et al. [118] investigated advanced and low-cost sorbents in terms of their hydrogel materials. Calcium chloride-based polyacrylamide hydrogels were low-cost materials that absorbed 0.92 and 2.38 grams of water per gram of dried matter at 30% and 70% RH, respectively (Fig. 17).

The experimental setup in Fig. 18 is carried out in Behshahr, northern Iran. The experiment is demonstrated by Rostami et al. [119] shows an atmospheric water production system that employs underground cooling, solar power, and rectangular underground coils to generate drinking water. The investigation focused on independent variables including coil length, coil perimeter, inlet mass flow rate, and varying specific humidity levels to assess the system's performance metrics.

The operational insights obtained from field demonstrations highlight both performance strengths and practical limitations, which can be more clearly interpreted through a structured comparative assessment.

Comparative Analysis

Table 8 compares the major AWHSs based on operational humidity levels, water production capacity, surface area, and energy requirements. For example, fog collection is appropriate at high relative humidity levels above 80%. In addition, fog collection has a water uptake capacity of 3-15 L/m^2/day. This makes it appropriate in foggy environments. On the other hand, radiative dew collection has a low water production capacity of 0.3-0.6 L/m^2/day. Active condensation systems demonstrate the highest water production rates, 10-100 L/m^2/day. Although this performance comes at the cost of moderate energy consumption. Sorption-based systems are capable of operating under lower humidity conditions and SEC. Thermoelectric cooling systems generate low water productivity and higher energy consumption, which limits their overall efficiency.

Table 9 summarizes sorbent materials for atmospheric water harvesting in terms of operating humidity range, water uptake capacity, regeneration temperature and cycling stability revealing important performance trade-offs. Silica gel operates effectively at moderate relative humidity 30-60 % with moderate water uptake 0.25-0.35 g_{H2O}/g but requires relatively high regeneration temperatures 80-120 °C due to strong physical adsorption, while its rigid structure has high cycling stability exceeding 100 cycles. MOF-801 and MOF-303 are capable of harvesting water at low humidity levels of 10-40 %, with MOF-303 showing higher uptake 0.45-0.5 g_{H2O}/g than MOF-801 0.3-0.35 $g_{H2O}/$

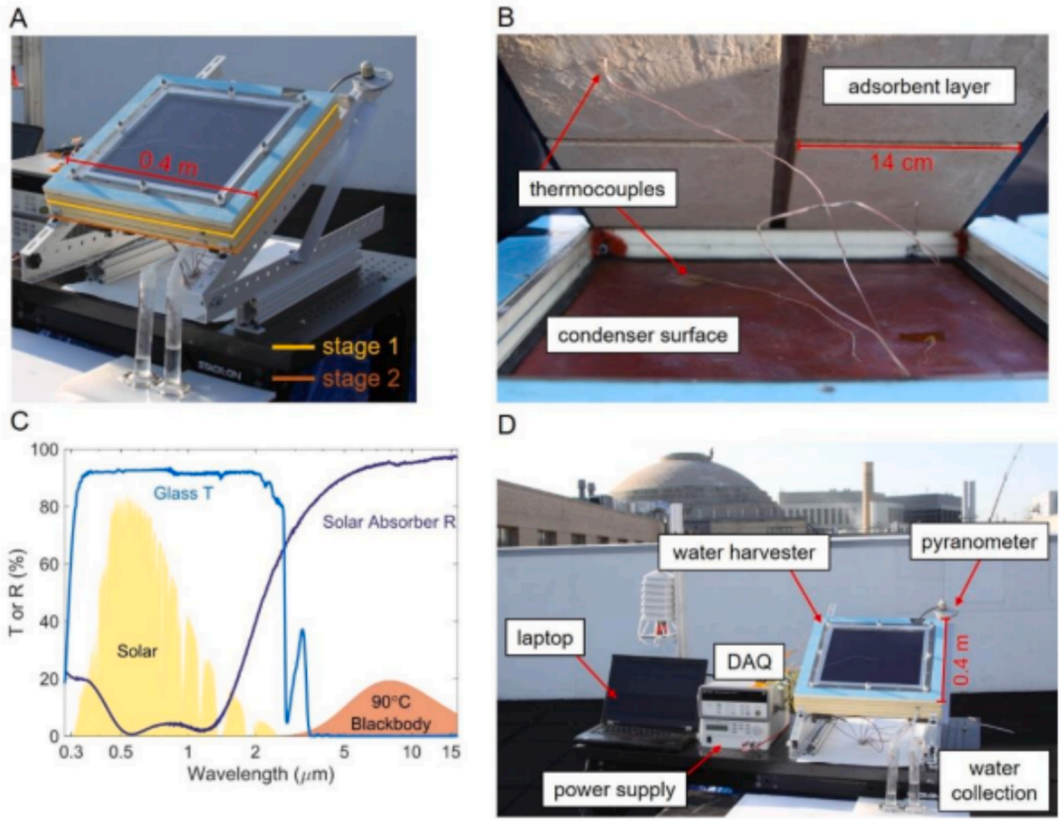


Fig. 15. Dual-stage prototype and experimental setup [116].

