Perspective

Adsorption-based atmospheric water harvesting

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SUMMARY

Atmospheric water harvesting (AWH) is a promising solution to the world's water shortage. Meanwhile, adsorption-based atmospheric water harvesting (ABAWH) has shown a higher ability to supply water in arid areas using clean and cheap energy. Numerous modern adsorbents for this application have been introduced so far, and many prototypes have been provided. However, there is still a long way to go for widespread and practical use of this technology. Dedicated designs, operating strategies, environmental compatibility, and energy supply are issues that still need further consideration. This article has tried to summarize what has been achieved so far in ABAWH, analyze the challenges ahead, and provide solutions to continue the path.

Context & scale

In recent years, humidity has been introduced as a reliable source of water. Among the various technologies, adsorption-based atmospheric water harvesting (ABAWH) has shown apparent advantages, especially in arid areas. So far, most research in this field has been done on developing modern and efficient adsorbents. The difference in climatic conditions and applications makes it impossible to introduce an ideal adsorbent. While adsorption kinetics is preferred in quasi-continuous systems, adsorption capacity is more desired in discontinuous systems. Despite its crucial role, the adsorbent is only part of the process of converting moisture to liquid water in an ABAWH system. Multicycle systems, face challenges such as switching methods, sensible heat, and RH fluctuations. Additionally, in solar-powered systems, an auxiliary energy supply is necessary to continue the production process at night. Moreover, the desorption rate is limited by the distillation rate in the condenser. Using hybrid surfaces and supply cold sources can improve system performance. In this article, we have tried to consider the whole ABAWH system where structures, strategies, and components of a device in various applications, including drinking water, agriculture, and water recovery, have been examined, and the features, challenges, and path

INTRODUCTION

When we turn on the faucet for bathing, we may think that the lack of water is far away from us, but this is not true. By 2025, 1.9 billion people will live in countries or regions with absolute water scarcity, and two-thirds of the world's population will be under stress.[1] Population growth has led to a sharp decline in water resources per capita. This is while the total amount of freshwater resources has decreased mainly because of climate change, which has led to the retreat of glaciers, reduced river flow, and shrinking lakes. Many groundwater aquifers are over-pumped, and the area's annual rainfall is not enough to replace it. Besides, many available water sources are polluted, saline, unsuitable, or inaccessible for drinking, industrial, and agricultural use.[2] Although the optimal use of water can be helpful in many areas, freshwater resources are not evenly distributed across the globe,[3] so many region's economic and social development depends on the development of water resources.

Providing water resources in remote areas can help distribute the population proportionally worldwide and reduce the pressure on existing water resources.[4] Today, seawater desalination is a standard and practical method of water supply. Although seas and oceans cover two-thirds of the earth's surface, access to saline water is impossible for many human communities in landlocked areas. High energy consumption, environmental pollution, high maintenance costs, centralized production, and the need for a distribution network are among the desalination weaknesses.

Humidity is a reliable source of freshwater that is more or less present everywhere on earth. The water volume in the atmosphere is estimated at 12,900 cubic kilometers, six times the total volume of rivers worldwide.[5] This water source can meet part of water demand in the drinking, agricultural, and even industrial sectors. If we assume a certain volume of humid air as a thermodynamic system, reduction in entropy and enthalpy are required to change the phase of water from vapor to liquid, so energy must leave the system. The transfer of latent water vapor energy is possible only when the ambient temperature is lower than the dew point temperature. This happens in only two cases. One is to place the system in the vicinity of a cold source with a temperature below the dew point, as with direct cooling and dew collection systems. The second case is that by increasing the system pressure, the dew point temperature rises above the ambient temperature. This increase in pressure can be absolute or partial, meaning that only the water vapor pressure increases, as occurs in membrane-based systems.[6]

The supply of cold source in direct cooling systems consumes high energy, either using conventional compression cycles[7] or using the Peltier effect.[8] The lower the relative humidity of the air, the lower the dew point temperature, and as a result, the difference between the ambient temperature and the dew point temperature will be greater, which will increase energy consumption exponentially. Simultaneously, a significant amount of energy is spent on the useless cooling of moisture-carrying air. Moreover, when the dew point is below 4.5°C, direct cooling systems require a unique design and a high amount of energy to be able to produce water.[9,10] In membrane-based systems,[6] the lower the air's absolute humidity, the more energy is consumed per unit mass of water produced because more air mass must be compressed. This makes these technologies practically inefficient and not economically viable for use in arid and semi-arid regions.

Water augmentation technologies like cloud seeding[11] and fog collection[12,13] do not require heat transfer, as these two methods bind liquid water particles in the air to form a droplet, and no phase change occurs.[14] Nevertheless, cloud seeding is expensive, and its efficiency is still under evaluation. Also, fog is only available in limited areas on some days of the year. Tu et al.[14] and Salehi et al.[10] have presented comprehensive studies to compare different methods of producing water from humidity.

Adsorption-based systems are commonly known as chillers,[15] heat pumps,[16] and desalination units.[17] The main advantage of these systems is the increase in pressure by using low-temperature thermal energy to replace the compressor's mechanical work. This advantage allows adsorption systems to operate using inexpensive and clean energy such as solar energy or waste heat instead of electricity.

In recent years, utilizing adsorption technology to produce water from air humidity has been the subject of research by reputable scientific centers worldwide. Compared with other methods, the most critical advantage of adsorption-based atmospheric water harvesting (ABAWH) is its ability to produce water at low relative humidity. Depending on the adsorbent, ABAWH can produce water from scorching deserts to the tropics. Also, the rate of the increase in energy consumption per unit of water produced with a decrease in relative humidity is much less than other technologies because the sensible heat of the adsorbent and the device's body is a constant amount.

In the major studies and reviews presented so far, the main focus is on developing adsorbents in terms of the amount of water adsorption mass and the adsorption/desorption kinetics. Despite the undeniable importance of adsorbents, many parameters can affect an atmospheric water harvesting (AWH) system's performance. Even if it does exist, an ideal adsorbent does not guarantee system functioning. As with other applications of adsorption technology, mass and heat transfer may play a crucial role in system performance.[18,19]

The valuable articles by Zhou et al.[20] and LaPotin et al.[18] focus on the development of adsorbents and can provide complete information about adsorbents' future.

ahead of each have been described with examples and practical ideas. This article can guide designing and optimizing ABAWH devices toward widespread use of this technology.

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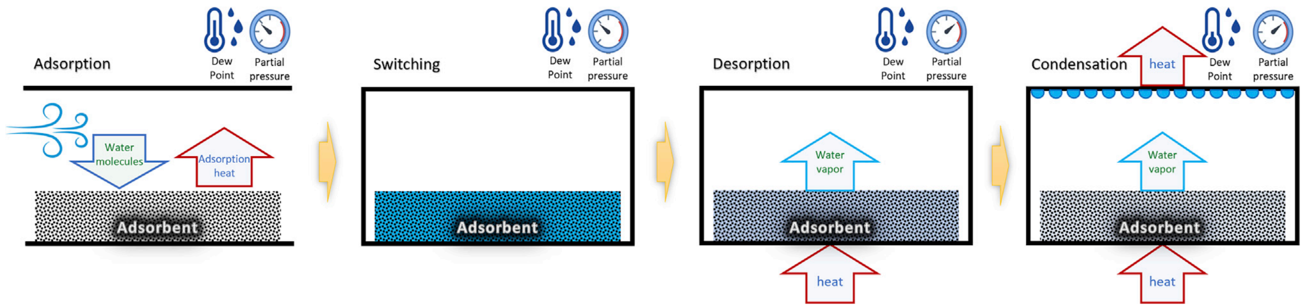

Figure 1. Schematic of adsorption-based atmospheric water harvesting working procedure

Therefore, we suffice here with a brief look at the adsorbents. In this article, we try to provide an overview of the development of ABAWH-related devices. Hence, while discussing key design points, we examine the problems and challenges facing the expansion of ABAWH uses.

GENERAL STRUCTURE OF ABAWH

In ABAWH, the adsorption phenomenon can increase the partial pressure of water vapor in the system during an open and discontinuous cycle. The basics are simple. As shown in Figure 1, the adsorbent is first exposed to the open air to adsorb moisture owing to its hydrophilicity. The system is then closed, and the adsorbent is heated. As the adsorbent temperature increases, the hydrophilicity of the adsorbent disappears, and water vapor begins to desorb. The release of water vapor in a closed environment increases the system's partial pressure slightly. In the condenser, water droplets form owing to heat exchange with a cold source with a temperature below the dew point of the system's inside. Once the droplets have grown enough, they leave the condenser owing to gravity and enter the collection tank.

