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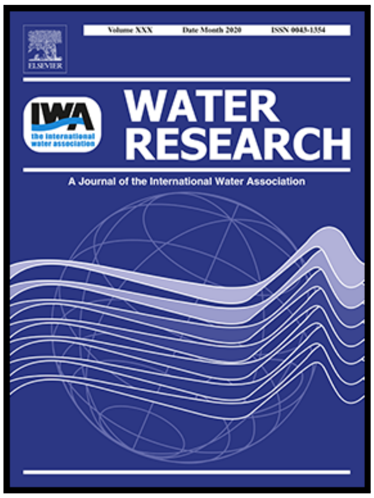

Towards a better understanding of atmospheric water harvesting (AWH) technology

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Highlights

- Extracting water from the sky would be a breakthrough in solving the water crisis.
- Integrated technology is the trend for AWH systems.
- Sustainable energy to drive AWH will be green, energy-saving and efficient.
- Portable and irrigation water supply are two key areas of application for the AWH.
- Advancing the safety and commercial value of atmospheric water is a future goal.

Towards a better understanding of atmospheric water harvesting (AWH) technology

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Abstract

Atmospheric water harvesting (AWH) technology is an emerging sustainable development strategy to deal with global water scarcity. To better understand the current state of AWH technology development, we conducted a bibliometric analysis highlighting three water harvesting technologies (fog harvesting, condensation, and sorption). By comprehensively reviewing the research progress and performing a comparative assessment of these technologies, we summarized past achievements and critically analyzed the different technologies. Traditional fog collectors are more mature, but their efficiency still needs to be improved. External field-driven fog harvesting and active condensation need to be driven by external forces, and passive condensation has high requirements for environmental humidity. Emerging bio-inspired fog harvesting and sorption technology provide new possibilities for atmospheric water collection, but they have high requirements for materials, and their commercial application is still to be further promoted. Based on the key characteristics of each technology, we presented the development prospects for the joint use of integrated/hybrid systems. Next, the water-energy relationship is used as a link to clarify the future development strategy of AWH technology in energy driving and conversion. Finally, we outlined the core ideas of AWH for both basic research and practical applications and described its limitless possibilities for drinking water supply and agricultural irrigation. This review provides an essential reference for the development and practical application of AWH technologies, which contribute to the sustainable utilization of water resources globally.

Keywords: Atmospheric water harvesting, technology, energy, application

1. Introduction

Freshwater scarcity, linked to food security, climate change, environmental quality, and population poverty, has been regarded as one of the world's great challenges (Mekonnen et al., 2016; Koop et al., 2022). The World Health Organization (WHO) reports that more than 2 billion people living in countries with water scarcity are projected to increase in some areas of climate change and population growth (WHO, 2022). Even though 70% of the Earth's surface is covered by water, only about 2.5% of it is freshwater, while just 0.3% is in liquid form (Oki et al., 2006). It is estimated that in 2050, approximately 50% of the world's population will be living in areas of water scarcity. In the past decades, scholars have focused their research on a variety of technologies to explore and exploit potential freshwater resources, including but not limited to seawater desalination (Liu et al., 2019)., rainwater harvesting (Zavala et al., 2018), wastewater treatment (Wang et al., 2022a), etc. However, the geographical environment and climate conditions in remote or inland areas and the problems of cost, energy consumption, and secondary pollution restrict the development of the technology (Pinto et al., 2017; Ejeian et al., 2021). There is therefore a strong need to develop a promising technology to address the situation of remote areas or areas where the economic level does not support a centralized treatment and distribution network (LaPotin et al., 2019).

If surface water is not enough to meet human needs, can we get it from the "sky"? As a huge regenerative reservoir, the atmosphere contains about 12,900 cubic kilometers of water, enough to meet part of the water needs for domestic, agricultural, and industrial purposes (Tu et al. 2018b). Except for microscopic water droplets in fog and clouds, most atmospheric water is in the form of water vapor (Beysens et al., 2000). Water vapor is widely existing in the atmosphere in a molecular state, even in the driest desert regions (Kim et al., 2017). Atmospheric water harvesting (AWH), which produces freshwater by harvesting moisture from the air, enables sustainable water transport where there are no centralized facilities and no geographic and hydrological restrictions (Wang et al., 2022b). A viable AWH technology should satisfy the following primary criteria: efficient water harvesting performance, low energy consumption, cheap, stable, and less constrained by environment and climate (Liu et al., 2022). To date, numerous AWH technologies have been developed from a methodological perspective, such as natural capture (Malik et al., 2014), bionic collection (Liang et al., 2019), vapor compression (Salehi et al., 2020), Peltier effect (Panigrahi et al., 2019), water-absorbing materials (Lu et al., 2022), etc. A bibliometric analysis in the field of AWH was performed using VOSviewer (https://www.vosviewer.com/), and the results are shown in Fig. 1. Keywords that appear more frequently include air, atmospheric water harvesting, adsorption, metal-organic framework, fog, etc. These keywords were divided into four groups after cluster analysis, three of which are classified by different AWH technologies, and the fourth group is divided from the macro concept of AWH, such as performance, system, design, etc. As can be seen from the overlay visualization in Fig.S1, energy, freshwater, and hydrogel are new terms that are appearing in more recent research. Over the past decade, research and development on AWH has been encouraging and prospective (Raveesh et al., 2021). The already developed strategies to extract water from the air mainly include fog harvesting (Yu et al., 2022), condensation (Gido et al., 2016), and sorption-based atmospheric water harvesting (SAWH) (Yang et al., 2021). Fog harvesting uses large nets to capture small water droplets suspended in the air. Condensation harvesting is a phase change process in which vapor in the air is condensed and collected. SAWH uses sorbents and low-grade energy to capture water vapor from the air and produce fresh liquid water. Moreover, the principle of atmospheric water harvesting can be extended to a broader horizon, based on which novel applications have sprung up, spanning the areas of potable water supply, agricultural irrigation, thermal management, humidity management, and power generation. This also makes us realize that mastering the air-water-energy relationship is crucial to achieving sustainable resource management.

Numerous publications have discussed the concept of AWH technology. However, these technologies are large gaps in the level of research and development trends. Therefore, this review aims to provide a better understanding of AWH technologies, to review the current status of each technology development, and to comprehensively discuss them to revisit future directions. A brief diagram of the various AWH techniques is shown in Fig. 2. We highlight the main open questions, what strengths and weaknesses of the current technology, how future research can address these weaknesses, and how to advance the practical application of AWH technology. Given the geographic, climatic, and economic constraints of the global water challenge, we use the atmosphere-water-energy nexus to focus on the potential for wider application of AWH technology in rigorous environments and to present objective requirements for technology development.

2. Atmospheric water harvesting Technology

2.1 Fog harvesting technology

2.1.1 Traditional fog collector

Traditional fog collector is a simple and sustainable technology, achieved by exposing a mesh material to a foggy air mass (Fig. 3a) (Klemm et al., 2012). Some fog droplets are deposited on the mesh material by impaction, combining to form larger droplets, which are collected by gravity and flow into the drain and ultimately into the tank or distribution system (Fig. 3a) (Park et al., 2013; Rivera, 2011; Montecinos et al., 2018). Collectors are divided into standard fog collectors (SFCs) and large fog collectors (LFCs). SFCs are normally applied in exploration studies to assess the volume of water that can be collected as fog water under specific conditions (Fernandez et al., 2018). LFCs are primarily applied in practical fog harvesting (Klemm et al., 2012; Park et al., 2013; Schemenauer et al., 1994). If the SFC has high fog harvesting efficiency, the next move is to put in an LFC. After the mid-1980s, traditional fog harvesting projects achieved great success in Chile and began to be implemented in several parts of the worl (Fessehaye et al., 2014). These regions have a naturally favorable climate and geography, mostly in dry tropical and subtropical climates, and high terrain. The most popular fog collector in most countries is a Raschel mesh placed vertically between two poles to harvest water from fog (Rajaram et al., 2016). The meshes are woven in an approximately triangular pattern with mm-scaled filaments and pores (Fig. 3b). Woven polyolefin Raschel meshes have been a popular collection material with treated UV resistance and a shading coefficient of 35% (Shanyengana et al., 2003). The “Eiffel” is a 3D fog collector composed of two layers of Raschel mesh with 10 strips of mesh. It can be used to collect wind-blown fog parallel to the collector, and its collection efficiency can reach 281.2 L•day^{-1}, which is 10 times higher than the standard full-size fog collector (Fig. 3c) (Lummerich, 2011). But the conditions for fog collection with this ideal wind direction are limited. Because of that, the advent of the "Harp" and "Diagonal Harp" fog collectors have further broken through this limitation

(Fig. 3d-e). They consist of a series of closely spaced vertical stainless steel wires that act like a fog net without horizontal lines to harvest fog from the wind blowing in all directions and also effectively enhance the droplet descent rate to avoid clogging, thereby improving the performance of the collector (Shi et al., 2018). However, most traditional fog collectors only capture a portion of the droplets in a flowing fog, and collection efficiency is low. Some of the droplets will pass through the mesh without hitting the mesh fibers, and some droplets could collide elastically with the mesh fibers back into the air stream. Moreover, most of the current work to improve these systems has focused on the study of the mesh topology of traditional fog collectors. There has not been a sufficient amount of research investment in the functional modification of the mesh surface and the preparation of long-lasting functional surfaces for applications to address the limitations of wind speed, atmospheric humidity, droplet size, and other geographical environmental factors.

2.1.2 External field-driven fog harvesting technology

In recent years, methods to actively control droplets by electric, magnetic, or other fields have attracted much attention (Oliveira et al., 2005). In 2004, Dorvee et al. (Dorvee et al., 2004) demonstrated that superparamagnetic nanoparticles of Fe_3O_4 could be incorporated into porous nanostructures, allowing the material to accompany microliter-scale droplets when applied to a magnetic field. In 2009, Mugele (Mugele, 2009) explained that electro-wetting is used as a generic way to manipulate the typically sub-millimeter size of various microfluidic applications, and discussed how electro-wetting generates from the interaction of conductive liquid drops with externally applied electric fields. In 2017, B. Traipattanakul et al. (Traipattanakul et al., 2017) studied hopping water droplets on superhydrophobic surfaces with electric fields, revealing that the constant electrostatic force acting on the droplets in the air and the maximum electrostatic force acting on the droplets on the superhydrophobic surface droplets are independent of gap width and applied electric field strength.

The mechanism of active droplet control by external field has been successfully applied to the research of fog trapping technology. Cruzat et al. (Cruzat et al., 2018) designed and fabricated an electrostatic fog collector by generating a radial electric field between two electrodes that applied electric power to the fog droplets and guided them to the collection point. Laboratory simulation and outdoor fog collection experiments show that the device has good performance, and the collection efficiency was about 60% higher than that of the traditional fog collector (Fig. 3g). Damak and Varanasi (Damak et al., 2018) argued that traditional fog collectors are inherently limited by aerodynamics. An additional electric force was therefore introduced to overcome aerodynamic drag forces. An ion emitter was used to inject a net charge into the droplets and an electric field is used to direct them to the collector (Fig. 3h). The electric field line runs from the emitter to the ground collector. When the electric forces are much larger than the air drag forces, the fog droplets are deposited along the field line on both sides of the collector wire. The number of fog droplets deposited on the wire was shown to dramatically increases using this technique. However, when the array of wires is used instead of meshes, the fog droplets can pass through the wires, thereby reducing efficiency. When the electrostatic method is used to collect the fog droplets on the mesh, the low shedding rate and blockage of the mesh can reduce the efficiency of the system. Therefore, Seyyedmajid and Hanif (Sharifvaghefi et al., 2021) combined conventional mesh and electric drive techniques to minimize the limitation of shedding rates and aerodynamic deviations from droplets around individual wires. The results show that the total efficiency of the combined system is 84%, which is higher than the efficiency of each method when used alone, and the energy efficiency of the technology can be improved by a factor of 100 compared with the traditional fog collector.

2.1.3 Bio-inspired fog harvesting technology

In some extremely dry deserts, organisms there can use their special structures and functions to capture water mist from the environment to meet their own survival needs. There are many organisms in nature that show the ability of hyperfiltration (Zhang et al. 2017). The diverse interfacial wetting phenomena and characteristics of nature have inspired the design and construction of super-wetted surfaces that can efficiently harvest fog. The design idea of bionics not only opens the door to the field of atmospheric water collection, but also opens another window to solving the problem of water scarcity (Malik et al., 2014).