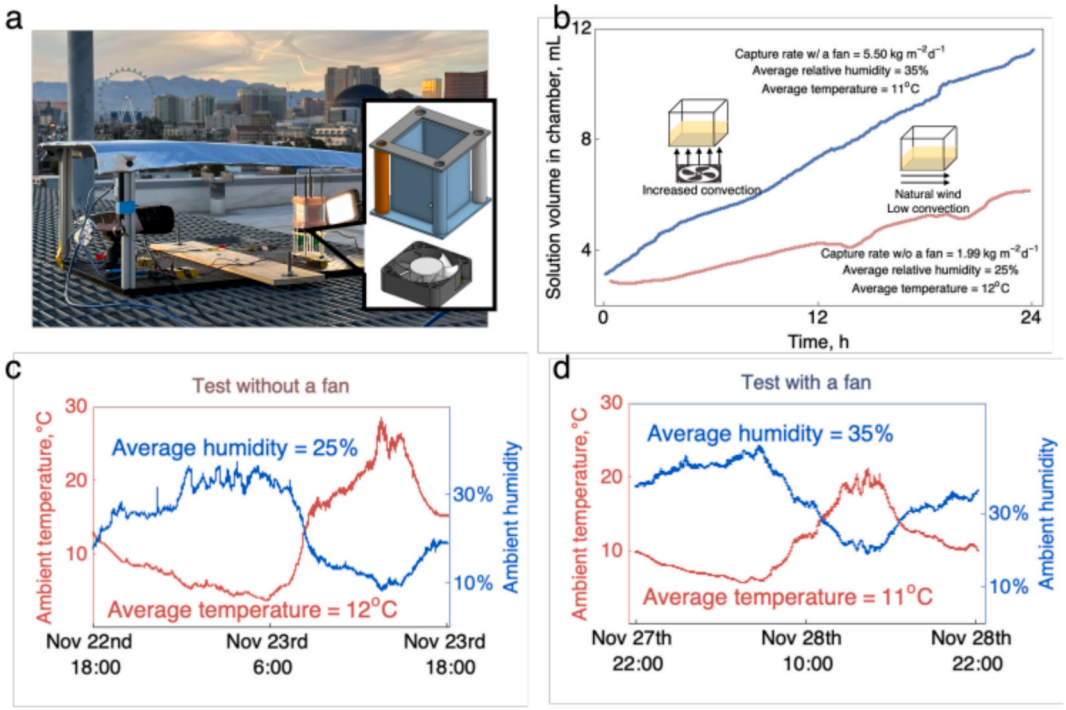


Fig. 16. Outdoor water capture tests demonstrated high water capture in Las Vegas [117].

g owing to its higher density of hydrophilic adsorption sites; both materials regenerate at low temperatures 45-65 °C, enabling energy-efficient operation, though their cycling stability is moderate 50-100 cycles. Zeolites exhibit lower water uptake 0.2-0.28 g_{H2O}/g and require very high regeneration temperature 150-250 °C, but it provides an exceptional structural robustness and very high cycling stability (>100 cycles). Calcium chloride salts achieve the highest water uptake capacity of 1.0 g_{H2O}/g) across a wide humidity range 20-80 % due to its