ADSORBENTS

The adsorbent is the heart of adsorption technology. Many adsorbents have been introduced for various applications so far, and much research is being done on the development of modern adsorbents. In general, adsorbents can be classified as follows.

Physical adsorbents

Silica gel is a three-dimensional porous polymer composed of quadrilateral units of silicon dioxide. Silica gel is a suitable adsorbent for a wide range of materials such as water, alcohol, phenols, and amines, which address through hydrogen bonds. Various silica gel grades have been produced so far, which follow type I or VI of adsorption (based on IUPAC classification), depending on the cavities' size. Low cost, commercial availability, low regeneration temperature, non-toxicity, and good adsorption kinetics have made silica gel widely used across all applications of adsorption technology.[21] However, silica gel generally has a low adsorption capacity, especially at low RH, and is not a good thermal conductor, limiting its use in ABAWH.

Zeolite can be considered the first adsorbent used in a device based on adsorption and is still one of the main adsorbents of adsorption technology. Zeolite is a type of alumina silicate crystal combined with alkaline or alkaline earth elements present in different grades, both mineral and artificial. The aluminosilicate structure has a cage shape and is usually associated with six groups of pores that can adsorb large amounts of extra molecules. However, high regeneration temperature, low adsorption capacity, and poor thermal conductivity can be weaknesses of zeolites. In recent years, different grades of zeolites like aluminophosphates[22] have been introduced that have promising properties.

Polymeric adsorbents

Metal-organic frameworks (MOFs) are a subclass of coordination polymer that includes metal ions or clusters of ions coordinated with organic ligands to form one-, two-, or three-dimensional structures. High adsorption capacity, high porosity, very high specific surface area, the ability to adjust the uniform pore size, low density, high biocompatibility, and low enthalpy of desorption process are the most critical advantages of MOFs. What makes MOFs attractive for using ABAWH is the ability to optimize the adsorbent to suit the application, using hydrophilicity adjustment, pore size, and adsorbent geometry.[20] However, no MOFs have been designed on this approach so far, and many studies that have focused on the MOFs have used existing types. The stability of moisture-adsorbing MOFs is a challenge because, in the presence of water molecules, the hydrolysis reaction can destroy metal-ligand bonds, so water-stable MOFs require strong coordination bonds or considerable steric hindrance.[23] The uniformity of the holes also makes it challenging to create macropores to transfer mass to the adsorption site, so controlled compression[24] or host metal matrixes[25] are employed. On the other hand, MOFs are expensive and barely commercially available, making the prospect of their widespread usage dependent on increasing global demand and investment. In addition, the toxicity of MOF still needs further evaluation. The presence of metal ions and functional groups, the crystal's size, and the solvent residues used in the synthesis can be effective in possible toxicity.[26] Moreover, water-adsorbing MOFs generally have low thermal conductivity. Valuable articles[27–30] have been written introducing MOFs' structure and application that can be useful for a deeper understanding.

Hydrogels are widely used in our daily lives and include various applications from tissue engineering to personal hygiene products that generally absorb water from the liquid phase in significant volumes. Hydrogels that have the ability to adsorb moisture have been considered in recent years for the use of ABAWH. The desired functionality, high adsorption capacity, high adsorption density, cyclic stability, and operation in a range of relative humidity are the main advantages of hydrogels.[31] Unlike MOFs, hydrogels are not inherently porous; however, there are standard methods to create porosity, such as the use of reduced graphene oxide,[31] controlled freezing,[32] and electrospinning technique.[33] Also, the adsorption kinetics in hydrogels are relatively slow, and they generally face swelling.[34] In recent years, efforts have been made to increase adsorption kinetics and water retention by adding metal bonds to polymer chains.[35–37] Hydrogels also have a significant ability to host and immobilize other hydroscope materials like LiCl and $CaCl_2$.[35,37,38] The high capacity for storing liquid water contributes to this property. Another significant point is the high compatibility of hydrogels with applied materials that can be used to improve mechanical properties such as photothermal performance and thermal conductivity.[35,36] By copolymerizing two or more different monomers, different properties can be created in a polymer network.[39] This feature also makes it possible to create optical, electrical, and electrochemical properties in a hydrogel that can aid in adsorbent side applications.[40,41]

Supposing that the adsorbent expels the adsorbed water molecules in liquid form while eliminating the distillation process and the need for a cold source, a much lower enthalpy is expected for the desorption process. In a study conducted by

Zhao et al.,[34] the integration of hygroscopic/hydrophobic polymers at the molecular scale in a network with controlled interaction between gels and water molecules adsorbs moisture and liquefies it *in situ*. This results in a high density of water sorption and the release of water in liquid form, which can create a new method in AWH, requiring a separate hardware structure. For more information on moisture-sorbing hydrogels and their uses, see the article published by Guo et al.[39]

Chemical sorbent

Hygroscopic salts are common sorbents that can participate in the sorption process in both anhydrous and soluble salts. The sorption of water vapor by anhydrous salts is a hydrothermal hydration reaction[42] and occurs in solution owing to the vapor pressure gradient.[43] The high ability of some salts to sorb water causes the salt crystals to dissolve in the taken water. Deliquescence relative humidity (DRH) refers to the relative humidity in which salt changes from a solid phase to a saturated solution.[19] The use of high DRH salts such as $MgSO_4$ and $CuCl_2$ results in adsorbent stability in the solid phase.[42] However, deliquescence salts such as LiCl and $CaCl_2$ have a higher sorption capacity and, besides, can continue to sorb moisture by decreasing the concentration in the solution phase. A solution of a deliquescence salt can capture water vapor molecules on the surface of the liquid and transfer them into the solution owing to the difference in concentration. This spontaneous mass transfer provides an opportunity for continuous water production.[43,44] Chance of contamination, the possibility of equipment corrosion, and the limited exposure surface to fresh air are the challenges of liquid sorbents.[10]

Composite sorbent

Hygroscopic salts have a high ability to make composites to improve mass and heat transfer and/or boost the hydrophilic properties. The host matrix, such as activated carbon fiber felt[45] and hollow carbon sphere,[46] can just create a stable and porous environment for the solid phase and fixed and unmovable conditions for the solution through the capillary effect.[45,47] Such a composite can be called three-phase sorption by adsorbing water vapor in the solid phase and continuing in the liquid phase.[45] In this case, even though the adsorbent is solid in the macroscopic dimension, it also has the advantage of transferring the mass to the inner layers through diffusion.[47] The host matrix can also be a moisture adsorbent like silica gel[48] and MOF,[49] in which case, because of the variety of adsorption factors, the kinetics will be faster, and also the composite will be functional in a broader range of RH. The presence of liquid phase sorbents[38] can also improve the sorption and storage capacity of the adsorbent. Besides, the use of two salts in the production of composites prevents the production of an impenetrable salt lattice, which results in better mass transfer and faster kinetics.[50]

Hygroscopic salts are cheap and widely available in the market and generally offer linear isotherms. This means that they can operate in a wide range of relative humidity. However, potential corrosion, agglomeration, leakage, and high desorption enthalpy are the issues that need to be addressed in using hygroscopic salts and their composites.

DEVICES

Materials scientists usually emphasize yield water production rate ($g_{water}/g_{adsorbent}$) in a cycle[29] but may usually neglect the fundamental parameters such as the size of an AWH device, the energy consumption per liter of water produced, and materials cost. Also, as an adsorption process is followed by a desorption process, the cycle time of the device be vital. So far, many systems have been introduced that can be evaluated in terms of the number of beds, the number of cycles per day, whether active or passive and the amount of water production.

The device is active or passive in four aspects. Heating the adsorbent, supplying fresh air, transferring mass from the adsorbent bed to the condenser, and switching between the adsorption and desorption process. A system can be active in all or part of these aspects. The closer the system is to the passive state, the less equipment and energy consumption is needed. Typically, a device is called passive when the sunset and sunrise determine the switch between the process of adsorption and desorption.

Two types of strategies can be adopted for the operation of the device. In the first strategy, during a 24-h cycle, moisture is adsorbed at night and desorbed and distilled during the day, while in the second strategy, several cycles of adsorption and desorption are repeated during the day. The choice between these strategies depends on the expected production volume and application. In most devices built so far, the first method has been adopted in proportion due to the fact that it is also suitable for using solar energy, and the second method has been mentioned only in some concept designs and small prototypes.[51] However, most of the adsorbents introduced so far have been developed by looking at the second method. This can be influenced by borrowing essential features from previous research on chillers and desalination plants.