Namib desert beetle, spider silk, and cactus were once considered nature's best atmospheric water collector. The Namib Desert is close to the sea and is often foggy at night, so the beetles that live there have developed a very unusual ability to collect water (Mitchell et al., 2020). In 2001, Parker and Lawrence (Parker et al., 2001) first discovered that Namib desert beetles harvest water by utilizing a complementary superhydrophobic-superhydrophilic skeleton on their backsides. Tiny droplets will preferentially condense on the hydrophilic bulge and grow rapidly by fusing with each other. Due to the hydrophobic state around the hydrophilic bulge, the grown droplet can easily slip off the surface and fall into the beetle's mouth. The structure of this alternating hydrophilic-hydrophobic region is widely believed to account for its high water collection efficiency (Nørgaard et al., 2010). Inspired by this attractive strategy, scientists have scholars have succeeded in synthesizing a variety of bionic materials based on photolithography (Moazzam et al., 2018), recombination of different wettability materials (Colusso et al., 2019), inkjet printing (Zhu et al., 2018), laser ablation (Kostal et al., 2018) and other methods (Yu et al., 2021; Guo et al., 2022a). To achieve the purpose of efficient water collection. Gou et al. (Gou et al., 2020) fabricated a hierarchical $CuO@TiO_2$-coated surface with alternating hydrophilic-hydrophobic chemistry patterns and modulated the wettability of the $CuO@TiO_2$-coated surface by controlling the deposition time of the TiO_2 multilayer on the copper oxide and the UV irradiation time (Fig. 3i). It is often observed in the early morning or in the field that the spider's web is covered with crystal water droplets, which gather at the intersections of the webs (Bai et al., 2014; Chen et al. 2014). In 2010, Zhang et al. (Zheng et al., 2010) first discovered the directional water-collecting ability of spider silk, and designed and developed micro/nano composite materials mimicking spider silk. Since then, water harvesting research has ushered in the "bionic era of spider silk". At present, bionic spider silk fibers prepared by dip-coating, electrodynamics, fluid-coating, microfluidics and other technologies have been used for efficient water collection in foggy or humid atmosphere (Thakur et al. 2017; Shi et al., 2021a). Biomimetic spindle-junction microfiber with a cavity knot fabricated by Tian et al. (Tian et al., 2017) through a simple gas-in-water microfluidic method have been demonstrated the ability of large-scale and efficient water collection. Liu et al. (Liu et al. 2020) synthesized biomimetic nanofibrils hump fibers (BNFs) capable efficiently trapping of fog droplets and delivering water through channels between nanofibrils under wet conditions, thus allowing droplets to coalesce and be efficiently delivered to the hump for directional collection (Fig. 3j). Cactus's highly efficient fog harvesting system is formed by a combination of Laplace pressure gradient, surface free energy gradient and multifunctional integration (Ju et al., 2012). Inspired by the fog trapping performance, magnetorheological drawing lithography, 3D printing, kirigami cutting, dip coating and spray coating techniques were applied to fabricate various cactus-like FHD. Yi et al. (Yi et al., 2019) developed a magnetorheological drawing lithography method to fabricate 3D cactus-inspired conical spines superimposed on a super-hydrophilic porous substrate (Fig. 3k). Bai et al. (Bai et al. 2020) simplified the cactus-inspired fog harvesting spines from 3D structure into a 2D plane structure through designing a cactus kirigam, which effectively captured the fog droplets and quickly refreshed the collection interface by directional fog droplet self-advancing. In addition to one described above, the fog gathering ability of some other organisms has also been reported and successfully applied to the fog bionic device, such as nepenthes plant (Fan et al., 2021), lotus leaves (Barthlott et al., 1997; Pei et al., 2018; Wang et al., 2022c), lizard (Comanns et al., 2011), leaf veins (Lin et al., 2018), butterfly wings (Ding et al., 2020), moth (Chen et al., 2021a), wheat awn (Ma et al., 2015), and so on.

However, the fog harvesting ability of a single biomimetic surface is limited. With the further development of research, it was widely reported that the fog water collection equipment's designed based on the combination of multiple organisms have amazing fog collection efficiency. Inspired by cactus and beetle, Zhu et al. (Zhu et al., 2021) fabricated six super-hydrophilic wedge-shaped patterns with P25 TiO_2 nanoparticles (NPs) on candle soot nanoparticles-polydimethylsiloxane (CS@PDMS) superhydrophobic coating. This structure not only effectively traps water from the mist but also creates a Laplacian pressure gradient that drives the water away more quickly. Inspired by the natural creatures of beetle, cactus spines, and Nepenthes, Zhao et al. (Zhao et al., 2023) constructed a wedge-shaped slippery patterned surface of hydrophilic lubricant, which has very high water transport, water condensation, and water collection capabilities. Inspired by cactus spines, desert beetle back, spider silk and lotus leaf, Li et al. (Li et al., 2023a) designed a quadruple biomimetic Janus composite material that achieves an excellent fog capture efficiency of 80.57 $mg \cdot min^{-1} \cdot cm^{-2}$ through efficient fog capture and unidirectional droplet transport. It remains a great challenge and a direction to be explored to design a multifunctional fog water collector using the inspiration of multiple biological water harvesting to maximize the efficiency of water harvesting (simultaneous capture, condensation and de-misting of fog water).

2.2 Condensation technology

Condensation technology refers to the process of obtaining fresh water resources from the atmosphere by water vapor cooling and condensation after moist air touches a cooler surface. The earliest use of condensation dates back to 600s BC, when the ancient Greeks first used dew condensers to collect water (Shafeian et al., 2022). The active refrigeration required for condensation is mainly provided by the use of vapor compression refrigeration (VCR), thermoelectric cooling (TEC). Following the same operating principle as refrigerators and air conditioners, VCR-AWH technology has a high energy performance (Kwan et al., 2022). The moist air enters the evaporator of the VCR system with the help of a controlled fan, and the circulating liquid refrigerant receives heat from the air, reduces the temperature below the dew point, condensates and precipitates water on the evaporator coil, and filters it for storage (Raveesh et al., 2021; Peters et al., 2013). At the same time, the cooler air takes the heat away from the condenser and returns it to the environment. A schematic diagram of water production process and commercial device of the vapor compression condense are shown in Fig. 4a. Sahar et al.(Zolfagharkhani et al., 2018) developed a computer program for a flexible thermodynamic model of a gas compression refrigeration cycle dedicated to freshwater production and analyzed water yield and energy intensity under different climatic conditions. In the tropical sample area, the proposed system can produce 22-26 L/day of water, while the energy intensity is between 220 and 300 Wh/L. Trevor et al. (Kwan et al., 2022) conducted a meta-analysis comparing the energy optimality of existing atmospheric water harvesting technologies based on theories derived from the Gibbs free energy principle. The final conclusion is that the vapor compression cycle yields the highest ϕ_{2nd} value, peaking at 12%. Therefore, this is a suitable direction for further development. TEC is an atmospheric water collection method similar to VCR-AWH (Siddiqui et al., 2022). TEC-AWH uses the Peltier effect to apply voltage at the junction of two different metals. The temperature difference occurs at the junction. When humid air contacts the cooling fin located on the cooling side, the temperature gradually decreases and condensates to produce water. The system has many advantages such as compact structure, no moving parts, low maintenance cost, long life and sensitive performance. Shourideh et al. (Shourideh et al., 2018) designed an atmospheric water generator using the Peltier effect with the performance coefficient and water yield of the system as the main design criteria (Fig. 4b). The effects of different wind speeds, relative humidity, and current were tested, and it was concluded that in some cases the inclusion of an intake fan reduced water production, that water production increased with increasing relative humidity, and that increasing the current of a single TEC led to an increase in the rate of water production. Kadhim et al. (Kadhim et al., 2020) built a small prototype with a thermoelectric module to collect water from the atmosphere (Fig. 4c). The system consisted of a solar PV, a Pelletier module, a cold side, a radiator, and a fan to enhance the capacity of condensed water from humid air with minimal energy consumption. It had a maximum water yield of 20 mL/hr and a maximum air flow velocity of 1 m/s. In addition, active condensation technology also includes adsorption/absorption refrigeration and Electromagnetic refrigeration. Adsorption/absorption refrigeration systems (Fig. 4d) generally use lithium bromide or ammonia solution as the circulation mechanism and rely on heat as the driving force to achieve energy conversion (Ibrahim et al., 2016). Electromagnetic refrigeration technology is based on the magnetic heating effect, by controlling the strength of the magnetic field, increasing or decreasing the temperature of the solid refrigerant to achieve atmospheric water collection (Gschneidner et al., 2018). However, the operation cost of these two technologies is high, which is not suitable for the large-scale promotion of single system.

2.3 Sorption technology

In recent years, sorption-based atmospheric water harvesting (SAWH) is the most rapidly developing AWH technology, and a great deal of effort is invested in exploring efficient sorbents and sorption systems to improve the performance of water harvesting (Salehi et al., 2020). The sorption-based AWH work is mainly divided into three steps: 1) water absorption by adsorbents; 2) Use heat to release the heat in the adsorbent; 3) Condensation and liquefaction of water vapor.

2.3.1 Sorbents

Sorbents are the core of SAWH, and rational adsorbents should have the following characteristics (Zhou et al., 2020a): excellent water absorption performance, rapid adsorption/desorption ability, low energy demand, and long-term stable recycling application ability. So far, various sorbents have been extensively developed and studied, and the sorbents commonly used for SAWH mainly include hygroscopic material, metal-organic frameworks, polymeric gels, liquid sorbents, etc.

Hygroscopic material: Hygroscopic materials collect atmospheric water mainly by absorbing water from the surrounding environment, such as silica gel, zeolite and hygroscopic salt materials (Gido et al., 2016). Silica gel and zeolite are the first generation of AWH materials, with abundant polar hydroxyl groups and aluminum metal sites serving as adsorption centers, respectively. However, the low adsorption capacity and poor thermal conductivity of these two materials limit their application in AWH (Ejeian et al., 2021; Gido et al., 2016). Hygroscopic salts are cost-effective adsorbents (Fig. 5a), mainly including CaCl, LiCl, LiBr, etc., which can ensure high water absorption efficiency under medium to low RH conditions (Li et al., 2018; Yang et al., 2020b). Although these hygroscopic salts have received widespread attention in the AWH field due to their water absorption capacity, some key shortcomings limit their practical application, such as their eventual dissolution in collected water resulting in reduced absorption kinetics, poor cycling, and susceptibility to corrosion of operating systems (LaPotin et al., 2019). This problem can be effectively solved by the incorporation of degradable salt into a designed matrix, which acts as a container for salt and the loaded salt traps water molecules (Wasti et al., 2022). Therefore, in order to improve the water collection performance, a lot of studies have been carried out on the development of functional host matrices. At present, the reported matrices mainly include porous materials, fiber matrices, polymer networks and polymer gel. An et al. (An et al., 2023) developed a hygroscope-salt modified MOF ($CaCl_2$@MOF-808-11.8) that overcomes the shortcomings of its respective composition and is seven times more efficient than MOF-808 in water absorption at low RH. It can collect 1.8 kg of water per kilogram of material in a self-made water collection device, and has good structural stability and cycling performance (Fig. 5b). Wu et al. (Wu et al., 2022) employed an economic strategy to develop transition metal superhygrophilic hydrogels, which were constructed by an easy fit between metal salts and ethanolamine (Fig. 5c). Fe and Co ions in the hydrogel served as double adsorption sites to trap water, and the water absorption efficiency was improved by 5.22 g g^{-1} at 95% RH.

Metal-organic frameworks (MOFs): As a new type of porous material, MOFs are widely used in the AWH field (Song et al, 2023). The MOFs water collector is the first device in human history to obtain drinking water from the desert atmosphere. The first-generation MOF water collector was a device equipped with 1.2 kg MOF-801, which produced 100 g of water per kg of MOF-801 per day and night cycle under conditions using only natural cooling and ambient sunlight as energy sources (Fathieh et al., 2018). Standards regarding the energy, material, and air requirements for the actual production of water from desert air should apply to all regions of the world. The second-generation MOF water collector is designed based on the microporous aluminum-based organic framework MOF-303, which can perform adsorption-desorption cycles in a matter of minutes (Hanikel et al. 2019). This opens up new ways to achieve rapid and continuous efficient water collection. Matthew et al. (Logan et al., 2020) conducted parameter studies on nine hydrolytically stable MOFs with different structures (Al-MIL-53, Ti-MIL-125, Zr-UiO-66, Cr-MIL-101, Ti-MIL-125-NH_2, Zr-UiO-66-NH_2, Zr-MOF-808, Zn-ZIF-8, and Cu-HKUST-1), and found that Zr-MOF-808 outperforms in most cases, producing up to 8.66 L_{H2O} kg^{-1}_{MOF} day^{-1}. Hanikel et al. (Hanikel et al., 2023) proposed a linker expansion strategy to generate MOFs with excellent moisture absorption properties, applying this design approach involving experimental and computational results to MOF-LA_{2-1}. This approach increases the void volume of the MOF while retaining its ability to collect water in a long-term cycle in arid environments and reducing regenerative heat.