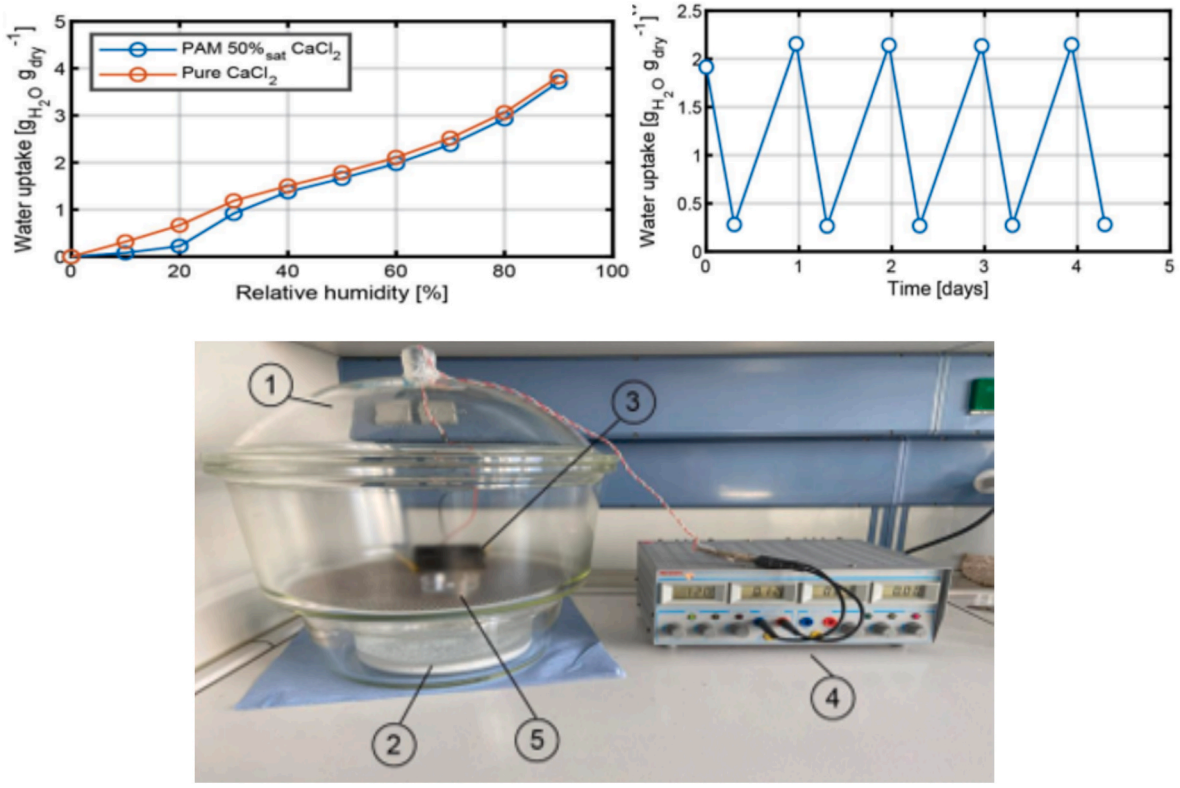


Fig. 17. Water harvesting performance of the $CaCl_2$-loaded PAM hydrogel [118].

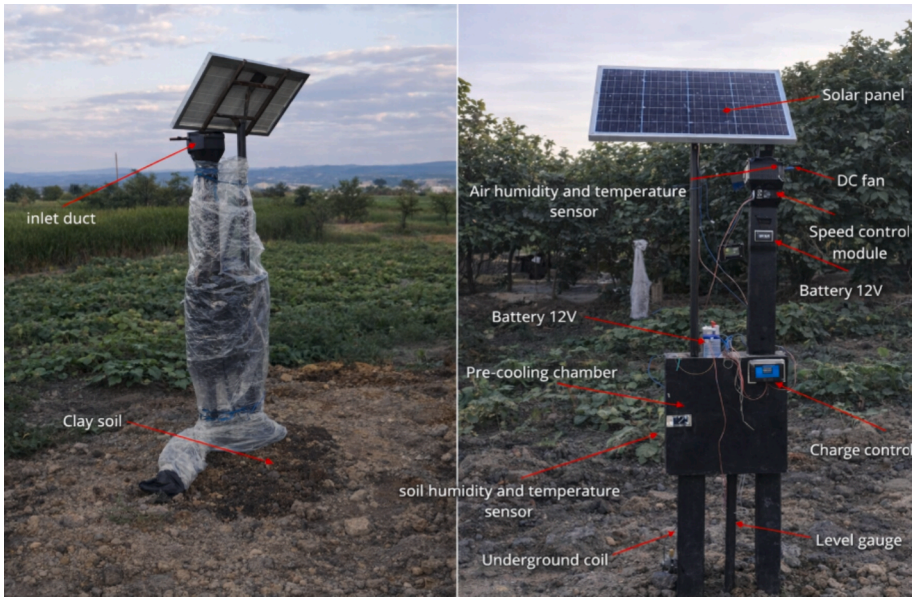


Fig. 18. Experimental setup of surface cooling and solar power-based atmospheric water harvesting system [119].

Table 8
The range of water uptake based on are of condensation.

Technology type	RH (%)	Amount of water harvested (L/m^2/day)	Reference basis	SEC (kWh/L)
Fog	>80	0.1–15.6	Projected frontal mesh area exposed to wind	Passive
Radiative dew	80	0.3–0.6 L/m^2/day	Condensing surface area	Mostly passive
Active condensation	80	10–100 L/m^2/day	Effective condenser heat transfer surface area	0.5–1.2
TEC	80	0.2–2 L/m^2/day	Cold-side heat sink area	1.5–2

Table 9
Comparison of water uptake capacity based on sorbent type.