An adsorption-based system cannot operate continuously.[19] Therefore, any system with only one adsorbent bed is inevitably subject to discontinuous operation unless it creates a quasi-continuous process by increasing the number of beds and simultaneous operation with phase differences. Therefore, ABAWH systems can be divided into two major categories, discontinuous or quasi-continuous operation.

Two different structures for discontinuous systems have been proposed so far. The first structure is similar to solar stills.[52] The adsorbent bed is located on the floor of a box. A sloping glass cover is placed on the box, which practically acts as a condenser(Figure 2A).[53] Fathieh et al.[54] moved the condenser to the sidewalls using a reflective cover around the adsorbent bed (Figure 2B). Moisture adsorption occurs at night. During the day, direct sunlight on the adsorbent causes desorption. Hot water vapor rises and is distilled on the glass surface owing to the heat transfer. Increasing the size of the droplets causes it to slip on the sloping surface of the glass, and eventually, water is collected in the tank. The system is opened and closed manually, but other parts of the system are completely passive.[53]

Placing the heat source under the condenser creates a convectional heat transfer current inside the system, which, although it helps to transfer mass, also causes heat loss. The formation of water droplets on the glass also reduces the penetration of the sunray. Also, the heat transfer rate and distillation on the glass are limited owing to the low thermal conductivity of glasses.[55]

In another structure of passive discontinuous systems, the adsorbent bed is located at the top of the device, and the condenser is located at the bottom (Figures 2C and 2D). In these systems, the mass is transferred from the bed to the condenser owing to water vapor diffusivity in air.[24,47,56] Given that almost all such devices are built on a very small scale, mass transfer is not a problem. However, in a larger-scale device, the mass diffusivity cannot be relied on alone. Therefore, a passive or an active mechanism is needed for mass transfer.

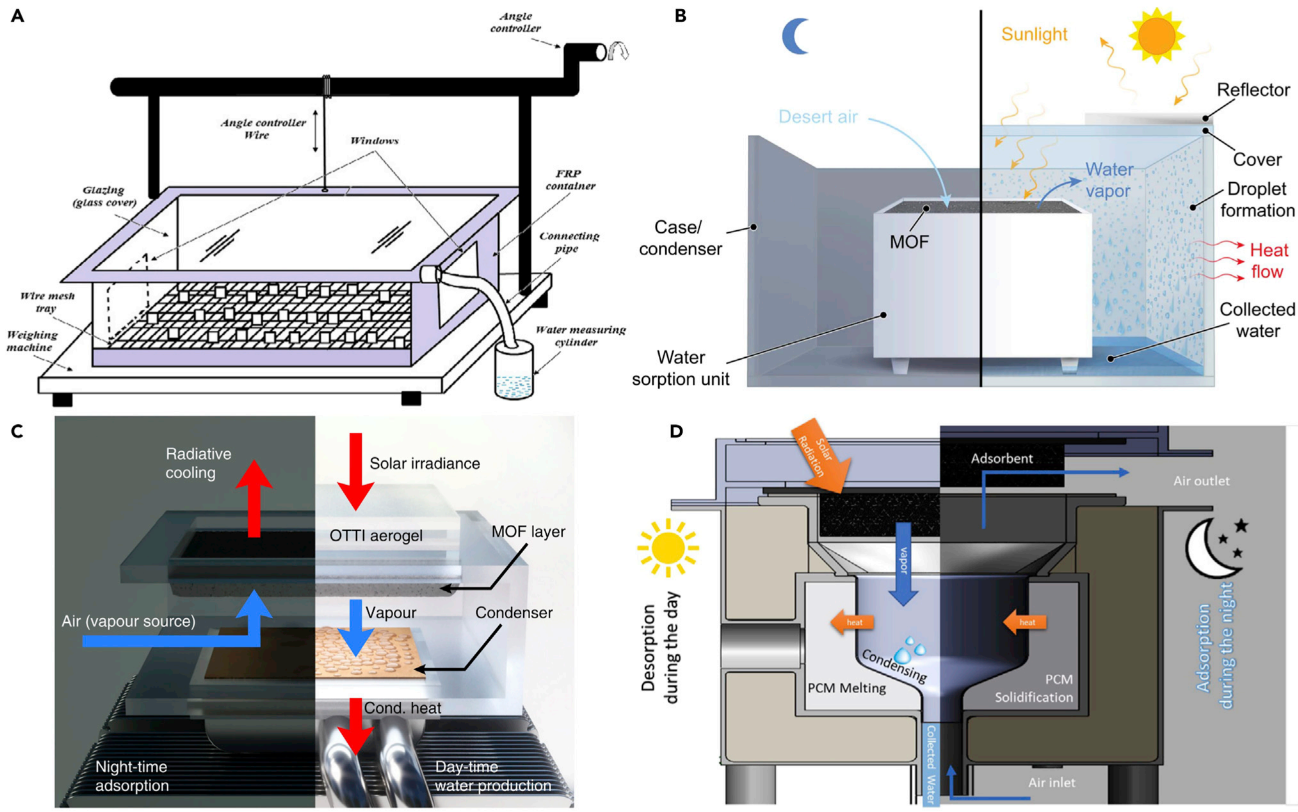

Figure 2. Discontinues passive solar-powered ABAWH device

(A) Similar to solar stills, adsorbent bed at the bottom, uses glass cover as the condenser (reprinted from Kumar et al.,[53] with permission. Copyright 2015, Elsevier B.V.)

(B) Uses sides of the box as the condenser (reprinted from Fathieh et al.,[54] with permission. Copyright 2018, Science Advances).

(C) Adsorbent bed at the top, horizontal condenser at the bottom (reprinted from Kim et al.[24]).

(D) Adsorbent bed at the top, funnel shape condenser at the bottom next to PCM box (reprinted from Ejeian et al.,[47] with permission. Copyright 2020, Elsevier).

Although no quasi-continuous system has been reported so far, many adsorbents have been introduced to suit this approach. Most of these studies have provided single-bed and multicycle prototypes,[57,58] which allow the use of two or more beds simultaneously in these systems. Figure 3A shows one of these systems. Theoretically, quasi-continuous systems could be similar to adsorption desalination systems, except that the evaporator is removed, and moist air enters the adsorbent bed directly. In a different structure, Li et al.[46] introduced a prototype of an ABAWH continuous system in which the adsorbent is loaded on a rotational cylinder and exposed to sunlight through a closed environment on top of the device. The rest of the circle is exposed to the open air (Figure 3B). It is too early to comment on the efficiency and effectiveness of this structure, but in dehumidifiers, desiccant-coated heat exchangers (DCHEs) have performed better than rotary wheels.[21,59,60]

Cycle time is when an adsorbent substrate performs each of the adsorption and desorption processes once, and it is a key parameter in the efficiency of quasi-continuous systems. Cycle time optimization is done to maximize daily water production capacity, which means that the number of cycles per day multiplied by the amount of adsorbent recovery per cycle is maximum. In this case, the adsorbent does not necessarily reach its maximum adsorption capacity. The cycle time in each system has an optimal value proportional to the adsorption kinetics, desorption

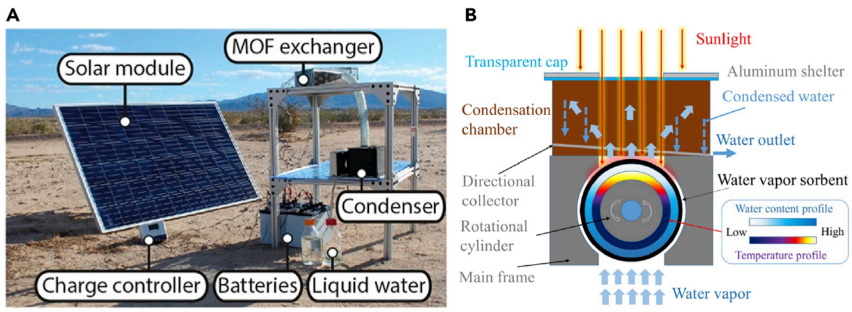

Figure 3. Multicycle ABAWH systems

(A) Electrically heated adsorbent bed with fast kinetic adsorbent and separated condenser (reprinted from Hanikel et al.,[57] with permission. Copyright 2019, American Chemical Society).
(B) ABAWH system using a desiccant-coated rotational cylinder (reprinted from Li et al.,[46] with permission. Copyright 2019, Elsevier).

temperature, system cooling temperature, and mass transfer efficiency in the system. Obviously, the shorter the optimal cycle time, the greater the nominal capacity of the system. Therefore, faster adsorption kinetics is prioritized above the final adsorbent capacity.[57]

Unlike the adsorption desalination systems, which have almost constant inlet conditions,[61] in AWH, the adsorption kinetics are also affected by the temperature and relative humidity of the inlet air. While both of these parameters change during the day and night, they do not necessarily have a linear connection with each other. However, the desorption kinetics is also affected by the rate of energy entering the system and the temperature of the condenser.[62] If solar energy is used, these two factors will not be constant. Therefore, an optimal fixed cycle time cannot be found for multicycle systems, and the cycle time must be actively determined based on the measurement of inlet temperature, relative humidity, and condenser temperature. This would mean that a more complex and energy-intensive control system is required.