Polymeric gels: Polymer materials are one of the most important materials in AWH applications, which capture water from the atmosphere and store it in polymer networks. Hydrogels have a highly tunable molecular structure, such as hydrophilic functional groups and ionic sites, and swell during water absorption, not limited by their original pore volume (Salehi et al., 2020). These properties contribute to their super water absorption (Loo et al., 2021). Using an innovative strategy of pore foaming-vacuum drying, Lyu et al. (Lyu et al., 2022) synthesized a simple, low-cost, macroporous hydrogel with a high specific surface area capable of full contact with external air in an AWH device and thus providing unlimited possibilities for large-scale and high-performance AWH. However, the influence of external factors such as temperature and wind speed could lead to the loss of hydrophilic salt during the cycling of the hydrogel. To counter this drawback, Zhang et al. (Zhang et al., 2022) developed a photoresponsive multi-layered pore core-shell hydrogel consisting of a shell sodium polyacrylate (PAAS) hydrogel with an open pore structure and a core thermosensitive poly N-isopropyl acrylamide (PNIPAAm) hydrogel with a large pore size. The mutual and synergistic moisture absorption between the core and shell layers accelerates water capture, transport, and storage, and achieves continuous and high-capacity water adsorption.

2.3.2 Sorption systems

Although superior-performance adsorbents are the focus of adsorption-based AWH technology, the transfer and kinetic properties of adsorbents directly determine the capital cost of AWH during large-scale deployment. The water captured by the adsorbent is released by heating, diffused to the condenser driven by the vapor pressure gradient, and finally collected by liquefaction. Therefore, a reasonable design is required to improve the mass and heat transfer capacity of the sorption bed to achieve better water collection efficiency of the AWH system. To enhance mass transfer, improve energy efficiency and reduce system size, two system designs are commonly used. The system based on water heating desiccants coating heat exchanger uses water cooling and condensation and introduces a sorbent made from a water adsorption heat exchanger to internally cool or heat the desiccant, to further reducing the needed heat source temperature and the outlet air temperature of the desorber (Tu et al., 2017b). A solar photovoltaic driven system on the basis a desiccant enhanced heat pump cools and dehumidifies part of the air, while heating and humidifying the other part (Fig. 5d). When two air streams enter the heat recovering condenser, the moisture in the hot and humid air will get condensed (Tu et al., 2018a). Currently, some scholars proposed new AWH systems assisted by multi-stage desiccant wheels (Li et al., 2023b; Tu et al., 2017a). Tu et al. (Tu et al., 2019) proposed a process in which the air is humidified by multi-stage desiccant wheels and then dehumidified by an evaporator to collect water. This method not only increases the evaporation temperature, but also greatly improves the water collection rate. Using an optimized MOF, Shahvari et al. (Shahvari et al., 2023) developed a multi-stage desiccant wheel system with a 5-20% increase in regeneration efficiency and a 20-40% increase in system dehumidification efficiency. System-level research also lays a good foundation for the integrated/hybrid use of different technologies.

3. Comparative evaluation of different technologies

Table. 1 summarizes all characteristics of known AWH technologies, as well as their respective advantages and drawbacks. Although the traditional fog collectors are well developed and cost-effective system, the whole process of mist capture, droplet supply, droplet transport and removal are difficult to be continuous and its efficiency is low. Different from the traditional means of mist collection by simple passive impact, the active guidance of droplets by external stimuli such as heat, light, magnetic and electricity to triggering droplet movement will help to achieve higher collection effect. The biomimetic water harvesting strategies open another window to solving freshwater shortages by enabling the directional transport of droplets without external energy input to access their own water resources. However, the current bionic mist collectors are relatively immature technologies (such as cumbersome manufacturing processes, complex structures, and low efficiency), making it difficult to achieve commercial applications. At the same time, some bionic water harvesting materials can collect water on a large scale in humid environments, but their water harvesting efficiency in water scarcity or even dry environments is limited or not well studied, and they still face significant challenges in practical applications. Active condensation technology generally needs a high energy input to maintain the continuous operation of the equipment, limited by environmental factors, and is usually applied in the actual industrial production process. Passive condensation technology generally does not require energy input, but environmental temperature, humidity, wind speed, wind direction and vapor pressure have great influence on the process of air water extraction. The amount of water available for collection through passive condensation is limited and may be restricted to the provision of potable water to small communities, being thus not suitable for large-scale applications. Adsorbent based AWH can spontaneously capture water from the environment, and is developed for unsaturated humidity environments. It offers a broader range of RH applications and greater water harvesting capacity. However, the water harvesting and release process also involves differing energy and temperature requirements, and different types of adsorbents have to face different challenges. For example, adsorbents with strong hydrophilicity inevitably make it difficult to release the collected water, and external energy supply is also required to enable hydrolysis and absorption. During the operation of the adsorption system, leakage of adsorbent may corrode the machinery and seriously contaminate the collected clean water. Although technological progress has released great potential and many ideal features, different technologies have their own advantages and disadvantages. In addition, Malik et al. (Malik et al., 2014) proved through research that the productivity of water harvesting is high dependence on weather and climate, and that different locations could have different requirements for the operation of atmospheric water collection devices. Therefore, AWH technology has to be adapted to specific atmospheric collection conditions. In order to meet more technical requirements, the combination of different technologies will be one of the popular research trends in the new generation of AWH systems.

Recent research shown that different AWH technologies can be combined with each other or with other equipment to improve the performance of conventional AWH systems. For example, external field-driven fog harvesting is essentially a combination of conventional fog collection technology and external field-driven technology. In addition to this, effective condensation is the critical to improving the yield of traditional fog harvesting and SAWH, and the combination of bionic concepts with sorption and condensation technologies has also become a new vision for the future development of AWH technology (Haechler et al., 2021; Li et al., 2020b) Ritwick Ghosh et al. (Ghosh et al., 2015) investigated the water harvesting potential of fog collectors installed in industrial cooling towers. This collector currently captures almost twice as much water as the other traditional fog collectors and 40% of the collected water can be reused in cooling towers or treated appropriately as drinking water (Fig. 6a). Guo et al. (Guo et al., 2022b) designed a centimetre-scale super-hygroscopic polymer film that sits on top of a flexible heating plate whose temperature can be controlled by an outside power supply. The condenser walls are inclined at 45° to allow rapid transport of condensed water droplets down the water harvesting channel (Fig. 6b). Vertical heating plates are attached to the other walls to slightly raise their temperature so that water vapor can only condense on the colder condensing surfaces. This integrated technology simultaneously achieves excellent water absorption rate at low relative humidity, low material costs and eco-friendliness. Combining bio-inspired fog collection and interfacial solar steam generation to design an all-day freshwater collection device (Fig. 6c) could achieve a water collection efficiency of approximately 34 L•m^{-2} per day (Shi et al., 2021b). Also, Fig. 6d illustrates a novel atmospheric water harvesting system with synergistic integration of multiple mechanisms, including thermal sorption effects, radiative cooling and multi-scale cellulose-water interactions, to enhance water harvesting performance with minimal active energy input over a relative humidity range of 8% to 100% (Zhu et al., 2023). An outdoor AWH experimental setup demonstrated water capture (water uptake) of up to 6.75 L kg^{-1} day^{-1} (70% RH, 21.6 °C) and water production of up to 5.97 L kg^{-1} day^{-1} with a material cost as low as 3.15-5.86 USD kg^{-1} after eight continuous capture-release cycles at 0.9-1.1 sun (0.9-1.1 kW m-2). 5.86 US$ kg^{-1}. However, despite ongoing progress, many of the ideas in this ensemble/hybridization direction remain conceptual. Rational selection of components and incorporation of functions in combination with the fundamental demands of global water challenges is a key need for the development of quality atmospheric water collector.

4. Energy development strategies

4.1 Sustainable energy drives water harvesting

The three technologies mentioned in section 2 have varying degrees of energy dependency in their application. Natural resources (e.g.: solar, wind) are good substitutes for energy consumed in AWH processes, with the advantages of being abundant, easily available, eco-friendly and sustainable. Solar energy is the most easily obtainable and abundant resource of energy. In general, solar energy may be converted directly into thermal, electrical or chemical energy through creative nanotechnology (Li et al., 2021). The conversion energy obtained could be applied to facilitate the application of AWH technology, and this sustainable cycle is shown in Fig. 7. There are generally two strategies for using solar energy for atmospheric water harvesting. The typical strategy is to use surface cooling technology to condense water in the atmosphere, mainly involving solar-electric compression refrigeration (SECF) and solar-thermal compression refrigeration (STCF). When there is insufficient electricity available for daily use, photovoltaic panel arrays convert solar to electrical energy, which is used to run a specialized compressors and achieve cooling by means of direct current motors. More importantly, the combination of daytime radiation cooling technology and nanomaterials technology breaks through the limitations of low humidity and no electricity. Passive radiative cooling absorbs heat from the surface and radiates it into space as atmospheric transparent infrared radiation (Zhai et al., 2017). This effect allows the cooling foil with hydrophilicity and high NIR emissivity to cool below the dew point temperature of the air, allowing water to condense on its surface (Fig. 8a) (Khalil et al. 2015). Wang et al. (Wang et al., 2021) reported that a layered structured polymethyl methacrylate film with an array of micropores combined with random nanopores enables efficient daytime and nighttime passive radiative cooling (Fig. 8b). To achieve continuous, efficient, and fully passive AWH, Ivan et al. (Haechler et al., 2021) designed a 24-hour AWH system that collaboratively synergistically combines radiative shielding and cooling dissipating the condensed latent heat radiation into outer space with a fully passive superhydrophobic condensates collector using a polymerization-induced water removal mechanism. This system allows us to collect dew at a relative humidity as low as 65% under direct solar radiation and for a longer collection time than existing technologies.

At the same time, this strategy has a greater economic benefit due to freely available and the low servicing requirements. STCF, on the other hand, captures solar thermal energy directly through flat plates and vacuum tubes, and then uses the captured thermal energy for cooling through a heat engine that drives a mechanical compressor. Another strategy is based on adsorption/desorption technology, where the adsorbed atmospheric moisture is desorbed by the solar thermal effect and released by the nanomaterials, which are subsequently collected. In the practical application of atmospheric water collection, it is necessary to combine components such as adsorption beds and solar condenser to form an integrated system. According to different operation modes, it is mainly divided into monocyclic collector, multicyclic collector, dual-stage collector, and automatic seepage collector. Monocyclic harvester performs a daily adsorption-desorption cycle, typically trapping water from the atmosphere at night and releasing it in sunlight (Kim et al., 2018). Multicyclic collector differ from monocyclic collector by carring out numerous sorption-desorption cycles per day, with faster adsorption and desorption kinetics (Li et al., 2020a) Dual-stage collector is formed by design modifications to further increase the top layer temperature, and the daily production rate is roughly twice that of the single-stage configuration (LaPotin et al., 2021). However, conditions such as the necessity of sunlight to carry out and the complexity of the cycling process limit the rate of water harvesting by this technique to some extent. Therefore, Yilmaz et al. (Yilmaz et al., 2020) reported an atmospheric autonomous seepage method for autonomous water release and independent atmospheric water supply without the need for an auxiliary evaporator/condenser.

Wind energy is another promising sustainable driver of atmospheric water harvesting. For example, Fig. 8c shows a commercial wind turbine containing a wind-driven cooling compressor with an output of ~30 kW and a collection volume of ~1000 L•d^{-1}. This integrated system does not have any additional energy requirements other than wind energy.

4.2 Energy conversion

The energy imported in the AWH procedure could be converted into other types of energy, such as electrical and chemical energy (Fig. 8d-e), providing a novel approach to deal with worldwide water and energy crises (Chen et al., 2021b). In the case of AWH systems for power production, for example, for thermal-electric transfer system, the sorption heat released by the hygroscopic material during water sorption is transferred from the sorbent layers to the thermal-electric module, which generates electricity through the thermal-electric effect. As the sorbent layers is exposed to solar radiation to release the water, the thermal-electric module could generate electricity from the extra heat. The technology also allows for the combination of wind and solar energy to increase electricity production dramatically. In addition to this, materials such as MOFs could trap water and carbon dioxide (CO_2) from the atmosphere, and could also be able to generate hydrogen and hydrocarbon fuels by combining the AWH with photocatalytic hydrogen production. In summary, the energy in the AWH process can be efficiently utilized.