Material	RH range (%)	Water uptake capacity ($g_{H2O}/g_{sorbent}$)	Regeneration Temperature (°C)	Cycling stability
Silica gel	30–60	0.25–0.35	80–120	High (100 +)
MOF801	10–30	0.3–0.35	45–65	50–100
MOF303	10–40	0.45–0.5	45–60	50–100
Zeolite	20–50	0.2–0.28	150–250	Very high (100 +)
$CaCl_2$ (salt)	20–80	1.0	60–100	Moderate
Hydrogels	20–80	0.4–1.0	40–70	Moderate-high

hygroscopic and deliquescent behavior. The cycling stability is limited by salt agglomeration and material loss during repeated hydration/dehydration. Hydrogels provide moderate to high water uptake of 0.4-1.0 g_{H2O}/g under a high humidity condition with low regeneration temperature ranges 40-70 °C, while its cycling stability ranges from moderate to high depending on polymer formulation and resistance to swelling fatigue.Table 10.

Techno-Economic and Environmental Perspectives

The levelized cost of water in atmospheric water harvesting systems is highly sensitive to both ambient humidity and energy input requirements. To calculate the levelized cost of water [120].

$$LCOW = \frac{Levelizedanualcost}{Anualwaterharvested} = \frac{CAPEX{\cdot}CRF + OPEX}{Anualwaterharvested} \quad (8)$$

$$CRF = \frac{i(1+i)^n}{(1+i)^n - 1} \quad (9)$$

where, LCOW levelized cost of water (USD/L), CAPEX capital expenditure (USD), CRF capital recovery factor, i discount rate, n system lifetime (years), *OPEX* operational expenditure.

Increasing airflow enhances water productivity but results in higher fan power consumption and larger heat exchanger requirements, thereby increasing both operating and capital costs. Similarly, improving heat exchanger effectiveness enhances COP and reduces SEC, but at the expense of increased capital investment. Therefore, technoeconomic optimization is required to balance energy efficiency and system cost.

Techno-economic modeling investigated by Siegel and Conser [121] shows the solar-driven AWH operating in dry climates, the specific energy demand can range from 0.158 to 1.021 kWh/L, resulting in a minimum LCOW of $0.006.5/L under optimal conditions. Active cooling (dehumidification) systems, even in a humid climate, have a substantial energy demand, causing their LCOW costs to exceed $0.02/L [122]. In a sorbent-based AWH system employing the MOF-303 material that could work at RH as low as 13%, regeneration energies of around 1000 kW per m^3 were recorded, resulting in an LCOW of approximately $0.01-0.012/L depending upon geographical location. A grid-connectable and solar-based AWH units investigated by Gayoso et al. [120] showed that the LCOW is highly sensitive to humidity and renewable energy. Micari et al. [123] demonstrated that the LCOW of atmospheric water harvesting ranges from $0.033 to $0.325 per liter in a membrane-based unit. Compared to AWH, current technology for reverse osmosis of seawater desalination has an LCOW of between $0.003 and $0.0025 per liter, depending on the capacity of the plant and fuel type.

Generally, the reported levelized cost of water for atmospheric water harvesting systems varies significantly, primarily due to differences in climatic conditions, technology pathways, energy sources, system scale, and economic assumptions [78]. Climate has a major influence, with higher relative humidity in the tropics increasing the moisture content and hence decreasing the amount of specific energy required. In arid climates, more energy has to be supplied per unit of water produced due to low absolute humidity. [1,2]. Passive fog collection systems exhibit the lowest LCOW (0.01–0.05 USD/L) because they rely on natural droplet interception and gravitational drainage, thereby avoiding energy-intensive phase change processes [5]. In contrast, condensation-based systems incur higher operational costs due to latent heat removal, with LCOW strongly influenced by electricity price, coefficient of performance, and ambient psychrometric conditions [2,6]. Sorption-based and metal-organic framework (MOF)-driven systems demonstrate broader variability, reflecting differences in regeneration energy demand, adsorbent material cost, sorbent durability, and prototype-scale operation [3,4,7]. Furthermore, discrepancies arise from inconsistent inclusion of capital expenditure, replacement intervals, discount rates, and auxiliary components such as storage and post-treatment [2,6]. Laboratory-scale systems frequently report inflated LCOW due to limited daily water yield and underdeveloped economies of scale [3,7]. Therefore, methodological heterogeneity and strong climate dependency collectively explain the wide cost dispersion observed across AWH studies.

Table 11 presents a summary of the levelized cost of water for various atmospheric water harvesting systems across different climatic conditions and energy sources. The values are highly dependent on climatic conditions. For condensation-based systems in tropical climates

Table 10
Applicability of different technologies to arid, semi-arid, and humid climates.

Climate Zone	Relative humidity	Suitable technologies	Performance and considerations
Arid	Very Low (< 30–40%)	Adsorption-based systems using advanced sorbents (MOFs, hydrogels, composites)	Operates efficiently where cooling-based methods are impractical due to high energy costs. Performance depends on sorbent's affinity for water vapor at low partial pressures.
Semi-arid	Low to Moderate (40–70%)	Adsorption-based systems with high-capacity materials; Active cooling systems may be feasible but with lower efficiency.	A broader range of sorbents become viable. Ionogel achieved max. water production potential of. Active cooling's energy consumption can be high; one study in a semi-arid zone found energy expenditure of 0.576–0.926 kWh/L
Humid	High (>70%)	Cooling-based condensation (dew harvesting); Fog harvesting (in specific coastal/foggy areas); High-capacity sorption materials.	Direct cooling becomes thermodynamically efficient. The Moisture Harvesting Index is more favorable.