A portion of the energy entering the adsorbent bed is used to increase the temperature of the adsorbent and the bed body, which is called sensible heat.[63] This heat is most often returned to the environment during the switch to the adsorption process. The unavoidable presence of sensible heat reduces energy efficiency in all adsorption systems. Therefore, the lower the ratio of sensible heat to the adsorption heat, the higher the energy efficiency of the device. Regardless of the possible heat loss, the presence of sensible heat causes the energy intensity to be higher in multicycle systems than in single-cycle systems. The production capacity of multicycle systems is expected to be more than single cycle, and as a result, the total amount of energy consumption is higher. Therefore, more attention needs to be paid to the desorption enthalpy.[57] Because of the limited energy resources, less adsorption enthalpy can increase daily production capacity or reduce the cost of peripheral equipment of a multicycle system.

Cooling the adsorbent bed to start the adsorption process is another challenge in a quasi-continuous system. The lower the bed temperature in the adsorption process, the higher amount and rate of the adsorption. Using a cooling tower makes no sense here, and there is practically no choice but to utilize an air heat exchanger to cool the interface fluid. Therefore, it is predictable that the bed temperature at the beginning of the adsorption process is slightly higher than ambient temperature, and the fresh air passing through the bed will remove the adsorption heat from the system. The need to cool down the bed for the switch means that designing a cooling cycle in the energy-intensive system increases the sensible heat of the device and requires more peripherals.

APPLICATIONS

Water consumption is divided into four groups: household, agricultural, industrial, and environmental. ABAWH can be beneficial in all four areas. However, each of these applications has its conditions and standards. Continuous or discontinuous production, demand volume, expected quality, air intake conditions, and minimum daily production are the parameters that distinguish these applications from each other.

The expected water quality is different in each application. For example, lower standards of agricultural water compared with drinking water provide a wider range of adsorbents or eliminate the need to purify the water produced. Apart from environmental pollution, the most critical factors that affect water quality are the type of adsorbent, the temperature of regeneration, and the type of internal mass transfer. On the other hand, some impurities in the water can be safe for humans and are harmful to plants. For example, lithium chloride composites are common adsorbents in ABAWH. Although increasing the amount of lithium in water is safe for humans,[64] it can cause poisoning for some plants.[65] There has always been a trace of adsorbent elements in the produced water. The higher the regeneration temperature, the higher the number of impurities seen in the water.[35] Also, a comparison of ions found in water produced by Wang et al.[66] and Entezari et al.[45] shows that despite the similarity of the adsorbent, the amount of lithium ion and chloride ions is higher in a device that has used forced convection.

Drinking water supply is the primary human need and necessity of life. Access to safe drinking water is one of the most urgent human rights. According to the World Health Organization, a person needs at least 2.5 to 3 L/day water to survive, while it is recommended to supply 20 L/day water, as a minimum, for drinking, food, and hygiene.[67] A passive discontinuous device can provide the minimum necessary water to survive or meet part of the water demand. It has also been shown that a discontinuous active device can produce 0.22 to 1.05 $kg_{water}/kg_{adsorbent}$ of water per day, depending on the geographical location.[68] As expected, quasi-continuous systems can provide higher capacity. For example, a study by Hanikel et al.[57] shows a capacity of 0.7 $kg_{water}/kg_{adsorbent}$ in a dry environment. The important point is the scalability and capability of ABAWH devices to increase efficiency.

In designing a drinking water production system, it should be noted that the device should be able to produce water every day of the year, so it is necessary to pay attention to the minimum relative humidity during the year. When using solar energy, care must be taken that the device can also produce water for most of the winter. In domestic use, although the priority is to provide drinking water, the importance of sanitary water cannot be ignored, which means that higher water quality standards for drinking water are requested. Although there are many ways to purify water, avoiding an extra step can positively affect the cost effectiveness and ease of use of the device.

Recycling of evaporated water is one of the most attractive applications expected from ABAWH, which can apply in industries and agriculture. For example, in the steel industry, large volumes of water evaporate to cool molten steel in a closed environment. Such an application requires a deficient level of quality. In the case of agriculture, Entezari et al.[69] showed that 3.3 of 9.5 tons of water released through ventilation in a greenhouse in a semi-arid area could be recovered, which can reduce greenhouse water demand by 50%. There is more stability in air intake conditions in water recycling, and relative humidity is significantly higher. Besides, the availability of heat loss in industrial applications is a great advantage. It should be noted that water recycling is applicable when humidity increases in a closed environment, and there is a necessity for ventilation. In such cases, it is may possible to use other moisture capturing methods in the presence of cheap energy.

Yang et al.[58] have also presented a promising plan to use ABAWH in smart farms, which can be used in wetlands to develop greenhouse cultivation and food production. Here, it should be noted that many plants cannot grow in high-humidity conditions that is created by such a system in the greenhouse.

The great advantage of ABAWH is the possibility of distributed production in a small scale. Such an advantage can irrigate trees,[70] which, besides gardening, can be effective in vegetation development and preventing desertification. Although a tree or shrub needs a certain amount of water to survive or bear fruit, it is not a constant and daily essential. Many trees do not require water during winter and, on the contrary, can withstand a few days of drought in summer. The device does not have to meet the entire plant water needs. In many areas, water resources limit the area under cultivation. Part of the plant needs can be met by using ABAWH, and when the plant needs more water, common sources can be used. Therefore, farmers can cultivate more land. Passive discontinuous systems can be a perfect match for these conditions. Coordinating water production schedules with plant needs and selecting plants suitable for this irrigation method requires further research.

Energy resources

As mentioned, the primary advantage of adsorption systems is the possibility of using low-temperature heat sources as an energy source. Inexpensive and clean resources are generally utilized, such as solar energy,[38,71] biomass,[72,73] or waste heat.[74] Naturally, none of these energies have a standard mode such as 220 V electricity, and the use of these energies requires unique design and attention to environmental conditions. Among these, the researchers are most focused on using solar energy because there is a direct relationship between water demand and solar radiation. Besides, sunrise, sunset, and the difference between day and night temperatures provide natural conditions for passive and discontinuous designs.

The available energy types and the temperature of the heat source also affect the choice of adsorbents because the regeneration temperature of each adsorbent is different. This is clearer in using solar energy and waste heat because the temperature of the heat source is limited. However, methods such as heat pumps[75] or solar concentrators[71,76] can increase the source temperature. Higher temperatures can reduce the moisture trapped in the adsorbent and increase the moisture-carrying capacity of the internal air circulation.

Other adsorption-based systems that operate quasi-continuously, such as chillers or desalination plants, generally use an interface fluid, mostly water, to heat the adsorbent bed. The same can be done for an ABAWH device. Hot water can be supplied by using a biomass boiler, geothermal energy, or waste heat. However, it is more difficult for quasi-continuous systems to use solar energy because solar energy is not available at night, the most reasonable hours to capture moisture from the air. Therefore, the use of solar energy for quasi-continuous production requires installing a separate system for storing heat or the use of auxiliary energy so that the system can also produce water during the night. Moreover, with increasing air temperature and decreasing relative humidity during the day, the rate and amount of adsorption will be lower, which leads to a decrease in system capacity.

LaPotin et al.[56] have proposed a dual-stage configuration based on the reuse of distillation heat, in which the first-stage condenser transfers the received heat to the second-stage adsorbent. The second-stage desorption process takes place at a lower temperature than the first stage, and similarly, the first-stage condenser temperature is higher than the second-stage condenser temperature. This structure has increased water production compared with the single-stage model with the same input energy of 18%, which can be increased by using different adsorbents in the stages and optimizing the adsorbent mass of each. A similar configuration is also proposed for solar seawater desalination.[77] Although LaPotin et al.[56] initially used solar radiation in the device, this configuration can be more efficient using other thermal energy sources because the water production of a single-stage system, with twice the collector area and the same amount of adsorbent, will still be more than the proposed system. On the other hand, a higher initial temperature is expected from waste heat or biomass, and the amount of input energy cannot be increased.