Application

At present, the core of AWH technology applications is water-food-energy sustainability, and the most widespread applications are mainly focused on the provision of portable water and agriculture irrigation water. Combined with the analysis of global water challenges, AWH technology is a way to ignore geographic and climatic constraints, is able to address the urgent need for decentralized water supply in poor and disadvantaged areas, and is considered to be the most prospective substitute strategy for transport of portable water and irrigation water in water-scarce areas. An overview diagram of the basic research and practical application of AWH technology is shown in Fig. 9.

5.1 Portable water supply

Extracting water from the atmosphere is often referred to as a 'portable oasis', capable of turning out drinking water almost anywhere in an increasingly thirsty world. Dash et al. (Dash et al., 2015) created a portable device with two Peltier devices that will first condense atmospheric water and then purify it, while reducing energy consumption through the utilization of solar energy, to satisfy the water needs of an average household. The design produces water for drinking that meets the WHO drinking water quality standards, while also meeting the characteristics of ease of use, operational safety, maximum efficiency and minimum cost. He et al. (Shan et al., 2022) demonstrated a high performance, portable water collector to meet individual daily water needs. The water collector has a scalable, low-cost, lightweight sorbent and also shows significant advantages in terms of weight and space of the overall unit. Five typical global climates, including arid, semi-arid and humid climates, were selected to assess its water production potential and impressive record-breaking metrics demonstrate its high yield portable water production that can be achieved almost anywhere at any time. Given that arid regions generally have abundant sunlight, the potential of using solar photovoltaic (PV) systems to enhance low-carbon water harvesters was evaluated, proposing that human-portable thin-film solar cells could be useful for portable water harvesting, while silicon solar cells could power water harvesters in regions where there is no electricity network. Almassad et al. (Almassad., et al. 2022) developed an environmental adaptive device based on MOF that effectively responds to daily changes in weather conditions and continuously produces considerable liquid water in harsh desert conditions, with produced water conforming to Jordanian national drinking standards. In the city of Tel Aviv, Israel, Inbar et al. (Inbar., et al. 2020) carried out the first comprehensive assessment of the chemical properties of water extracted by an atmospheric water generator (AWG) over several months. AWG will provide an outstanding replacement source of safe potable water in a heavily developed city. Portable water from the sky breaks through the limitations of factors such as population density and geographical location and can be applied in arid areas such as deserts and the Gobi desert, making it the best strategy for achieving a safe drinking water supply in the future. It is estimated that a fully functional water production station can produce at least 1100 litres of fresh water per day, which could meet the drinking supply requirements for approximately 150 people, and that the process is safe, reliable, cheap and efficient. This means that the technology is expected to provide a source of life for combat troops, disaster relief teams and people in remote areas far from drinking water sources.

5.2 Agricultural irrigation

AWH technology can provide a sustainable irrigation water source for agricultural development. The AWH system can be miniaturized and modularized independently of existing centralized water supply lines, and can therefore be used for rooftop, farms, and other urban agriculture, easing the pressure on the food supply due to population growth in cities. Taking atmospheric water as the irrigation water source can help to further develop the non-traditional cultivated land resources, effectively increase the area of cultivated land, and improve the economic and ecological benefits (Yang et al., 2023). Li et al. (Li et al., 2022) reported a self-sustained and solar-powered integrated hydropower-crop co-production system based on the atmospheric water adsorption-desorption cycle. The integrated system, which can generate and supply electricity and water to isolated and disconnected communities and can be deployed in arid areas without the need for long-distance water transportation, is expected to make a solid contribution to improving food security in water-scarce areas and the global water-energy-food relationship. Yang et al. (Yang et al., 2020a) developed a wholly automatic, self-sustaining, solar-powered intelligent farm setup in which a copper composite collects and stores atmospheric water at night and effectively frees adsorbed water when exposed to sunlight. Water harvesting and re-irrigation processes could be suitably adapted for optimizing the planting of different types of crops in different climatic areas. As intelligent farms operate, the need for freshwater irrigation water will be significantly decreased, and urban farming like large-scale rooftop farming will become possible. In addition, soil-based super-absorbent gel irrigation systems free crop planting in less developed and arid regions from long distance hydropower supplies and also offer promise in terms of mitigating soil related environmental problems such as global desertification. All three agricultural irrigation systems can be geographically and hydrologically independent (Zhou et al., 2020b). In the future, based on the air water intake technology, the desert into an oasis will become a reality, and the sustainable greenhouse agricultural facilities will provide infinite possibilities for human beings to expand their living space.

5. Conclusions and Prospects

In view of the challenges facing water resources globally, several established and emerging technologies are presented in the review to harvest new water resources from the atmosphere. As established technology, traditional fog collector and active condensation have achieved a certain application base, but efficiency and energy consumption still limit their development. External field-driven fog harvesting, passive condensation, bio-inspired fog harvesting and sorption as emerging technology are gradually developing with the development of new materials and new systems, but the current level of research also restricts the popularization and application of these technologies. From the assessment of the various AWH technologies, we propose that integrated/hybrid systems of different technologies and equipment will be the future trend in atmospheric water harvesting. At the same time, the joint development of technologies and system design can inspire us to overcome geographical, climatic and economic constraints and create new possibilities for the world's supply of safe potable water and irrigated agricultural water. We are confident that AWH technology will deliver fresh water to any part of the world. Despite the tremendous progress made in recent years in AWH technology research, an efficient, sustainable and widely applicable technology has yet to be fully realized. Based on the current comprehensive review, we make the following observations:

- As materials science advances, emerging AWH technologies unlock obvious potential and many expected capabilities. Hybridizing two or more materials may be able to utilize their strengths for enhanced performance. And based on the eco-friendly needs of portable and irrigation water, biomass-based material design will help promote the large-scale application of AWH technology. In addition, the mechanism of water-material interaction and the evolution process of moisture still need to be deeply explored.
- The development of integrated systems is critical to move AWH towards real-world applications. It is still extremely challenging to integrate advanced technologies into an operational module with no compromise its inherent performance. At the same time, combining with functions such as

water quality management, heat conversion, dehumidification and power generation will help to realise the overall potential of the system.

- Solar-powered AWH technology has gradually become a hot topic for future research. When faced with special conditions where solar energy cannot be applied in time, a system with a multi-energy setup would be a good choice. Renewable energy resources including geothermal, industrial waste heat and biomass can also be utilized as supplementary energy supplies for the system.
- The potable water produced by AWH technology must be safe. Current atmospheric pollution problems (e.g. soot particles, heavy metals, organic pollutants etc.) can have a serious impact on water quality. The implementation of this technology is closely linked to the local environmental situation. The solution to this problem can generally be sought in two ways, by adding an air purifier at the front of AWH for pre-treatment of the atmosphere or a water filter after AWH for post-treatment of aquatic products.
- The value of AWH technology research is to achieve commercial dissemination. In order to ensure that technological outputs bring real commercial value, the innovation process of technology should emphasize the combination of technology push and market pull. The cost of user expenditures and the resources acquired should be matched. Follow-up research should strengthen the design and development of low-cost materials and efficient operating systems, and conduct detailed and accurate economic analyses of them, so as to lay the foundation for commercial applications.
- Global water scarcity will eventually lead to the challenge of socio-economic-political traditional constraints in some countries and regions. Research institutions, in collaboration with all levels of government, health organizations and water and environmental associations, can better research, develop, manage and disseminate this technology. This will also make a significant contribution and active influence in overcoming the worldwide water crisis.

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Competing Interests

The authors declare that no competing interests.

Additional information

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References

Almassad, H. A., Abaza, R. I., Siwwan, L., Al-Maythalony, B., Cordova, K.E., 2022. Environmentally adaptive MOF-based device enables continuous self-optimizing atmospheric water harvesting. Nat Commun. 13, 4873.

An, H., Chen, Y., Wang, Y., Liu, X., Ren, Y., Kang, Z., Li, J., Li, L., 2023. High-performance solar-driven water harvesting from air with a cheap and scalable hygroscopic salt modified metal–organic framework. Chem. Eng. J. 461, 141955.

Bai, H., Wang, L., Ju, J., Sun, R., Zheng, Y., Jiang, L., 2014. Efficient water collection on integrative bioinspired surfaces with star-shaped wettability patterns. Adv Mater. 26, 5025-5030.

Bai, H., Zhao, T., Wang, X., Wu, Y., Li, K., Yu, C., Jiang, L., Cao, M., 2020. Cactus kirigami for efficient fog harvesting: simplifying a 3D cactus into 2D paper art. J. Mater. Chem. A. 8, 13452-1345.

Barthlott, W. , Neinhuis, C., 1997. Purity of the sacred lotus, or escape from contamination in biological surfaces. Planta. 202, 1-8.

Beysens, D., Milimouk, I., 2000. The case for alternative fresh water sources. Sécheresse. 11, 1-16.

Chen, X., Li, X., Zuo, P., Liang, M., Li, X., Xu, C., Yuan, Y., Wang, S., 2021a. Three-Dimensional Maskless Fabrication of Bionic Unidirectional Liquid Spreading Surfaces Using a Phase Spatially Shaped Femtosecond Laser. ACS Appl. Mater. Interfaces. 13, 13781-13791.

Chen, Y., Zheng, Y., 2014. Bioinspired micro-/nanostructure fibers with a water collecting property. Nanoscale. 6, 7703-7714.

Chen, Z., Shi, J., Li, Y., Ma, B., Yan, X., Liu, M., Jin, H., Li, D., Jing, D., Guo, L., 2021b. Recent progress of energy harvesting and conversion coupled with atmospheric water gathering. Energy Convers. Manag. 246, 114668.

Colusso, E., Martucci, A., Neto, C., 2019. Fabrication of Biomimetic Micropatterned Surfaces by Sol-Gel Dewetting. Adv. Mater. Interfaces. 6, 1801629.

Comanns, P., Effertz, C., Hischen, F., Staudt, K., Böhme, w., Baumgartner, w., 2011. Moisture harvesting and water transport through specialized micro-structures on the integument of lizards. Beilstein J Nanotechnol. 2, 204-214.

Cruzat, D., Jerez-Hanckes, C., 2018. Electrostatic fog water collection. J Electrostat. 96, 128-133.

Damak, M., Varanasi, K. K., 2018. Electrostatically driven fog collection using space charge injection. Sci. Adv. 4, eaao5323.

Dash, A., Mohapatra, A., 2015. Atmospheric water Generator: To meet the drinking water requirements of a household in coastal regions of India. Department of Mechanical Engineering, NIT, Rourkela, Odisha-769008.

Ding, Y., Tu, K., Burgert, I., Keplinger, T., 2020. Janus wood membranes for autonomous water transport and fog collection. J. Mater. Chem. A. 8, 22001-22008.

Dorvee, J. R., Derfus, A.M., Bhatia, S.N., Sailor, M.J., 2004. Manipulation of liquid droplets using amphiphilic, magnetic one-dimensional photonic crystal chaperones. Nat Mater. 3, 896-899.

Ejeian, M., Wang, R. Z., 2021. Adsorption-based atmospheric water harvesting. Joule. 5, 1678-1703.

Fan, H., Guo, Z., 2021. WO_3-based slippery coatings with long-term stability for efficient fog harvesting. J Colloid Interface Sci. 591, 418-42.

Fathieh, F., Kalmutzki, M.J., Kapustin, E.A., Waller, P.J., Yang J.J., Yaghi, O.M., 2018. Practical water production from desert air. Sci. Adv. 4, eaat3198-.

Fernandez, D. M., Oliphant, A., Bowman, M., Torregrosa, A., Weiss-Penzias, P.S., Zhang, B.J., Sorensen, D., Cohen, R.E., McKinley, G.H., Kleingartner, J.A., 2018. Fog Water Collection Effectiveness: Mesh Intercomparisons. Aerosol Air Qual Res. 18, 270-28.

Fessehaye, M., Abdul-Wahab, S.A., Savage, M.J., Kohler, T., Gherezghiher, T., Hurni, H., 2014. Fog-water collection for community use. Renew. Sust. Energ. Rev. 29, 52-62.

Ghosh, R., Ray, T.K., Ganguly, R., 2015. Cooling tower fog harvesting in power plants - A pilot study. Energy. 89, 1018-1028.

Gido, B., Friedler, E., Broday, D.M., 2016. Assessment of atmospheric moisture harvesting by direct cooling. Atmos Res. 182, 156-162.

Gou, X., Guo, Z., 2020. Hybrid Hydrophilic-Hydrophobic CuO@TiO_2-Coated Copper Mesh for Efficient Water Harvesting. Langmuir 36, 64-73.

Gschneidner, K.A. Pecharsky, V.K., Jiles, D., Zimm, C.B., 2018. Development of vehicle magnetic air conditioner (VMAC) technology. Final report. Office of Scientific & Technical Information Technical Reports. https://doi.org/10.2172/771244.

Guo, J., Huang, W., Guo, Z., Liu, W., 2022a. Design of a Venation-like Patterned Surface with Hybrid Wettability for Highly Efficient Fog Harvesting. Nano Lett. 22, 3104-3111.