Table 11
Summary of energy cost per liter of water.

Reference	Zone type	Technology Type	Energy Source	LCOW (USD/L)
[120]	Tropical	Condensation	Grid	0.06–0.17
	Arid, temperate, and tropical	Condensation	Solar PV	0.02–0.09
[124]	Arid Coastal	Fog Collection	Passive	0.01–0.05
[125]	Temperate	Desiccant/ Nanofluid	Grid	0.022
[122]	Global	Condensation	Grid	0.1
[126]	Temperate	Sorption	Grid	0.45
[91]	Global	MOF-Based	Hybrid	0.1–0.25
[37]	Temperate	Sorption	Grid	0.33

powered by grid electricity, there is a high-cost variation in the range 0.06-0.170 USD/L. This suggests a strong dependence of the system on electricity for condensation. For solar photovoltaic-powered condensation systems in arid, temperate, and tropical climates, the LCOW values are relatively low in the range 0.02-0.09 USD/L. This suggests a low cost due to reduced electricity consumption. For passive fog collection systems in arid coastal climates, the LCOW values are relatively low in the range 0.01-0.05 USD/L. This suggests a low cost due to natural fog occurrence. For advanced material-based systems in temperate climates powered by grid electricity, desiccant or nanofluid-based systems have relatively competitive values in the range 0.022 USD/L. This suggests a strong potential for increasing the efficiency of the system through improved desiccant kinetics. For grid-powered systems in temperate climates based on the same advanced materials, the LCOW values are relatively higher at 0.450 USD/L. This suggests a low productivity or low system efficiency. Global-scale assessments of grid-powered condensation systems report LCOW values around 0.1 USD/L, reinforcing the conclusion that conventional AWH remains energy intensive. MOF-based hybrid systems, evaluated globally, show LCOW values between 0.1 and 0.25 USD/L, reflecting promising water uptake performance but still-high material and regeneration costs.

As indicated in Table 12 lowest costs (0.0004 USD/L) are achieved by large-scale SWRO plants in Dubai, whereas higher costs (0.0026 USD/L) are observed in conventional RO systems under different regional and operational conditions. This cost range provides a benchmark for evaluating atmospheric water harvesting systems..

Table 13 compares the LCOW values for atmospheric water harvesting technologies are substantially higher than those of desalination technologies, owing to lower maturity levels, climate dependency, and energy intensity per unit of water. In addition, passive technologies such as fog collection are found to have lower costs compared to desalination technologies. On the other hand, sorption technology and MOF technology are found to have markedly high LCOW values owing to energy consumption for material regeneration. When comparing atmospheric water harvesting technologies with seawater reverse osmosis technology, particularly in Dubai, it has been found that the lowest LCOW values are obtained owing to large-scale deployment and optimized infrastructure. Although desalination technology has lower climate dependency and can be easily scaled up for large water demands, atmospheric water harvesting technology has strategic importance for water-scarce regions where desalination technology cannot be deployed. Even though it has a higher cost of water production compared to conventional seawater desalination technology, it has notable competitive advantages. The most important competitive advantage of atmospheric water harvesting technology compared to conventional seawater desalination technology is that it can be used for off-grid water production. The water production facility can be located anywhere without any constraints related to connection to a water supply system or proximity to seawater or any other water resources. The ability of atmospheric water harvesting technology to produce potable water from ambient air without any connection constraints makes it an ideal technology for water-scarce regions such as islands and for locations where water supply infrastructure has failed owing to natural disasters. In addition, it can be used for water production in remote locations where it would be difficult to deploy desalination technology owing to the lack of electrical supply and water supply system connection. In addition to off-grid water production capability, another notable advantage of atmospheric water harvesting technology over desalination technology is that it can be used for point-of-use water production.

Table 12
Summary of energy cost per liter of water for desalination system.

Reference	Location	Desalination Technology	LCOW (USD / L)
[127]	Saudi Arabia	RO	0.001874–0.002647
[128]	Kuwait	RO	0.00103–0.00105
[129]	Dubai	Seawater RO	0.000365–0.000389
[130]	India	Hybrid/batch electrodialysis and RO	0.00166
[129]	Dubai	SWRO	0.000277
[131]	Dubai	Hybrid RO-MSF	0.00085–0.00184

Table 13
Comparison of Atmospheric Water Harvesting and Desalination Technologies.