Desiccant heat pumps[50] could be a good solution for energy management. A heat pump usually has an evaporation temperature of 15°C and condensing temperature of about 45°C. Thus, the desiccant-coated evaporator could adsorb moisture water from the air, while the condenser could regenerate water content, which could be condensed at a dew point temperature higher than the ambient temperature. The functions of the evaporator/condenser may switch easily by a four-way valve, which makes a quasi-continuous ABAWH system. Condensing heat can be partly utilized for the desorption process. Considering that the heat pump efficiency could be over 6, it is pretty attractive to handle such an ABAWH system with high energy efficiency.

Besides desorption heat, peripherals also require energy. Fresh air supply, control system, and possible fans and pumps each require a power source. Wind energy is a good option for situations where fresh air supply in natural ways is not enough.[78] Vertical turbines are a fit option for creating a continuous flow in the device. Minimizing the energy required by peripherals in passive systems will significantly impact the practical application and economy of these systems. Natural ventilation improvement techniques can provide fresh air.[79,80] Humidity-driven actuators, in addition to sensors, can be used in inlet and outlet valves or control systems to reduce electrical demand.[81,82] However, ensuring that the valve is completely sealed can be challenging.

Environmental pollution

When we talk about producing water from humidity and considering it as a solution to the water shortage crisis, we do not mean producing water in an isolated and clean environment, away from any pollution and disturbance. Part of the problem is the inevitable presence of environmental pollutants such as dust and sand, which are naturally present in most ABAWH target areas. The penetration of soil particles into the device can fill the porous structure of the adsorbent bed and reduce the adsorption capacity. On the other hand, depositing on the device's inner surfaces disrupts the internal mass transfer, acts as an insulation layer, and resists heat transfer. Although the severity of this phenomenon varies according to the situation in the area, if no equipment is provided to prevent dust entry, even a weak storm can disable the entire device.

The use of air filters in the fresh air inlet can largely prevent the entry of suspended particles into the device, but at the same time it makes the use of natural ventilation very difficult and practically makes the supply of fresh air dependent on the fan and more energy consumption. However, it is necessary to research the impact of pollution and the tolerance level of each adsorbent, as well as the grade required for air filtration. Also, the warm and humid environment of the device provides suitable conditions for the growth of microorganisms and algae, so in long-term use, a solution should be considered to prevent it.

KEY POINTS IN DEVICE DESIGN

Mass transfer

Regardless of the type of adsorbent, the substrate itself needs special attention. The most important factor here is to provide proper conditions for mass transfer to the inner layers and heat distribution throughout the adsorbent bed. It has been reported that the water adsorption inside the device is much lower or much slower than what is reported in the TGA device or humidity control chamber.[57] The reason for this is the lack of moisture penetration into the adsorbent inner layers. Obviously, the mass transfer conditions for several small granules surrounded by high-pressure airflow differ from those of a large but porous mass.

Improving mass transfer within the bed depends entirely on the form of the adsorbent. Regardless of the adsorbent kinetics, an adequate mass transfer within the bed depends on the water effective diffusivity, bed thermal conductivity, and adsorbent configuration.[29] In granular adsorbents, such as silica gel or zeolite, the space between the grains can be counted to mass transfer. Grain size plays a key role here. Larger grains mean better mass transfer, and finer grains mean better heat transfer.[62] Some adsorbents, such as silica sol or even MOF, have the ability to coat on the heat exchanger. Although such a structure does not have a high overall adsorption capacity, it improves the adsorption and desorption kinetics and reduces the cycle time.

Producing a porous block with micrometer and millimeter holes can make the adsorbent much easier to install and operate. In the case of powdered adsorbents such as MOFs, an acceptable amount of porosity in the block can be created by controlled compression, depending on the material's adhesion. In this case, the adsorption of water in the outer layer expands the layer and restricts the microchannels leading to the inner layers. Another solution is to use macroscopic porous structures such as metal foams, or carbon fiber felt like the host. Deliquescence salt composites have the advantage that the saline solution created within the matrix structure transfers the adsorbed water molecules to the inner layers.

Honeycomb structure could be designed as a reliable adsorbent bed, where the air is directly circulated, and heat and mass transfer between adsorbent bed and air could be enhanced simultaneously. The volume of water uptake rate could possibly be the highest, which is similar to the concept of the open system thermal battery.[83] The layer's thickness needs to be optimized to balance adsorption capacity, thermal resistance, and occupied area.

Mass transfer from the adsorbent bed to the condenser also plays a vital role in the system. The water vapor diffuse into the air, so the gradience in concentration between the adsorbent bed and the condenser transfer the water molecules. Discontinuous passive systems where the bed is located above the evaporation chamber use this effect.[24] However, experiments show that the mass transfer rate, in this case, is lower than the rate of desorption even in small devices, in the presence of a sufficient cold source.[47] The long desorption time in discontinuous systems may compensate for the slow mass transfer. Although this process does not seem to require energy consumption, in practice, mass transfer inefficiently prevents the flow of energy in the device, which leads to a loss of input energy.

When the bed is located at the bottom of the evaporation chamber, the convective flow plays a major role in mass transfer. Although this convective flow improves mass transfer, it also limits the bed temperature. In addition, the interference of hot upward and cold downward airflows causes significant energy loss in these systems.

In quasi-continuous systems, mass transfer efficiency directly affects the optimum cycle time and thus daily production. The point here is the difference between an ABAWH quasi-continuous system and other adsorption-based quasi-continuous systems. Chillers and desalination plants operate at a negative pressure (1 to 10 kPa), and only the working fluid is present in the system. Distillation in the condenser causes a negative vapor pressure gradient and creates a flow from the bed.[17] However, the bed's geometry, the ducts' size, and the distance between the two parts affect the efficiency of mass transfer.[84]

In contrast, an ABAWH quasi-continuous system operates at ambient pressure in the predominant presence of non-condensing gases. So, the pressure difference between the bed and the condenser is expected to be negligible. This means that the normal displacement of desorbed water molecules will be much slower than conventional adsorption systems. Therefore, on a large scale, the use of forced convection in a quasi-continuous ABAWH system seems inevitable. Besides, a return path for cold and dry air from the condenser to the bed must be considered, which requires a more complex design. From this point of view, DCHE[59,60] could also be a good option for ABAWH.

Heat transfer

Heating and cooling the adsorbent bed in all adsorption systems control the start and end of the process, which can be done through a heat exchanger or direct solar radiation. In the major designs proposed so far for adsorption systems, the energy is input to the system through the adsorbent bed. It is necessary to take measures for uniform distribution of energy in the adsorbent bed because it can negatively affect the system capacity and cycle time. The use of fins, a conductive host matrix, and the addition of conductive plugs to the adsorbent are strategies that can be adopted to improve in-bed heat transfer. By modifying the photothermal properties,[49,85] the adsorbent itself can be used directly as a solar radiation absorber, reducing energy loss and improving heat dissipation in the bed. However, in this application, the importance of adsorbent thermal conductivity becomes more apparent because of the need to transfer heat from the top layer to the bottom layers.

In a unique design, Wang et al.[66] solved the problem of heat transfer and mass transfer at the same time by heating the incoming air stream to the adsorbent bed and triangular cross-sectional design of the layers. This idea can also be adopted for quasi-continuous systems. Heating the indoor air as an interface fluid can also

Table 1. Priority and essential features of an adsorbent for different ABAWH systems

System	Possible applications	Priority	Essential features	General features
Discontinues passive	drinking water distributed irrigation	adsorption capacity	low desorption temperature high thermal conductivity wide RH-working range macrostructure porosity	high adsorption capacity low desorption temperature low desorption energy fast kinetics chemical stability cyclicity
Discontinues active	household water	adsorption capacity	wide RH-working range adoptable to a heat exchanger	
Quasi-continuous	household water water recovery	kinetics	cyclicity low desorption heat low sensible heat adoptable to a heat exchanger	

reduce system energy losses. The water remaining in the pipes during the switch occupies 30% to 50% of the sensible heat capacity of the device.[84]

However, it is essential to prevent heat loss in the system, especially in solar-driven passive applications. Insulation and reducing unnecessary heat load in the bed can play an essential role in reducing energy consumption.

Adsorbent selection

The search for the ideal adsorbent in all adsorption-based technologies is one of the main areas of research. For ABAWH, features such as high adsorption capacity, low desorption temperature and enthalpy, fast kinetics, chemical stability, cycling stability, and low cost are stated.[20,28] However, each adsorbent is suitable for working in certain environmental conditions.[86] Regardless of the adsorbent's general characteristics, the structure and the strategy of the device set priorities in the selection of the adsorbent, as shown in Table 1. Therefore, in various structures, the adsorbent's performance and the role it plays in the device are different, affecting the priorities for selecting the adsorbent.