Guo, Y., Guan, W., Lei, C., Lu, H., Shi, W., Yu, G., 2022b. Scalable super hygroscopic polymer films for sustainable moisture harvesting in arid environments. Nat Commun. 13, 2761.

Haechler, I., Park, H., Schnoering, G., Rohner, T.G.M., Tripathy, A., Milionis, A., Schutzius, T.M., Poulikakos, D., 2021. Exploiting radiative cooling for uninterrupted 24-hour water harvesting from the atmosphere. Sci. Adv. 7, eabf3978.

Hanikel, N., Prévot, M.S., Fathieh, F., Kapustin, E.A., Lyu, H., Wang, H., Diercks, N.J., Glover, T.G., Yaghi, O.M., 2019. Rapid Cycling and Exceptional Yield in a Metal-Organic Framework Water Harvester. ACS Cent Sci. 5, 1699-1706.

Hanikel, N., Kurandina, D., Chheda, S., Zheng,Z., Rong, Z., Neumann, S.E., Sauer, J., Siepmann, J.I., Gagliardi, L., Yaghi, O.M., 2023. MOF Linker Extension Strategy for Enhanced Atmospheric Water Harvesting. ACS Cent Sci. 9, 551-557.

Ibrahim, N.I., Al-sulaiman, F.A., Saidur, R., 2016. Performance assessment of water production from solar cooling system in humid climate. Energy Convers. Manag. 127, 647-655.

Inbar, O., Gozlan, I., Ratner, S., Aviv, Y., Sirota, R., Avisar, D., 2020. Producing Safe Drinking Water Using an Atmospheric Water Generator (AWG) in an Urban Environment. Water. 12, 2940.

Ju, J., Bai, H., Zheng, Y., Zhao, T., Fang, R., Jiang, L., 2012. A multi-structural and multi-functional integrated fog collection system in cactus. Nat Commun. 3, 124.

Kadhim, T.J., Abbas, A.K., Kadhim, H.J., et al. 2020. Experimental study of atmospheric water collection powered by solar energy using the Peltier effect. IOP Conf. Ser.: Mater. Sci. Eng. 671, 012155.

Khalil, B. Adamowski, J., Shabbir, A., Jang, C., Rojas, M., Reilly, K., Ozga-Zielinski, B., 2015. A review: dew water collection from radiative passive collectors to recent developments of active collectors. Sustain. Water Resour. Manag. 2, 71-86.

Kim, H., Yang, S., Rao, S.R., Narayanan, S., Kaoustin E.A., Furukawa, H., Umans, A., Yaghi, O.M., Wang, E.N., 2017. Water harvesting from air with metal-organic frameworks powered by natural sunlight. Science. 356, 430.

Kim, H., Rao, S.R., Kapustin, E.A., Zhao, L., Yang, S., Yaghi, O.M., Wang, E.N., 2018. Adsorption-based atmospheric water harvesting device for arid climates. Nat Commun. 9, 1191.

Klemm, O., Schemenauer, R.S., Lummerich, A., Cereceda, P., Marzol, V., Corell, D., Heerden, J., Reinhard, D., Gherezghiher, T., Olivier, J., Osses, P., Sarsour, J., Frost, E., Estrela, M.J., Valiente, J.A, Fessehaye, G.M., 2012. Fog as a fresh-water resource: overview and perspectives. Ambio. 41, 221-234.

Koop, S. H. A., Gruson, C., Eisenreish, S.J., Hofman J., Leeuwen, K., 2022. Integrated water resources management in cities in the world: Global solutions. Sustain. Cities Soc. 86, 104137.

Kostal, E., Stroj, S., Kasemann, S., Matylitsky, V., Domke, M., 2018. Fabrication of Biomimetic Fog-Collecting Superhydrophilic-Superhydrophobic Surface Micropatterns Using Femtosecond Lasers. Langmuir. 34, 2933-294.

Kwan, T. H., Yuan., S., Shen, Y., Pei, G., 2022. Comparative meta-analysis of desalination and atmospheric water harvesting technologies based on the minimum energy of separation. Energy Rep. 8, 10072-10087.

LaPotin, A., Kim, H., Rao, S.R., Wang, E.N., 2019. Adsorption-Based Atmospheric Water Harvesting: Impact of Material and Component Properties on System-Level Performance. Acc Chem Res. 52, 1588-1597.

LaPotin, A., Zhong, Y., Zhang, L., Zhao, L., Leroy, A., Kim, H., 2021. Dual-Stage Atmospheric Water Harvesting Device for Scalable Solar-Driven Water Production. Joule 5, 166-182.

Li, H., Zhang, Z., Ren, Z., Chen, Y., Huang, J., Lei, Z., Qian, X., Lai, Y., Zhang, S., 2023a. A quadruple biomimetic hydrophilic/hydrophobic Janus composite material integrating $Cu(OH)_2$ micro-needles and embedded bead-on-string nanofiber membrane for efficient fog harvesting. Chem. Eng. J. 455, 140863.

Li, R., Shi, Y., Shi, L., Alsaedi, M.K., Wang, P., 2018. Harvesting Water from Air: Using Anhydrous Salt with Sunlight. Environ. Sci. Technol. 52, 5398-5406.

Li, R. , 2020a. Improving atmospheric water production yield: Enabling multiple water harvesting cycles with nano sorbent. Nano Energy. 67, 104255.

Li, R., Shi, Y., Wu, M., Hong, S., Wang, P., 2022. An integrated solar-driven system produces electricity with fresh water and crops in arid regions. Cell Reports Physical Science. 3,100781.

Li, W., Dong, M., Fan, L., John, J.J., Chen, Z., Fan, S., 2020b. Nighttime Radiative Cooling for Water Harvesting from Solar Panels. ACS Photonics. 8, 269-275.

Li, Z, Tao, R., 2023b. Performance enhancement of desiccant wheels by adsorption/desorption in stages with type-S isotherm desiccants. Appl. Therm. Eng. 224, 120068.

Li, Z., Xu, X., Sheng, X., Lin, P., Tang, J., Pan, L., Kaneti, Y.V., Yang, T., Yamauchi, Y., 2021. Solar-Powered Sustainable Water Production: State-of-the-Art Technologies for Sunlight-Energy-Water Nexus. ACS Nano. 15, 12535-12566.

Liang, H., Abshaev, M.T., Abshaev, A.M., Huchunaev, B.M., Griffiths, S., Zou, L., 2019. Water vapor harvesting nanostructures through bioinspired gradient-driven mechanism. Chem. Phys. Lett. 728, 167-17.

Lin, J., Tan, X., Shi, T., Tang, Z., Liao, G., 2018. Leaf Vein-Inspired Hierarchical Wedge-Shaped Tracks on Flexible Substrate for Enhanced Directional Water Collection. ACS Appl. Mater. Interfaces. 10, 44815-44824

Liu, X., Beysens, D., Bourouina, T., 2022. Water Harvesting from Air: Current Passive Approaches and Outlook. ACS Mater. Lett. 4, 1003-1024.

Liu, Y., Yang, N., Gao, C., Li, X., Guo, Z., Hou, Y., Zheng, Y., 2020. Bioinspired Nanofibril-Humped Fibers with Strong Capillary Channels for Fog Capture. ACS Appl. Mater. Interfaces 12, 28876-28884.

Liu, Z. Wu, B., Zhu, B., Chen, Z., Zhu, M., Liu, X., 2019. Continuously Producing Watersteam and Concentrated Brine from Seawater by Hanging Photothermal Fabrics under Sunlight. Adv. Funct. Mater. 29, 1905485.

Logan, M.W., Langevin, S., Xia, Z., 2020. Reversible Atmospheric Water Harvesting Using Metal-Organic Frameworks. Sci Rep. 10, 149.

Loo, S.L. Vásquez, L., Athanassiou, A., Fragouli, D., 2021. Polymeric Hydrogels—A Promising Platform in Enhancing Water Security for a Sustainable Future. Adv. Mater. Interfaces. 8,202100580.

Lu, H., Shi, W., Guo, Y., Guan, W., Lei, C., Yu, G., 2022. Materials Engineering for Atmospheric Water Harvesting: Progress and Perspectives. Adv Mater. 34, e211007.

Lummerich A, T. K. 2011. Fog harvesting on the verge of economic competitiveness. Erdkunde. 65, 305-306.

Lyu, T. Wang, Z., Liu, R., Chen, K., Liu, H., Tian, Y., 2022. Macroporous Hydrogel for High-Performance Atmospheric Water Harvesting. ACS Appl. Mater. Interfaces. 14, 32433-3244.

Ma, X. Cao, M., Teng, C., Li, H., Xiao, J., Liu, K., Jiang, L., 2015. Bio-inspired humidity responsive switch for directional water droplet delivery. J. Mater. Chem. A. 3, 15540-15545.

Malik, F.T., Clement, R.M., Gethin, D.T., Krawszik, W., Parker, A,R., 2014. Nature's moisture harvesters: a comparative review. Bioinspir. Biomim. 9, 031002.

Mekonnen, M. M., Hoekstra, A. Y., 2016. Four billion people facing severe water scarcity. Sci. Adv. 2, e1500323.

Mitchell, D., Henschel, J.R., Hetem, R.S., Wassenaar, T.D., Strauss, W.M., Hanrahan, S.A., Seely, M.K., 2020. Fog and fauna of the Namib Desert: past and future. Ecosphere. 11, e02996.

Moazzam, P., Tavassoli, H., Razmjou, Warkiani. M.E., Asadnia. M., 2018. Mist harvesting using bioinspired polydopamine coating and microfabrication technology. Desalination. 429, 111-118.

Montecinos, S. Carvajal. D, Cereced. P., Concha. M., 2018. Collection efficiency of fog events. Atmos Res. 209, 163-169.

Mugele, F. 2009. Fundamental challenges in electrowetting: from equilibrium shapes to contact angle saturation and drop dynamics. Soft Matter. 5, 3377-3384.

Nørgaard, T., Dacke, M., 2010. Fog-basking behaviour and water collection efficiency in Namib Desert Darkling beetles. Front. Zool. 7, 23.

Oki, T., Kanae, S., 2006. Global Hydrological Cycles and World Water Resources. Science 313, 1068-1072.

Oliveira, R. F., Carneiro, L.A., Canάrio, A.V.M., 2005. Behavioural endocrinology: no hormonal response in tied fights. Nature. 437, 207-208.

Panigrahi, N., Venkatesan, K., Ramanan, M.V., 2019. Performance study of thermoelectric cooler using multiphysics simulation and numerical modelling. Int. J. Ambient. Energy 42, 1600-1606.

Park, K.C., Chhatre, S.S., Srinivasan, S., Cohen, R.E., McKinley,G.H., 2013. Optimal design of permeable fiber network structures for fog harvesting. Langmuir. 29, 13269-1327.

Parker A.R., Lawrence, C.R., 2001. Water capture by a desert beetle. Nature, 414, 33-34.

Pei, C., Peng, Y., Zhang, Y., Tian, D., Liu., Jiang, L., 2018. An Integrated Janus Mesh: Underwater Bubble Antibuoyancy Unidirectional Penetration. ACS Nano. 12, 5489-5494.

Peters, G. M., Blackburn, N.J., Armedion, M., 2013. Environmental assessment of air to water machines—triangulation to manage scope uncertainty. Int J Life Cycle Assess. 18, 1149-1157.

Pinto, F.S., Marques, R.C., 2017. Desalination projects economic feasibility: A standardization of cost determinants. Renew. Sust. Energ. Rev. 78, 904-915.

Rajaram, M., Heng, X., Oza, M., Luo, C., 2016. Enhancement of fog-collection efficiency of a Raschel mesh using surface coatings and local geometric changes. Colloids Surf. A Physicochem. Eng. Asp. 508, 218-22.

Raveesh, G. Goyal, R., Tyagi, S.K., 2021. Advances in atmospheric water generation technologies. Energy Convers. Manag. 239, 114226.

Rivera, J. d. D. 2011. Aerodynamic collection efficiency of fog water collectors. Atmos Res. 102, 335-

342.

Salehi, A.A., Ghannadi-Maragheh, M., Torab-Mostaedi, M., Torkaman, R., Asadollahzadeh, M., 2020. A review on the water-energy nexus for drinking water production from humid air. Renew. Sust. Energ. Rev. 120, 109627.

Schemenauer, R. S., Cereceda, P., 1994. A proposed standard fog collector for use in high elevation regions. J. Meteorol. Res., 1313–1322.

Shafeian, N., Ranjbar, A.A., Gorji, T.B., 2022. Progress in atmospheric water generation systems: A review. Renew. Sust. Energ. Rev. 161, 112325.