Category	Atmospheric Water Harvesting	Desalination
Primary Water Source	Atmospheric moisture	Seawater / brackish water
Representative Technologies	Condensation, Fog collection, Sorption, MOF-based, Desiccant/Nanofluid	RO, SWRO, RO–MSF, Hybrid RO–Electrodialysis
Climatic / Zone Dependence	Tropical, temperate, arid (highly climate-sensitive)	Coastal and inland (low climate sensitivity)
Energy Source	Grid, Solar PV, Passive, Hybrid	Mainly grid electricity and integrated power systems
LCOW Range (USD/L)	0.010–0.45	0.000277–0.002647
Lowest LCOW Reported	Fog collection (0.010 USD/L)	SWRO in Dubai (0.000277 USD/L)
Highest LCOW Reported	Sorption systems (0.45 USD/L)	RO in Saudi Arabia (0.002647 USD/L)
Scalability	Small to medium scale	Medium to very large scale
Technology Maturity	Emerging to experimental	Commercially mature
Infrastructure Requirement	Low to moderate	High (intake, pretreatment, brine disposal)
Best-Suited Applications	Remote, off-grid, water-scarce regions	Urban and industrial high-demand regions

Life cycle assessment and carbon footprint

Atmospheric water harvesting and desalination exhibit markedly different environmental profiles. Modern seawater reverse osmosis desalination, while energy-intensive, is a mature and highly scalable technology with well-characterized life cycle performance. In condensation and particularly sorption-based perspective, AWH systems can operate off-grid and avoid marine ecological impacts that typically remain limited to small or moderate scales. Consequently, their per-liter embodied GHG emissions and energy consumption tend to be higher than grid-connected RO, unless augmented by clean and sustainable renewable energy resources and sorbent materials. Therefore, currently, AWH has more niche applications based on its eco-friendliness in arid and or rural areas, and its feasibility for large bulk water production is still contingent on future research and development efforts aimed at improving sorbent longevity, sustainable production, and efficient integration of renewable energy resources.

Eiff et al. [132] have reported comprehensive LCA information about most of these desalination methods, reporting a carbon footprint of 2.1 g CO_2 eq/L for Hong Kong's seawater desalination plant, while Lee et al. [133] have reported comprehensive studies about hybrid RO, reporting negatively cogent carbon footprints based on certain combinations and orientations -2.66 0.04 g CO_2 eq/L. Also, Xue et al. [134] have undertaken comprehensive studies about electrodialysis desalination, reporting certain carbon footprint ranges, and other studies have reported around 2.46 g CO_2 eq/L [135].

Among AWH methods, condensation-based systems powered by the electrical grid are the most energy-intensive, with LCOW values reaching 0.060-0.170 USD/L and carbon emissions up to 80 g CO_2 eq/L, indicating poor cost and environmental performance when fossil energy sources are used. In contrast, solar-powered and sorbent-based AWH systems show improved sustainability, achieving LCOWs as low as 0.0065-0.0012 USD/L and emissions below 10 g CO_2 eq/L, suggesting that renewable integration and material innovation can significantly enhance feasibility. Conventional seawater RO remains the most economical and energy-efficient option, with LCOWs between 0.0003-

0.0025 USD/L and emissions below 2 g CO_2 eq/L, while solar-assisted ED also demonstrates low carbon intensity. Overall, while AWH offers a decentralized solution for water-scarce regions, its economic and carbon performance must improve substantially, mainly through renewable energy coupling and advanced material development to compete with established desalination technologies (Table 14).

Maintenance and durability

The recent advances in polyacrylamide-LiCl hydrogel systems and polymer-based MOF composites show promising water-uptake properties, which allow the material to be successfully cycled when encapsulated to avoid salt leakage. Optimized hydrogel formulations show good cycling stability with minimal salt loss during the process, with a water uptake capacity of up to 3.5 g/g at laboratory conditions [89]. However, the durability of the material also poses a problem due to the potential degradation of the adsorbents, such as hydrolysis, polymer degradation, and photochemical oxidation; deliquescence of the salts; compaction of the material during multiple wet/dry cycling; and surface fouling due to dust, biological matter, and airborne pollutants. Although the MOF structure has good stability, it has the potential to be compromised in humid environments unless stabilized or embedded in polymer matrices [140]. Among the recent studies, the following methods are considered effective in mitigating the durability issues associated with the adsorption capacity of the material: encapsulation of the salts within the polymer networks, the use of composites such as polymer@MOF hydrogel systems, and the application of surface coatings to prevent surface fouling [141].

Water Quality and Safety

An atmospheric water harvesting system should demonstrate compliance with WHO standards for metals, nitrate, and microbiological indicators before distribution. Recent AWH studies demonstrated three contaminant categories of particular concern: (1) metals leached from wet surfaces and heat-exchange/condensing components like Copper, Aluminium, or alloys where corrosion or galvanic interactions occur under varying pH/oxygen conditions [142], (2) organic leachates or extractables from polymeric materials [143], and (3) microbial growth (biofilms, opportunistic pathogens) fostered by stored condensate or wet sorbent surfaces [144–146]. Recent studies of modern sorbents reported that careful materials selection and immobilization strategies greatly reduce salt leakage and organics release, and that embedding MOFs into polymer matrices improves hydrolytic stability [147]. WHO household-treatment guidance recommends at least particle filtration, followed by validated UV disinfection to inactivate bacteria/viruses, and finally remineralization or alkalinity [148] (Table 15).