Apart from the device's structure, climatic condition is an independent and decisive factor in selecting the adsorbent. If relative humidity and ambient temperature are constant, such as water recovery in industry and agriculture, adsorbent selection has a simple procedure. This procedure involves evaluating adsorption isotherms, stability, kinetics, thermal characteristics, and finally, the adsorbent price, respectively.[29]

In many cases, the weather change in all four seasons of the year. Therefore, in choosing the adsorbent, we face whether the priority is to provide the minimum water supply on a specific day of the year or to use the maximum annual production as a design criterion. For example, for a cold and dry climate, adsorbents have a step in their isotherm and follow type IV adsorption, such as MOF-801, Co_2Cl_2(BTDD) and MIL-101 can guarantee a minimum production in summer. MOF303 is a suitable adsorbent in extremely dry areas.[87] This volume production will not change much in other seasons, although the relative humidity and the dew point temperature are higher. Therefore, when the maximum annual production is the design criterion, the adsorbent that follows quasilinear isotherm is preferred, such as salt composites[45] or hydrogels,[31] because the adsorbent capacity of the adsorbate water also increases in proportion to the increase in relative humidity. However, since higher

RH leads to faster adsorption kinetics, in multicycle systems, it is possible that reducing the optimum cycle time can compensate for this weakness for adsorbents with stepwise isotherm.

In discontinuous systems, the long cycle time creates the priority of adsorption capacity to kinetics. Besides, the adsorption process continues throughout the night, and the temperature and relative humidity also vary throughout this period. The relative humidity may never reach the step level, or the fresh air supply may not be sufficient during that time. Therefore, the selection of type IV adsorbents in this application must be made carefully.

The adsorbent's heat transfer coefficient is another factor that is effective in choosing the type of adsorbent for discontinuous or quasi-continuous states. In general, a high heat transfer coefficient is advantageous for adsorbents. However, it is more critical in discontinuous systems because the adsorbent layer is thicker, and the possibility of designing a mechanism for heat distribution in the adsorbent bed is more limited. Therefore, instead of introducing an ideal adsorbent, it is better to look for the optimal adsorbent for any application and climate.

Cold source

The rate of water distillation in the condenser depends on the heat transfer rate, so the greater the difference between the cold source temperature and the water vapor temperature, the higher the heat transfer rate and the higher the efficiency of the condenser. Two different strategies can be considered for the cold source. The first is to consider ambient air as a cold source, a source whose temperature may rise by more than 40 degrees depending on ambient conditions. However, improved heat transfer can be achieved by increasing the desorption temperature as well as increasing the intensity of the open airflow on the condenser. Similarly, Kim et al.[24] used a heat pipe to transfer heat from the condenser to an extended heatsink exposed to ambient air.

When ambient air is used as a cold source, another potential solution that can increase the efficiency of quasi-continuous systems is to use a two-stage configuration, such as that provided in desalination units[62] (different from the dual-stage configuration introduced in the available energy resources section). In adsorption desalination, the use of two-stage systems is justified when the condenser temperature is about 40°C, the hot source temperature below 60°C, and the co-generation of cold is also required.[88] In this configuration, the water vapor leaving the desorption process in the first stage enters the second stage's adsorbent bed and is readsorbed. Because the adsorption process of the second stage occurs at a higher pressure, the pressure in the desorption process and the condenser will be higher. In ABAWH, we can expect the second-stage adsorption process to be at high relative humidity so that the kinetics will be faster. Therefore, different adsorbents can work at higher relative humidity and have a higher adsorption capacity.

The second solution is to reduce the condenser temperature. Besides the conventional compressive systems,[57] solar-powered Peltier modules,[70] keeping night temperature using phase change materials (PCMs),[47] radiative cooling,[89] and underground temperature[90,91] are low-cost and low-energy consumption solutions that can help reduce condenser temperature. The type of cold source, like the energy source, depends on environmental conditions. For example, in humid areas, the efficiency of radiant plates is reduced by about 50% compared with dry areas.[89]

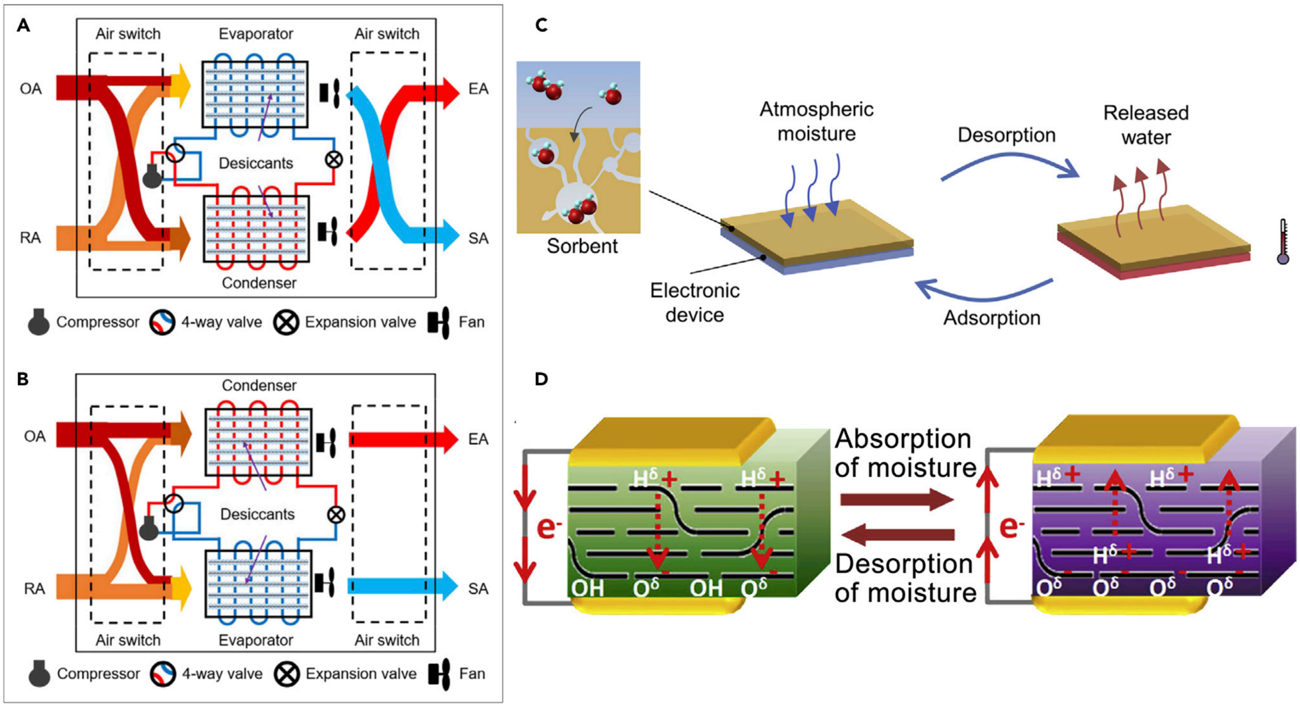

Figure 4. Some technologies suitable for hybridization with ABAWH

(A and B) (A) First and (B) second operational mode of an air-conditioning system using desiccant-coated heat exchangers (reprinted from Tu et al.[63]).
(C) Increasing the cooling efficiency of electronic equipment using the adsorption phenomenon. The adsorbent coating on an IC receives the generated heat and undergoes a complete adsorption and desorption cycle (reprinted from Wang et al.,[111] with permission. Copyright 2019, Elsevier).
(D) Mechanism of electricity generation in a moisture-driven hydroelectric cell. (Reprinted from Ye et al.,[116] with permission. Copyright 2017, Elsevier).

The desorption rate is limited to the distillation rate in the condenser. Therefore, the condenser temperature is more important in quasi-continuous systems because, as seen in desalination systems, the lower the condenser temperature, the lower the optimal cycle time, and as a result, the final production capacity will be higher.[92]

Heat pump with DCHE as condenser and evaporator may provide a paradigm to improved AWH. The adsorption temperature is dropped down (but may still above the dew point) and condensing temperature is reduced significantly owing to the enhanced water vapor desorption in the condenser. Such a system has been implemented for air conditioning with doubled COP successfully by Tu et al.,[63] and it could be a continuous AWH system that boosts water production rate. Figures 4A and 4B demonstrate the operation mode of a desiccant-coated heat exchanger heat pump.