Shahvari, S. Z., Clark, J. D., 2023. Approaching theoretical maximum energy performance for desiccant dehumidification using staged and optimized metal-organic frameworks. Appl. Energy. 331, 120421.

Shan, H., Li, C., Chen, Z., Ying, W., Poredoš, P., Ye, Z., Pan, Q., Wang, J., Wang, R., 2022. Exceptional water production yield enabled by batch-processed portable water harvester in semi-arid climate. Nat Commun. 13, 5406.

Shanyengana, E.S. Sanderson, R.D., Seely, M.K., Schemenauer, R.S., 2003. Testing greenhouse shade nets in collection of fog for water supply. J Water Supply Res T. 52, 237-241.

Sharifvaghefi, S., Kazerooni, H., 2021. Fog harvesting: combination and comparison of different methods to maximize the collection efficiency. SN Appl. Sci. 3, 516.

Shi, R., Tian, Y., Wang, L., 2021a. Bioinspired Fibers with Controlled Wettability: From Spinning to Application. ACS Nano. 15, 7907-793.

Shi, W., Anderson, M.J., Tulkoff, J.B., Kennedy, B.S., Boreyko, J.B., 2018. Fog Harvesting with Harps. ACS Appl. Mater. Interfaces. 10, 11979-11986.

Shi, Y., Ilic, O., Atwater, H.A., Greer, J.R., 2021b. All-day fresh water harvesting by microstructured hydrogel membranes. Nat Commun. 12, 2797.

Shourideh, A.H., Ajram, W.B., Lami, J.A., Haggag, S., Mansiuri, A., 2018. A Comprehensive Study of an Atmospheric Water Generator using Peltier Effect. Therm. Sci. Eng. Prog. 6, 14-26.

Siddiqui, M.A., Azam, M.A., Khan, M.M., Iqbal, S., Khan, M.U., Raffat, Y., 2022. Current trends on extraction of water from air: an alternative solution to water supply. Int J Environ Sci Technol (Tehran). 20, 1053-1080.

Song, W., Zheng, Z., Alawadhi, A.H., Yaghi, O.M., 2023. MOF water harvester produces water from Death Valley desert air in ambient sunlight. Nat Water. 1, 626-634.

Thakur, N., Ranganath, A.S., Agarwal, K., Baji. A., 2017. Electrospun Bead-On-String Hierarchical Fibers for Fog Harvesting Application. Macromol Mater Eng. 302, 1700124.

Tian, Y. Zhu, P., Tang, X., Zhou, C., Wang, J., Kong, T., Xu, M., Wang, L., 2017. Large-scale water collection of bioinspired cavity-microfibers. Nat Commun. 8, 1080.

Traipattanakul, B., Tso, C.Y., Chao, C.Y.H., 2017. Study of jumping water droplets on superhydrophobic surfaces with electric fields. Int. J. Heat Mass Transf. 115, 672-681.

Tu, R., Hwang, Y., 2017a. Efficient configurations for desiccant wheel cooling systems using different heat sources for regeneration. Int. J. Refrig. 86, 14-27.

Tu, R., Hwang, Y., 2019. Performance analyses of a new system for water harvesting from moist air that combines multi-stage desiccant wheels and vapor compression cycles. Energy Convers. Manag. 198,111811-.

Tu, Y.D., Wang, R.Z., Ge, T.S., 2018a. New concept of desiccant-enhanced heat pump. Energy Convers. Manag. 156, 568-574.

Tu, Y., Wang, R., Zhang, Y., Wang, J., 2018b. Progress and Expectation of Atmospheric Water Harvesting. Joule. 2, 1452-147.

Tu, Y.D., Wang, R.Z., Ge, T.S., Zheng, X., et al. 2017b. Comfortable, high-efficiency heat pump with desiccant-coated, water-sorbing heat exchangers. Sci Rep. 7, 40437.

Wang, M., Zhao, Z., Lin, S., Su, M., Liang, B., Liang, S., et al. 2022a. New insight into the co-adsorption of oxytetracycline and Pb(II) using magnetic metal-organic frameworks composites in aqueous environment: co-adsorption mechanisms and application potentials. Environ. Sci. Pollut. Res. 29, 50177-50191.

Wang, T., Wu, Y., Shi, L., Hu, X., Chen, M., Wu, L., 2021. A structural polymer for highly efficient all-day passive radiative cooling. Nat Commun. 12, 365.

Wang, W., Pan, Q., Xing, Z., Liu, X., Dai, Y., Wang, R., Ge, T., 2022b. Viability of a practical multicyclic sorption-based water harvester with improved water yield. Water Res. 211, 118029.

Wang, Z., Li, H., Yang, X., Guan, M., Wang, L., 2022c. Multi-Bioinspired Janus Copper Mesh for Improved Gravity-Irrelevant Directional Water Droplet and Flow Transport. Langmuir. 38, 2137-214.

Wasti, T. Z., Sultan, M., Aleem, M., Sajjad, U., Farooq, M., Raza, H.M., Khan, M.U., Noor, S., 2022. An overview of solid and liquid materials for adsorption-based atmospheric water harvesting. Adv. Mech. Eng. 14, 1-27.

WHO, 2022. Drinking-Water. https://www.who.int/news-room/fact-sheets/detail/drinking-water.

Wu, H., Xiong, Y., Yu, D., Yang, P., Shi, H., Huang, L., Wu, Y., Xi, M., Xiao, P., Yang, L., 2022. Fe-Co controlled super-hygroscopic hydrogels toward efficient atmospheric water harvesting. Nanoscale. 14, 18022-18032.

Yang, J., Zhang, X., Qu, H., Yu, Z.G., Zhang, Y., Eey, T.J., Zhang, Y., Tan, S.C., 2020a. A Moisture-Hungry Copper Complex Harvesting Air Moisture for Potable Water and Autonomous Urban Agriculture. Adv Mater. 32, e2002936.

Yang, K., Shi, Y., Wu, M., Wang, W., Jin, Y., Li, R., Shahzad, M.W., Ng, K.C., Wang, P., 2020b. Hollow spherical SiO_2 micro-container encapsulation of LiCl for high-performance simultaneous heat reallocation and seawater desalination. J. Mater. Chem. A. 8, 1887-1895.

Yang, K., Pan, T., Lei, Q., Dong, X., Cheng, Q., Han, Y., 2021. A Roadmap to Sorption-Based Atmospheric Water Harvesting: From Molecular Sorption Mechanism to Sorbent Design and System Optimization. Environ Sci Technol. 55, 6542-6560.

Yang, Y., Roderick, M.L., Guo, H., Miralles, D.G, Zhang, L., Fatichi, S., Luo, X., Zhang, Y., McVicar, T.R., Tu, Z., Keenan, T.F., Fisher, J.B., Gan, R., Zhang, X., Piao, S., Zhang, B., Yang, D., 2023. Evapotranspiration on a greening Earth. Nat Rev Earth Environ 4, 626–641.

Yi, S., Wang, J., Chen, Z., Liu, B., Ren, L., Liang, L., Jiang, L., 2019. Cactus-Inspired Conical Spines with Oriented Microbarbs for Efficient Fog Harvesting. Adv. Mater. Technol. 4, 1900727.

Yilmaz, G., Meng, F.L., Lu, W., Abed, J., Peh, C.K.N., Gao, M., Sargent, E.H., Ho, G.W., 2020.

Autonomous atmospheric water seeping MOF matrix. Sci. Adv. 6, eabc8605.

Yu, Z., Zhang, H., Huang, J., Li, S., Zhang, S., Cheng, Y., Mao, J., Dong, X., Gao, S., Wang, S., Chen, Z., Jiang, Y., Lai, Y., Namib desert beetle inspired special patterned fabric with programmable and gradient wettability for efficient fog harvesting. J Mater Sci Technol. 61, 85-92.

Yu, Z., Zhu, T., Zhang, J., Ge, M., Fu, S., Lai, Y., 2022. Fog Harvesting Devices Inspired from Single to Multiple Creatures: Current Progress and Future Perspective. Adv. Funct. Mater. 32, 2200359.

Zavala, M.Á.L., Cruz-Prieto, M.J., Rojas, C., 2018. Rainwater harvesting as an alternative for water supply in regions with high water stress. Water Sci Technol Water Supply. 18, 1946-1955.

Zhai, Y., Ma, Y., David, S.N., Zhao, D., Lou, R., Tan, G., Yang, R., Yin, X., 2017. Scalable-manufactured randomized glass-polymer hybrid metamaterial for daytime radiative cooling. Science 355, 1062-1066.

Zhang, S., Huang, J., Chen, Z., Lai, Y., 2017. Bioinspired Special Wettability Surfaces: From Fundamental Research to Water Harvesting Applications. Small. 13, 1602992.

Zhang, Z., Wang, Y., Li, Z., Fu, H., Huang, J., Xu, Z., Lai, Y., Qian, X., Zhang, S., 2022. Sustainable Hierarchical-Pored PAAS-PNIPAAm Hydrogel with Core-Shell Structure Tailored for Highly Efficient Atmospheric Water Harvesting. ACS Appl. Mater. Interfaces. 14, 55295-55306.

Zhao, C., Li, P., Li, Z., Peng, S., 2023. Incorporation of superamphiphobic and slippery patterned materials for water collection inspired by beetle, cactus, and Nepenthes. New J. Chem. 47, 1962-1972.

Zheng, Y., Bai, H., Huang, Z., Tian, X., Nie, F., Zhao, Y., Zhai, J., Jiang, L., 2010. Directional water collection on wetted spider silk. Nature. 463, 640-643.

Zhou, X., Lu, H., Zhao, F., Yu, G., 2020a. Atmospheric Water Harvesting: A Review of Material and Structural Designs. ACS Mater. Lett. 2, 671-684.

Zhou, X., Zhang, P., Zhao, F., Yu, G., 2020b. Super Moisture Absorbent Gels for Sustainable Agriculture via Atmospheric Water Irrigation. ACS Mater. Lett. 2, 1419-1422.

Zhu, H., Duan, R., Wang, X., Yang, J., Wang, J., Huang, Y., Xia, F., 2018. Prewetting dichloromethane induced aqueous solution adhered on Cassie superhydrophobic substrates to fabricate efficient fog-harvesting materials inspired by Namib Desert beetles and mussels. Nanoscale. 10, 13045-13054.

Zhu, H., Cai, S., Zhou, J., Li, S., Wang, D., Zhu, J., Wu, Y., Huang, Y., Yuan, S., Jin, S., Xia, F., 2021. Integration of water collection and purification on cactus- and beetle-inspired eco-friendly superwettable materials. Water Res. 206, 117759.

Zhu, W., Zhang, Y., Zhang, C., Shan, X., Rao, A.K., Pitts, S.L., Woodbury, T.J., Masnyk, T.S., Derome, D., Warsinger, D.M., Ruan, X., Mauer, L.J., Carmeliet, J., Li, T., 2023. Radiative cooling sorbent towards all weather ambient water harvesting. Commun Eng. 2, 35.

Zolfagharkhani, S., Zamen, M., Shahmardan, M.M., 2018. Thermodynamic analysis and evaluation of a gas compression refrigeration cycle for fresh water production from atmospheric air. Energy Convers. Manag. 170, 97-107.

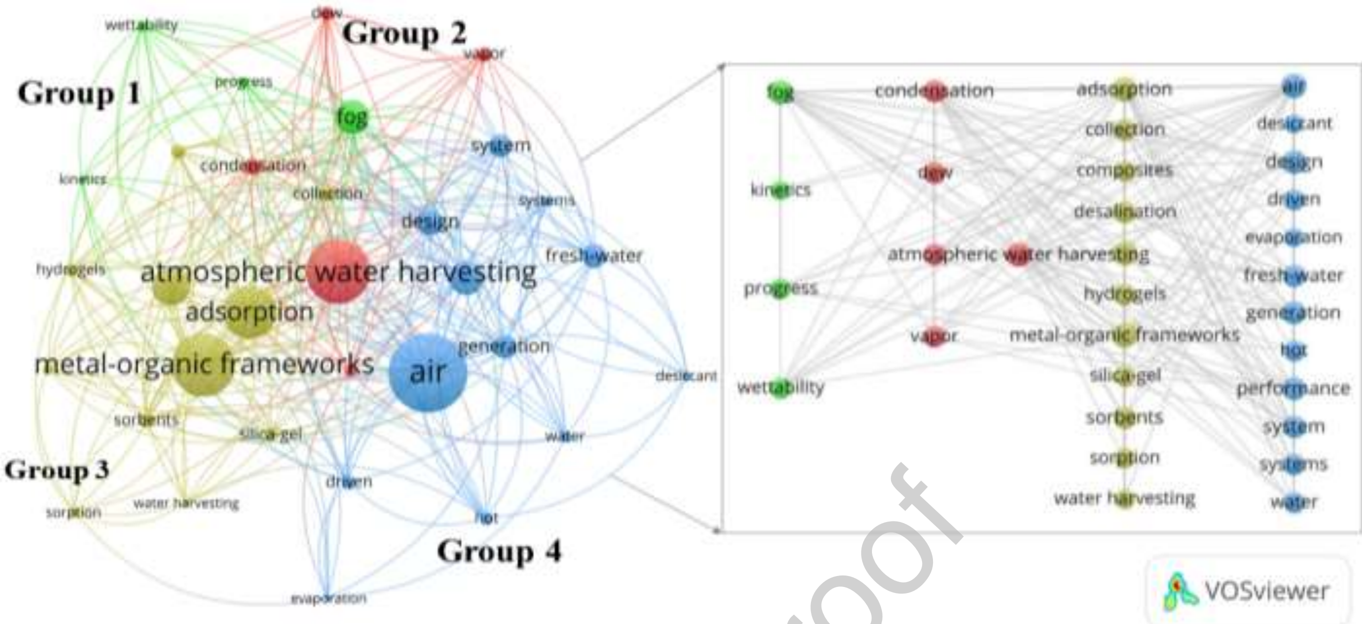


Fig. 1. A bibliometric analysis of the atmospheric water harvesting (AWH). Map of main keywords co-occurrence in the context of the studied subject Network visualization by cluster.