Table 14
Comparison of life cycle assessment and carbon footprint of atmospheric water harvesting and desalination system.

Technology Type	Energy Source	Typical LCOW (USD /L)	Carbon Footprint (g CO_2 eq /L)	Reference
Atmospheric Water Harvesting	Grid solar	0.06 – 0.17 0.02 – 0.09	95–570 –	Calculated based on the energy consumption
Reverse Osmosis	Renewable Coal power grid	0.0007–0.002 0.0008–0.018	0.1–0.4 1.8–11.7	[136]
Multi-stage flash	Natural gas	0.0015–0.003	6.7	[137]
Electrodialysis	Brackish water RO	0.0002 – 0.001	4.33	[138]
	Solar-powered ED	0.0003 – 0.0015	1.47	[139]

Technology Readiness Level and Real World Deployment Challenges

Although small-scale products and prototypes are available, the commercial use of these technologies is still in its infancy. There are many systems available in a rather experimental or demonstrative status, particularly outside laboratory environments (Fig. 19).

Reviews showed that the available technologies in atmospheric water harvesting, such as sorption, condensation, and fog harvesting, are still in the early stages in the technology readiness level scale, with most systems showing a high potential but with rather low maturity and high costs in real-world environments [153]. This low TRL is especially evident for sorption and advanced material-based systems when compared to conventional water supply solutions, because many designs have not yet been tested at scale outside controlled settings. Fog and dew harvesting integrated into building facades have demonstrated some small-scale feasibility, but remain largely experimental with limited field performance and unclear long–term reliability.

Outlook and Research Directions

This section discusses the directions for future research in atmospheric water harvesting, which must focus on sustainable design principles based on quantitative criteria. Technical feasibility for AWH has been provided in condensation, sorption, and passive fog-based approaches. However, scalability is not restricted by a single factor instead, it is hindered by interdependent thermodynamic, material, and system-level limitations. The major limitation for AWH is the high specific energy required for phase change or sorption processes, which is directly related to the levelized cost of water produced. Therefore, overcoming the scalability limitations requires concerted efforts in materials

Table 15
Water quality standards and treatments.

Parameter	WHO Guideline [149]	Typical AWH Water Results	Reference	Recommended Treatment
pH	6.5–8.5	6.5–7.9	[150–152]	pH adjustment via remineralization
Total Dissolved Solids (TDS) (mg/L)	< 500	1.7–8.71		Remineralization (calcite/dolomite bed)
Total hardness ($CaCO_3$) (mg/L)	100	< 10 mg L^{-1}		Remineralization
Chloride (mg/L)	200	0.7		
Sulphate (mg/L)	200	5		
Magnesium (mg/L)	150–300	32		
Copper (mg/L)	2	0.06		
Calcium (mg/L)	150–300	106		
Iron (mg/L)	0.3	0.09		Sediment filtration (if needed)
Manganese (mg/L)	0.05	0.03		Filtration (if elevated)
Turbidity (NTU)	5	0.1–0.37		Sediment Filtration, Coagulation/ Flocculation + Filtration, Ultrafiltration.
Nitrate (mg/L)	45	0.2		