Dropwise condensation

Condenser, especially in passive systems, requires careful and case design. The efficiency of the condenser is mainly affected by wetting, nucleation, and droplet departure behavior.[93] The distillation process in the condenser can be assumed as dropwise condensation. Much research has been done on the nature of dropwise condensation, which is mainly in the conditions of passing a vapor stream or a mixture of vapor and air over a cold surface,[94] which differs from the conditions in ABAWH. Research on the theory and modeling of dropwise condensation in a closed environment and its interaction with the desorption process can help predict the condenser's behavior and its optimal design in the future.

Continuous water distillation requires that the formed droplets leave the condenser quickly. The water droplets formed on the condenser wall act as a thermal insulator and reduce the heat transfer rate. Therefore, hydrophilic surfaces cannot be a good option for condensers. Moreover, the nature of droplet distillation in the presence of a non-condensable gas (NCG) such as air differs form a pure vapor stream. The presence of air reduces the number of nucleation sites on the condenser and reduces the droplet's growth rate by creating a diffusion resistance on the surface of the droplet.[95] Therefore, techniques that rely solely on hydrophobic surfaces, such as drop jumping, may not work well in ABAWH.[93]

Under such conditions, hydrophilic/hydrophobic hybrid surfaces can significantly improve the distillation rate because they provide both suitable sites for the nucleation and growth of drops and do not allow the drops to grow too much. Although much research on hybrid surfaces has focused on fog collection, valuable research has been done on condensation dynamics from humid air.[96,97] Using the capillary pressure phenomenon can also reduce the droplets' critical diameter and increase the droplet removal rate.[98] Directional slippery surfaces are also competent to improve nucleation and droplet departure rate.[99,100] Likewise, electrowetting can improve the coalescence, growth, and removal rate of distilled droplets.[101] However, integrating these technologies with ABAWH devices requires further research.

In solar stills, hydrophilic surfaces produce more water than hydrophobic surfaces. The effect of water droplets dripping also needs to be investigated, although it is expected that its effect on hydrophobic surfaces is more severe than on hydrophilic surfaces.[102]

GOING TO MARKET

Although there is much hope for ABAWH, there is still a long way to go before this technology becomes a daily use of the people. The world's existing water resources meet most human needs and applications; however, ABAWH is not supposed to meet all of society's water demands. From this perspective, identifying the conditions and situations that are cost effective and operational is the first step to bring this technology into action. To gain the support of consumers and investors to use ABAWH systems, more research is needed on measuring the efficiency of systems in different climates, which can be done through mathematical simulations.[68] Through an exergy analysis, Hua et al.[87] concluded that ABAWH systems are superior to direct cooling systems in all climates except the "tropical coastal region." Also, Gordeeva et al.[103] have developed a systematic approach to finding the optimal adsorbent that, although they have used it only for MOFs, can apply to other adsorbents as well.

Supplying drinking and sanitation water for remote residents who do not have easy access to water is the driving force behind much AWH-related research. Temporary accommodation of refugees caused by natural disasters and wars are other situations in which AWH is relevant, a situation in which there is not enough time and equipment to establish and maintain a water supply from conventional sources.[104] Obviously, the people caught in the mentioned conditions do not have the financial potential to use new technology, and it is the governments and non-governmental organizations that must be persuaded to support this technology.

Vapor-compression-refrigeration-based AWH is already market available; however, it is usually used in high-humidity areas where common water resources are accessible. ABAWH is advantageous in dry weather, but it could also be efficient in other areas. At the time of writing, a commercial AWH device with an annual production capacity of 10 tons in humid areas is selling in the market for 11,000 CNY. Wang et al.[68] estimated a solar ABAWH system's production capacity in a coastal area at 18.5 tons/year. Assuming mass production, if we estimate the price of their device at the same ratio of 20,350 CNY, also considering the expected return on investment period of 5 years and maintenance costs of 650 CNY per year, the cost of 1 L of water produced in a dry area like Yazd is 1 CNY, and it will be 0.5 CNY in a coastal area such as Trivandrum. Currently, in Shanghai, the price of drinking water purifiers is 1 CNY per liter, and a half-liter bottle of drinking water is 2 CNY. Considering the water footprint in the production, packaging, and distribution of water bottles (more than 4.5 L per bottle[105]) it can be shown that ABAWH, while being economical, can also effectively protect existing water resources.

Hybridization

The idea of serving the inhabitants of arid and remote areas is moral and humanitarian. However, in other areas and situations, the development of devices that only produce water may not compete with conventional water resources and drinking water bottles. If ABAWH can meet part of the water demand in water shortages, reducing the pressure on existing water resources will also strengthen water resources in remote areas.

Hybridization is a solution that can reduce the cost of water production and may be done in two aspects, combining the two methods of AWH and water production as a by-product. Generally, adsorption-based systems have a high ability to hybridize with other technologies. This hybridization can increase the efficiency and effectiveness of the system by exploiting the output[61] and providing the input,[106] or by using waste heat or unusable output of the system can cause a by-product.

As mentioned earlier, the efficiency of ABAWH systems highly depends on the condenser's efficiency, and AWH methods based on cooling and compression perform better at high relative humidity. By combining adsorption technology with these technologies, higher relative humidity can be provided at the input of other AWH methods, thus covering the weaknesses of both methods. The system proposed by Hanikel et al.[57] is practically an ABAWH hybridization with direct cooling where the output of the adsorbent bed provides the input of an electric compression cooler. This device produced 0.7 $kg_{water}/kg_{adsorbent}$ in a day from an average of 10% RH and 27°C where conventional AWH systems are not able to generate water,[9] and it is ten times greater than an air-cooled passive ABAWH[54] system tested by the same research group. The performance of such a system can be improved by using an internal heat pump. ABAWH can increase system production capacity and efficiency in combination with commercial direct cooling systems. The use of membranes can also increase the relative humidity of the air entering the system.

Waste heat can be a reliable source of heat for ABAWH. In this case, the presence of ABAWH does not affect the initial application and only prevents further energy loss. However, ABAWH can also be effective in improving primary application performance.

Water production is one of the by-products of vapor compression cooling systems, which is not desirable for users because it increases energy consumption (30%∼50%) and therefore is not economical. However, integrating AWH with air-conditioning systems is still an option that researchers are trying to achieve in energy efficiency.[107,108] Many studies have been done to use sorption technologies to reduce incoming moisture to compression chillers and dehumidifiers, but moisture is returned to the environment as vapor and is not collected in most of these studies. For example, in a study by Tu et al.,[63] 0.34 $kg_{water}/kg_{adsorbent}$ was returned to the exhaust air at each switch (Figures 4A and 4B). Also, in the device provided by Li et al.,[109] 28.38 g/h water enters the environment from a coated heatsink with a surface area of $0.29m^2$. In an inspiring study, Zhao et al.[110] developed a combination of dehumidification and a water harvesting system using membranes. DCHEs can also be considered as a proper potential atmospheric water harvester.[60] Such a combination can significantly reduce the energy consumption of the air-conditioning system by reducing the latent heat load.[63] It could be possible to double COP of air conditioning with a desiccant-coated heat pump, while water vapor desorbed could be collected.

Wang et al.[111] used the moisture adsorption phenomenon to cool electrical equipment by creating a layer on the heat sink of a circuit (Figure 4C). Although this has become operational on a small scale, the idea can also apply to cooling larger equipment that works intermittently. Both the adsorption process and the desorption process occur in the state, and predicting a distillation process can be a by-product for the system. Such that mechanism has utilized by Lee et al.[112] They came up with a great idea, and by covering the back of the photovoltaic cell with PAM-CNT-$CaCl_2$ hydrogel, they increased the electricity production by up to 19%, and while keeping the PV cool, it produced 0.08 g/cm^2 water.

In recent years, humidity has been introduced as a source of energy in addition to a water source.[113,114] Like ABAWH, the first step in obtaining energy from air humidity is taking moisture by the adsorbent, and this can provide an excellent opportunity to combine the two technologies. As shown in Figure 4D, in some materials, such as graphene-based protein polymers, external stimulation of relative humidity ionizes oxygen groups, and releases free protons. Thus, the difference between the chemical potential energy of water vapor and the adsorbed water is converted into electricity, called hydroelectric.[115,116] Although the water adsorption capacity of these materials is not considerable, hybridizing them to quasi-continuous ABAWH systems—in which relative humidity fluctuates—can be an attractive idea. Other mechanisms proposed are moisture battery and atmospheric water splitting, in which water adsorbed hydrogel acts as an electrolyte. The adsorbed water is consumed in a chemical process to produce hydrogen and electricity.[113,115]

Scale up and mass production

Many studies to date have been in small or tiny volumes (within a few grams). The conditions for mass and energy transfer at higher volumes will be very different. Water production in large volumes differs significantly from the production of a few grams of water. On a small scale, heat transfer and mass transfer within the system are not a problem. In other words, the extra interior space of a small device occupies a higher percentage of space than that of a large device.