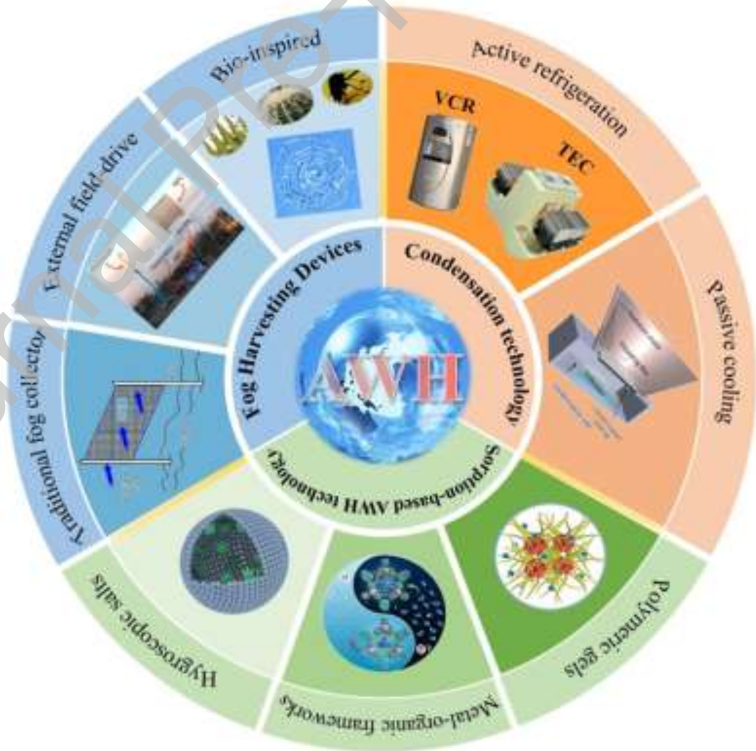


Fig. 2. Various technology for atmospheric water harvesting (AWH).

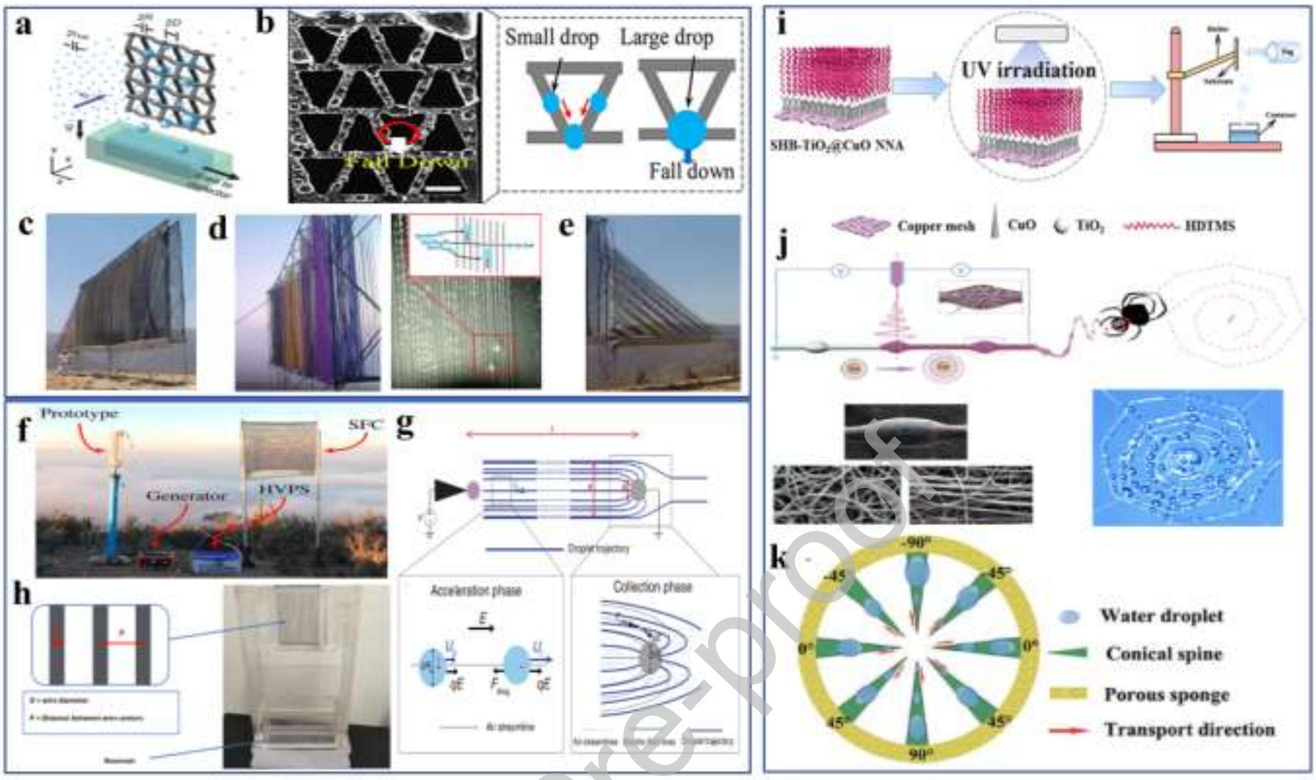


Fig. 3. Fog harvesting technology. a) The basic mechanism of traditional fog collection (Klemm et al., 2012). b) Mist flow on a Raschel mesh (Fessehaye et al., 2014). c) The "Eiffel" fog collector (Shanyengana et al., 2003). d) The "Harp" fog collector (Shanyengana et al., 2003; Lummerich, 2011). e) The "Diagonal Harp" fog collector (Shanyengana et al., 2003). f) Electrostatic fog water collection setup (Traipattanakul et al., 2017). g) Mechanism of droplet collection on a cylindrical wire (Cruzat et al., 2018). h)The fog droplets´ capture and collection section of the fog harvesting system (Damak et al., 2018). i) The preparation procedure of hydrophobic−hydrophilic CuO@TiO2 surface inspired by Namib desert beetles (Yin et al., 2017). j) Spider silk-inspired Nanofibril-Humped Fibers with Strong Capillary Channels for Fog Capture(Tian et al., 2017). k) Fog collection mechanism of a spine-based fog collector (Ju et al., 2012).

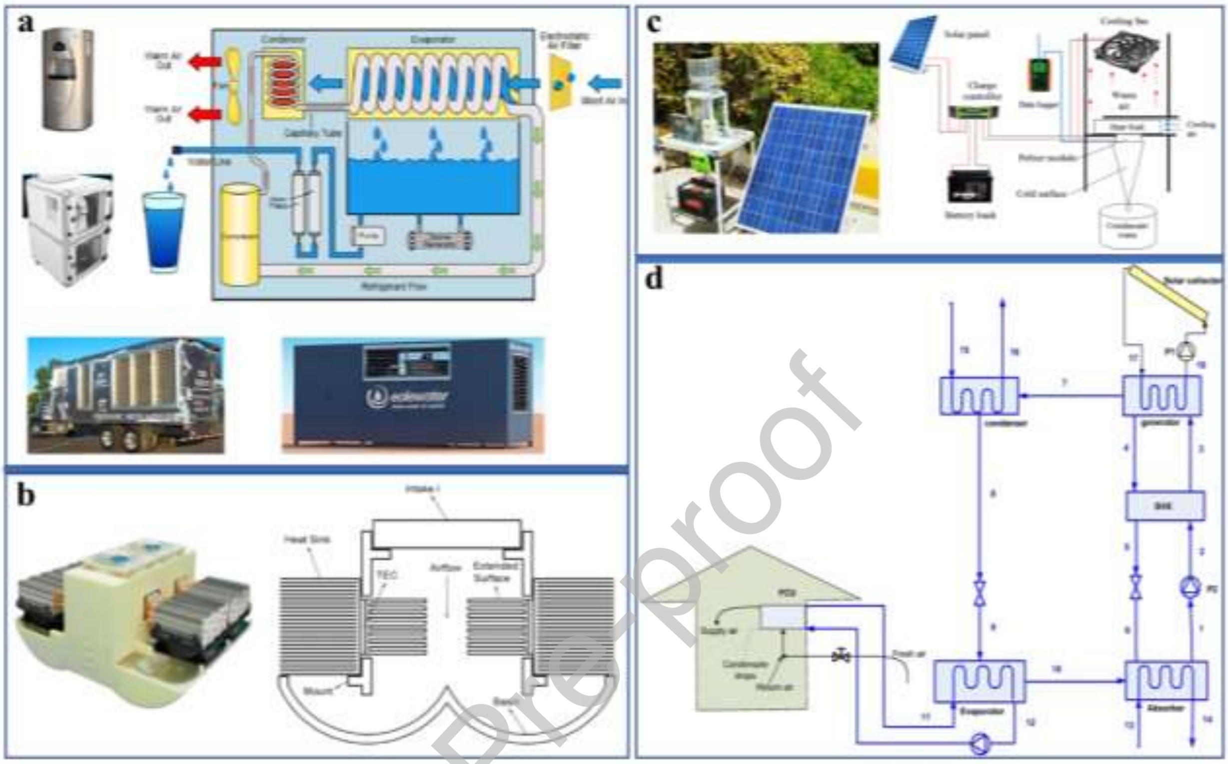


Fig. 4. Condensation technology. a) Water production process and commercial device of the vapor compression condense (Lu et al., 2022). b) Water production device and design concept of the Peltier Effect Method (Siddiqui et al., 2022). c) principle and equipment of solar condenser using Peltier effect (Shourideh et al., 2018). d) The system of absorption chiller (Kadhim et al., 2020).