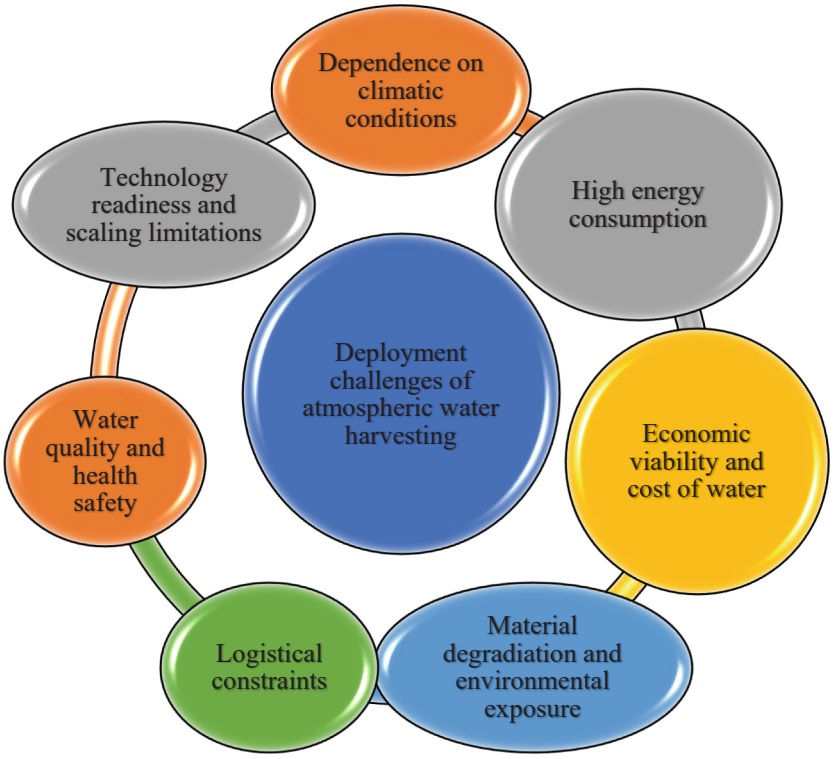


Fig. 19. Real world deployment challenges of atmospheric water harvesting.

development and thermal management and not just incremental improvements in materials properties.

For condensation-based systems, the thermodynamic limitations of cooling large air volumes below the dew point impose an intrinsic energy consumption. At scale, auxiliary loads from compressors and fans dominate total consumption. The most viable pathway toward improving scalability is therefore not further size reduction, but integration with low-grade waste heat, hybrid evaporative pre-cooling, or renewable-driven vapor compression cycles.

Sorption- and MOF-based systems are feasible under low-relative-humidity conditions, but their scalability constraints in heat and mass transfer coupling during adsorption/desorption cycling. Future studies should enhance the interfacial heat transfer between sorbent beds and heat exchangers, structuring or monolithic sorbent architectures to reduce pressure drop. Exploring low-cost synthesis methods (water-based high yield, micro-assisted synthesis, sorption-radiative cooling) and establishing standardized performance testing protocols.

Material innovation remains important, but cost-effective synthesis and long-term durability under cyclic loading are equally critical. Room-temperature or solvent-minimized synthesis routes (mechanochemical production) represent not only a materials advancement but also a pathway to reducing embodied energy and life-cycle emissions at scale.

Passive techniques of fog harvesting are inherently energy-efficient but geographically constrained. Their scalability is therefore spatial rather than technological, suggesting that deployment strategies should be regionally optimized rather than universally expanded.

Across all AWH technologies, climate sensitivity remains constrained. Productivity varies strongly with diurnal temperature swings, humidity fluctuations, and seasonal variability. Therefore, scalability must be evaluated through climate-resolved modeling coupled with long-term field validation rather than steady-state laboratory metrics. Standardized performance indicators and harmonized report are essential to enable cross-technology comparison and realistic techno-economic assessment.

From a technological roadmap perspective, future study should focus on:

- System-level optimization, standardized metrics, and validation under realistic environmental conditions.
- Modular, thermally integrated units capable of coupling with renewable or waste heat sources, alongside improvements in structured sorbent architectures and heat exchanger design.
- Hybrid systems that integrate advanced materials, intelligent control algorithms, and renewable energy infrastructures to minimize LCOW and carbon footprint while maintaining reliability under variable climates.

At the materials science level, advanced characterization techniques including in situ spectroscopy, neutron scattering, and synchrotron X-ray diffraction, combined with molecular simulations can clarify adsorption mechanisms such as hydrogen-bond network formation, capillary condensation, and cooperative clustering. However, these investigations should be explicitly linked to macroscale performance metrics, ensuring that molecular insights transform into improved cyclic stability, reduced regeneration enthalpy, and enhanced heat-transfer efficiency.

Similarly, studies of nucleation and droplet growth dynamics on condenser surfaces must connect microscale (microscopic mechanism) interfacial phenomena with system-scale condensation efficiency and durability.

Conclusion

Atmospheric water harvesting has observed as a promising decentralized approach to supplement conventional water supply systems, particularly in water stressed and limited infrastructure. Unlike desalination and water reuse, which are often challenged by high energy consumption, site dependency, and ecological concerns. AWH offers a unique capacity to leverage widely available atmospheric moisture across diverse climatic zones. However, its practical implementation remains highly site-specific with performance strongly limited by ambient humidity, temperature, and energy consumption. Recent improvements in hygroscopic materials, including metal organic

frameworks, hydrogels, ionic liquids, and ionogels have significantly improved water uptake under arid conditions to overcome the stated challenges. Such as, challenges related to sorbent stability, energy recovery, microbial growth, and system durability continue to impede real-world adoption. While AWH has not reached cost competitiveness with scaled-up seawater desalination, it covers a critical niche where a centralized infrastructure system is not viable to supply off-grid, remote, or disaster relief access to water while maintaining a seawater environment.

CRediT authorship contribution statement

Amir Zanj: Writing – review & editing, Writing – original draft, Supervision, Formal analysis. **Seyoum Nigussie:** Writing – review & editing, Writing – original draft, Validation, Methodology, Investigation, Formal analysis, 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.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ecmx.2026.101928.

Data availability

Data will be made available on request.

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