Currently, the energy consumed per liter of water produced by commercial AWH devices is higher than that of desalination or water transfer, which increases the cost.[10] Although the history of adsorption desalination plants[117] has shown that lower prices for water produced by ABAWH can be expected, more research is needed to examine the economics of ABAWH. To be marketed, the device must meet the minimum volume of water needs of the consumer. Ease of use and the ability to adapt to other home appliances are other factors that can help the acceptance of this

Table 2. ABAWH technology roadmap

		Short-term	Medium-term	Long-term
General	adsorbent	increase adsorption capacity improve kinetics improve thermal properties	design new materials tailored to the applications (MOF & hydrogel design with high sorption rate and low generation temperature)	reduction in costs, 1∼10 USD/kg possibly (MOF, hydrogel, or porous silica gel and Composite sorbents)
Household	discontinuous passive	system design with a capacity of 3∼5 L per day (solar thermal driven)	utilizing methods to improve the condensation rate, 10 L per day (coolant for equipment or radiation cooling)	utilization of intelligent materials in the control system, 10–20 L per day (fully automatic generated)
	discontinuous active	system design with a capacity of 20 L per day	diversification of energy sources (any kind of heating source)	portability and easy to install (water cost reasonable)
	quasi-continuous	design of units with a capacity of 20 L per day (with daily solar generation 3∼5 times)	hybridize with existing devices such as dehumidifiers or refrigerators, or heat pumps (water generation cycle 10∼60 min)	portability & ease of installation, 50 L per day (with water cost close to mineral water)
Industry and Agriculture	water recovery	identify applicable cases (such as desalination with adsorption)	design dedicated units Using waste heat or DCHE based electric heat pump (capacity 1∼10 ton per day scale)	integrated water supply system, a commercialized product with various AWH production series
Environment and Agriculture	distributed irrigation	design of units for 2∼10 L per day (solar thermal driven, hydrogel is preferred to store liquid water)	integration with modern irrigation methods Identify suitable plants (capacity 10∼20 L per day scale for moderate water demand plants)	utilization of intelligent materials in the control system (thermal or heat pump driven for AWH with low cost of energy per liter water)

technology in the community, which should be considered in both single application and hybrid applications. In summary, Table 2 presents the ABAWH technology roadmap, including short-term, medium-term, and long-term goals and plans for various applications and structures.

SUMMARY AND FUTURE OUTLOOK

Humidity is a reliable source of water that ABAWH can make available in most parts of the world. Despite the fantastic advances in ABAWH, there is still a long way to go before this technology can affect human life. ABAWH devices should move from a general concept to specialized applications. In this way, the designs should be tailored to the applications, and the type, amount, and rate of demand should be considered in it.

In the case of adsorbents, the current research on MOFs especially considers the use of S-shape isotherms in which the sudden changes of adsorption rate happen at a specific relative humidity (for example, 20%, 30%, and 40%). This does not suit the actual operation of an AWH in which adsorption may happen in the night and desorption during the day; there are many changes of temperature and humidity ratio for one day, and of course, for one year. A scale-up AWH should consider the daily, monthly, and yearly changes of atmospheric conditions. The single S-shaped adsorbent is suitable for a stable condition but might not be suitable for a scale-up and yearly operation system. In this case, composite adsorbents (formed by silica gel, MOFs combined with LiCl or $CaCl_2$ chemical solution) are more promising for long-term scale-up systems.

Hydrogel is another quite attractive material. When hydrogel has adsorption points with actively induced Li or Ca, the material could adsorb and store water in its polymer structure. By heating process, the change of its hydrophilic to hydrophobic may release water very quickly; it does not need much heating, while regular adsorbents like some MOFs and silica gel or even LiCl and $CaCl_2$ may need a large quantity of heat for regeneration.

Different structures and strategies can be adopted for an ABAWH device. Discontinuous systems require more sorbent, less energy and peripherals, and more precise design; it is good to be driven with solar energy. In contrast, quasi-continuous systems require more complex design and may need auxiliary energy input; if a cycle time is short, the production rate will be significant. Determining each of these systems' preferences based on the region's conditions and the intended application requires further research. In addition to solar energy, other thermal energy sources such as geothermal, waste heat, and biomass can be used as the main or auxiliary source.

Solar energy is a reliable and safe source for ABAWH, as there is generally a direct relationship between the need for water and solar radiation. The challenge here is the unavailability of efficient solar energy capture and conversion systems to supply ABAWH, as they are fundamentally different from conventional systems in terms of output and operating conditions. For example, heating the adsorbent with direct solar radiation may need high photothermal performance, in which some nanoparticles like carbon nanotubes mixed with sorbent may be used. Also, excellent thermal insulation to use aerogels is necessary to boost its solar-driven AWH water efficiency. A dual-stage configuration could be an excellent solution to yield a high solar transmission rate and excellent thermal insulation.[56]

The cooling source is critical as its temperature is related to the air's condensing state with the desorbed humid content. By using PCM (considering its phase change during the day and night time), an ABAWH system may have a natural cold source for condensing, leading to an increase in water generation efficiency. For a passive ABAWH using solar energy, radiation cooling may help the adsorbent bed cooled during night adsorption and help an optimized cooling surface (condenser) to have more efficient condensing during the day.

Studies have shown that the rate of desorption is limited by the rate of condensation in the condenser. However, the condenser is generally designed in a simple and basic way. Therefore, on the one hand, it is necessary to study more fundamental studies on the nature of distillation in the conditions of an ABAWH system, and on the other hand, more attention should be paid to condenser design, especially in passive systems. Hydrophobic/hydrophilic hybrid surfaces can also help increase condensation rates. Many studies are done to increase the dropwise condensation rate with these hybrid surfaces, and their combination with ABAWH condensers is expected in future studies.

Like other adsorption-based systems, the performance of ABAWH is highly dependent on the efficiency of mass and heat transfer within the device. The challenging point here is the adequate supply of fresh air and efficient internal flow in passive systems, which has led to system inefficiencies in some studies. Likewise, ABAWH peripherals such as fresh air supply, control system, and valves can significantly impact performance. Therefore, optimizing and synchronizing them requires special attention.

Using an internal electric heat pump could boost a quasi-continuous ABAWH system. The condensing heat will be used for the regeneration of the sorbent bed, while evaporation cooling could improve moisture adsorption. Thus, utilizing a DCHEs as evaporator/condenser may improve heat and mass transfer of sorbent bed significantly and reduce the switch time between adsorption and desorption; the water production rate could be significantly increased. A solar PV-powered DCHE heat pump system may create a highly efficient ABAWH system. In this case, MOFs may find their advantages when coated on heat exchanger, as it has high adsorption capacity and excellent sorption kinetics.

One of the significant challenges in drinking water purposes is the production rate of a device. ABAWH will be effective when it can meet the minimum human needs for water. Therefore, it is necessary to develop discontinuous or quasi-continuous production systems at a scale of at least 20 L per day to meet the drinking water needs of a household. It is essential to pay attention to the quality of water produced here. Not needing for a treatment will reduce costs and make users more comfortable in using the device.

The development of recovery systems to prevent water loss in industry and agriculture is a promising part of ABAWH's future applications. Designing dedicated systems for this purpose and classifying suitable conditions and cases for water recovery can be the subject of forthcoming studies. The industry scale application may need several tons per day water production scale.

ABAWH can create a paradigm for sustainable agriculture in arid regions. Desert blooms could be not a story but a reality. The possibility of distributed water production will be a key advantage for horticulture in which the use of passive systems and solar energy will be essential. Greenhouse cultivation can also be a good option where, in addition to water recovery, controlled water consumption can provide the advantage of providing water from humidity. Thus, ABAWH could be considered to dehumidify the greenhouse and recover water (70%–80% could be expected); meanwhile, the sorption heat could be used to assist heating to the greenhouse when it needs to be heated in winter.

Going to market, ABAWH may need a competing with commercially available electric-driven vapor compression condensing unit, energy consumption to produce 1-L water could be one main issue to be considered, a unified exergy-based comparison could be used for such application in consideration of the energy used (electric or thermal). The boundaries to select conventional vapor compression condensing units and ABAWH should be well defined. Meanwhile, the investment's initial cost is another critical issue; high-cost MOF materials are not welcome in ABAWH. Cheap MOFs or even conventional moisture sorbent may have their application potentials. The space occupied to produce 1-L water is another vital issue for the customers.

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DECLARATION OF INTERESTS

The authors declare no competing interests.

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