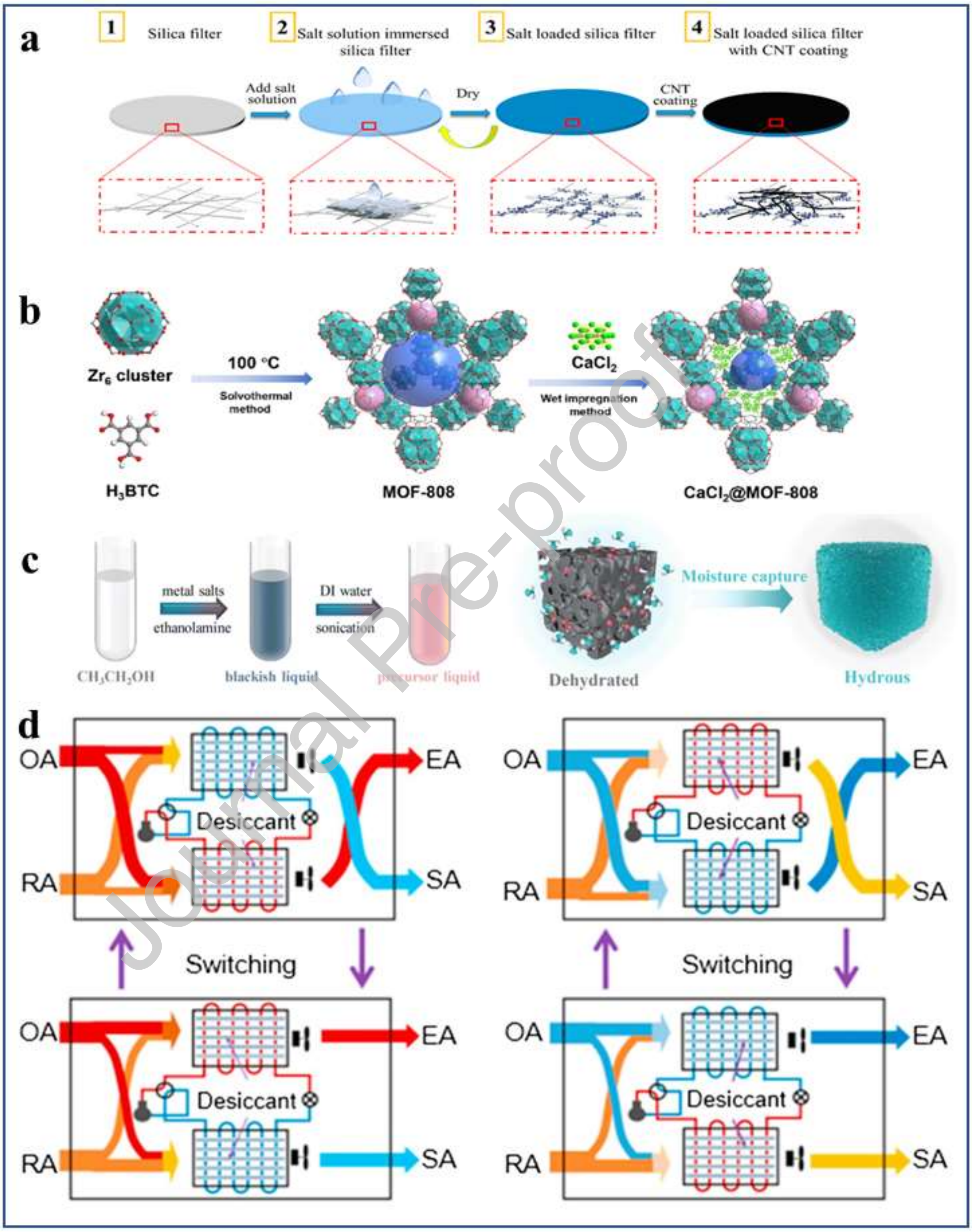
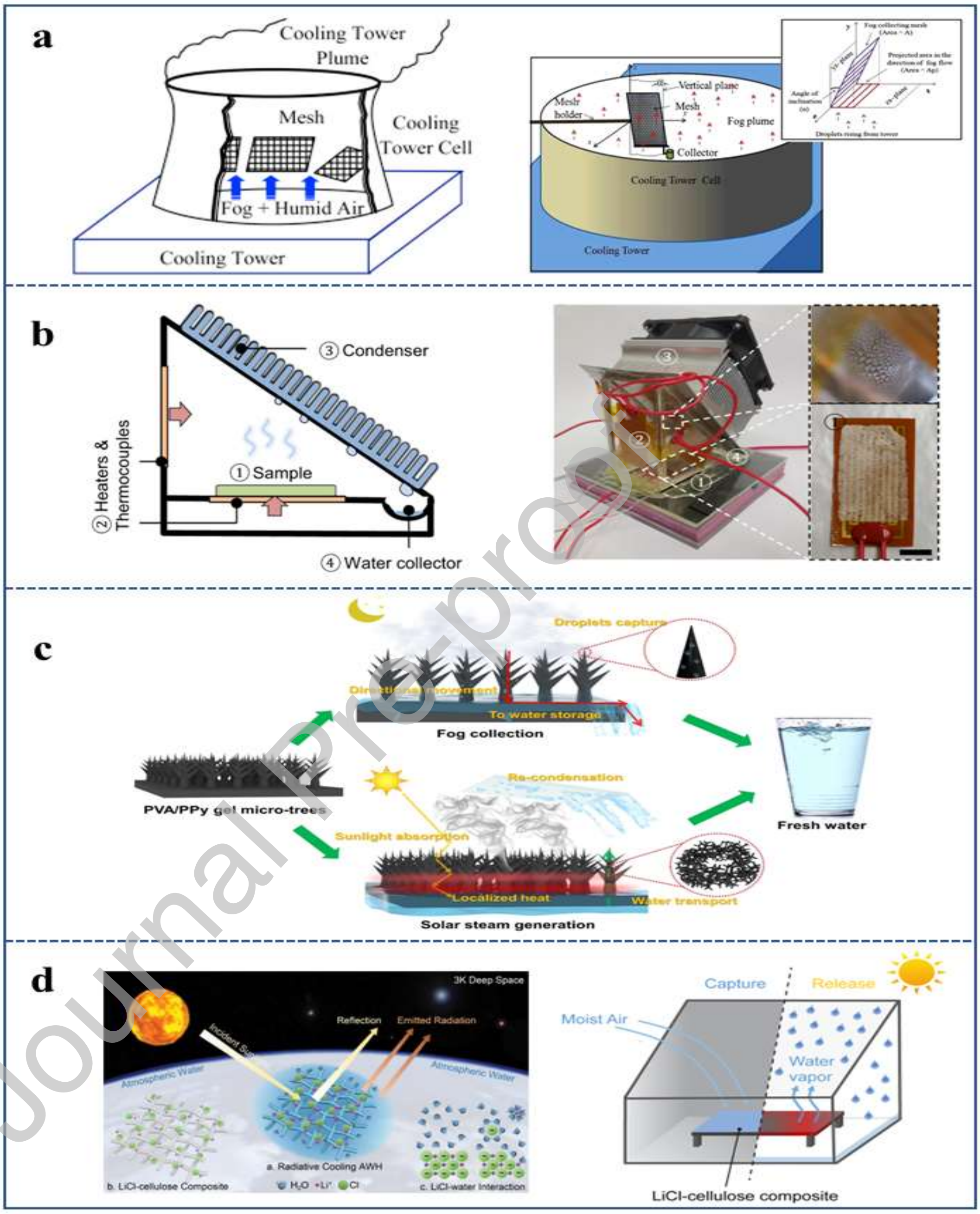


Fig. 5. Sorption technology. Preparation of a) salt-loaded water collector tray (Zhou et al., 2020), b)

CaCl$_2$@MOF-808 composite sorbent (Sun et al., 2021) and c) metal-based hydrogel (An et al., 2023).



d) Working principle of desiccant-enhanced direct expansion heat pump (Tu et al., 2017).

Fig. 6. AWH integrated systems. a) Hybrid of standard fog collector and condensing tower (Li et al., 2020). b) Adsorption atmospheric water collecting device equipped with active condensing device (Ghosh et al., 2015). c) Bioinspired fog collection and interface solar steam generation hybrid methods for all-weather water harvesting concept (Guo et al., 2022). d) Multi-mechanism energy-saving AWH (Shi et al., 2021).

Fig. 7. Sustainable water-energy nexus. Driving and conversion of atmospheric water harvesting by sustainable energy.

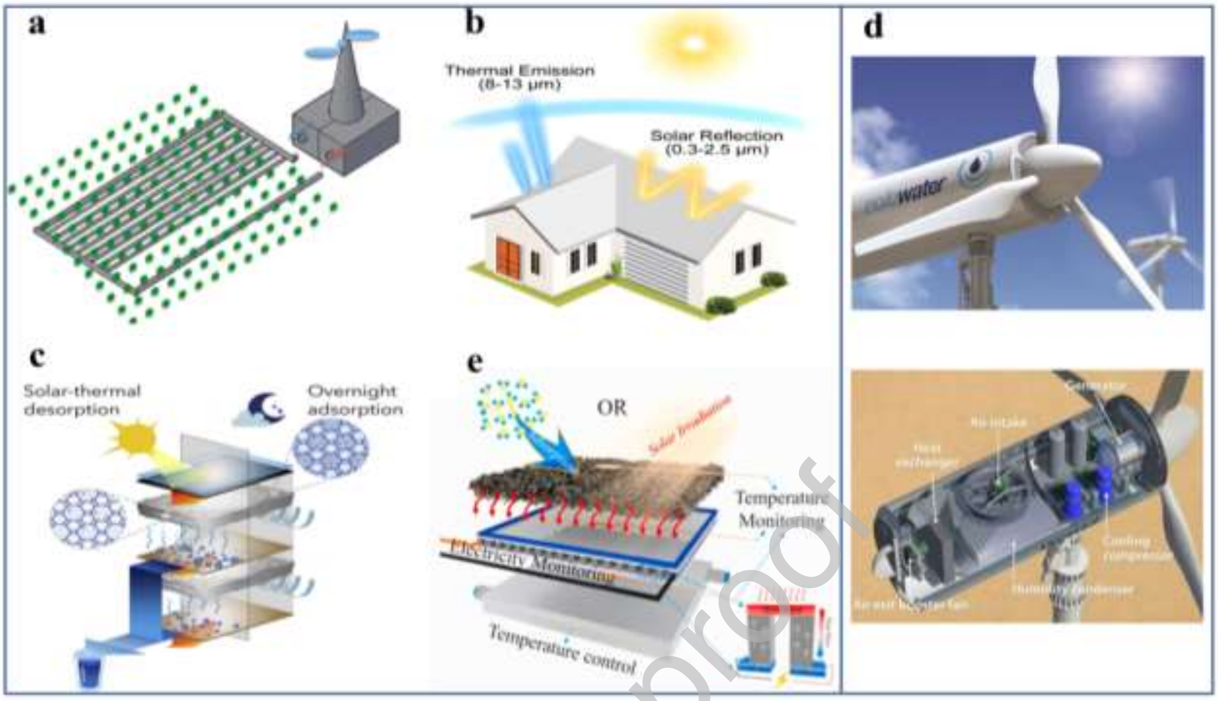


Fig. 8. Energy development strategies. a) An illustration of ground-coupled heat exchanger apparatus with the rotatable turbine tower (Zhai et al., 2017). b) Schematic of the basic principles of passive daytime radiative cooling (Khalil et al. 2015). c)Dual-Stage Atmospheric Water Harvesting Device for Scalable Solar-Driven Water Production (Yilmaz et al., 2020). d) Schematic diagram of the device with a layer of hygroscopic materials and a thermoelectric module (Liu et al., 2022).

Fig. 9. Overview diagram of basic research and practical application of AWH technology.

Table 1 Comparative analysis of different AWH technologies.

AWH technology		key steps	Advantages	disadvantages	Future Perspectives
Fog Harvesting Devices	Traditional fog collector	Droplet nucleation, growth, departure	Low cost. Easy to install. Technology is mature.	Inefficient collection. The mesh is easily clogged. Not enough research has been devoted to the functionalization of mesh surfaces. The application is limited by the geographical environment.	To modify fog mesh design to prevent fog droplets from clogging the mesh gaps.
	External field-driven fog collection technology	Active control of droplets by electric field, magnetic field, etc	Improve the efficiency of fog collection and energy utilization. Lower the construction cost of the collector. Increase the aerodynamic efficacy.	The possible driving mechanisms of internal mobility remain to be further studied.	By designing a reasonable electric field system, the high efficiency of water mist capture can be realized.
	Bio-inspired fog harvesting devices	Wettability gradient, laplace pressure gradient, liquid-gas interfacial tension	It could allow to avoid the water membrane obstruction, droplet retention, droplet accumulation and other problems to be overcome in the high humidity environment. Some biomimetic	The complex fabrication process, high cost and short life of biomimetic materials limit their practical application value.	Based on the multi-scale biomimetics, the industrial production of fog water collection device is developed. Explore a large area applicable, green and environmental protection method.

			materials have ultra-high water collection efficiency per unit mass or area, excellent elasticity, corrosion resistance, and biocompatibility.		
Condensation technology	Vapour compression refrigeration	Energy consumption, no environmental constraints, continuous water intake	The technology is relatively mature. Effectiveness is remarkable. Well-established infrastructure. Primary reliance on electricity supply.	High energy consumption. High expense. Easy to cause environmental pollution. Unable to operate at temperatures below the dew point.	To improve the performance of evaporator coils. To utilize energy saving and environmentally friendly devices.
	Thermoelectric cooling		Simple structure with small number of parts. No need for refrigerant. Long life and easy maintenance.	Higher component costs. Cooling temperature is related to the ambient temperature.	To enhance thermal management.
	Passive cooling	No energy input, radiation cooling	No additional power supply required. Easy to install and deploy.	Higher humidity requirements of the operating environment.	Integration with other technologies.

Sorption-based AWH	Water absorption and release.	Wide applicability and good performance in low humidity environments. Water absorption and release behaviour can be adjusted. More environmentally friendly.	Over-reliance on adsorbent performance. Research is still in its infancy and difficult to commercialize. Fewer system-level operational studies	To develop more economical, environmentally friendly and efficient water-absorbing materials. Optimize system settings to promote large-scale use. To improve water quality and quantity requirements. To strengthen practical application research.

Graphical abstract

Declaration of interests

☒ 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.

☐ The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: