The Future of Water Supply: A Global Review of Atmospheric Water Harvesting

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ABSTRACT

Faced with the burgeoning challenge of water resource crises, Atmospheric Water Generation (AWG) technologies have emerged as strategic and sustainable solutions. This review study provides a comparative assessment of four primary thematic axes in this field: active refrigeration methods (based on vapor compression cycles and thermoelectric coolers), vapor concentration techniques (utilizing desiccants and membrane processes), passive methods (dew and fog harvesting), and finally, the role of electric fields in performance enhancement. The findings of this research indicate that vapor compression systems exhibit maximum efficiency in climates with high relative humidity; conversely, the emergence of Metal-Organic Frameworks (MOFs) has initiated a fundamental paradigm shift in atmospheric water recovery in arid regions (with humidity below 20%). In the membrane technology sector, the implementation of selective membranes has resulted in an energy consumption optimization of up to 50%. Furthermore, results demonstrate that the application of an electric field in the fog harvesting process increases collection efficiency by up to 60% and facilitates a 40% recovery capacity of evaporated water in power plant units. Overall, the integration of passive methods with active systems, coupled with the utilization of renewable energy, is evaluated as the most efficient strategy for sustainable water supply across diverse climates.

Keywords: *Atmospheric Water Generation (AWG), Active Refrigeration, Metal-Organic Frameworks (MOFs), Selective Membrane, Electric Field*

1. *INTRODUCTION*

Following oxygen and food, water is considered the most vital human necessity, which, unlike energy sources, lacks any substitute [1]. Despite the long history of human utilization of liquid and solid water resources, the potential of atmospheric water vapor has been largely overlooked [2]. Today, the freshwater scarcity crisis has evolved into a global predicament [3]; notably, in the past century, while the population grew by 300%, water consumption experienced a 600% increase [4]. International statistics indicate that 70% of water resources are consumed in the agricultural sector, 22% in industry, and 8% for domestic purposes [5]. Currently, approximately 783 million people are deprived of access to safe drinking water [6], and annually, 340,000 children under the age of five perish due to waterborne diseases related to poor water quality [7]. This crisis is classified into two dimensions: "physical" (lack of resources) and "economic" (infrastructural weakness) [8]. Access to contamination-free water is vital not only for the survival of living organisms but also for industries such as semiconductor manufacturing, papermaking, refineries, and agriculture [9]. Furthermore, climate change and natural disasters have doubled the importance of providing safe water in critical conditions by destroying water distribution networks [7]. Given that only 2.5% of the planet's water reserves are fresh—the majority of which is trapped in polar ice [8]—existing resources will not meet the burgeoning demand by the year 2050 [3]. The Earth's atmosphere, containing approximately 50,000 km^3 of renewable water, holds equivalent to 10% of the world's total freshwater resources [10]. Atmospheric

Water Generation (AWG) technology is a process for extracting this moisture, which, if integrated with renewable energy, would be a fully sustainable and environmentally friendly solution [4]. The most common approach in this technology is reducing the ambient air temperature below the dew point and collecting the resulting condensate. However, due to the requirement for high cooling power and overcoming the latent heat of condensation (2450 kJ/kg at 20 °C), this process is energy-intensive [10]. According to calculations, the minimum theoretical energy required for water vapor condensation and the production of one cubic meter of freshwater is estimated at approximately 681 kWh [11]. Unlike traditional methods such as Reverse Osmosis (RO) or distillation, which are dependent on surface or saline water sources [3, 10, 12], AWG systems possess operational capability in remote and arid regions. The key challenge in developing this technology is the high energy consumption required to overcome the latent heat of condensation barrier [11]. The efficiency of these systems is heavily influenced by climatic parameters, particularly the dew point temperature [12]; Specifically, a dew point temperature above 2° C is considered the threshold for the economic operation of these devices [4]. Finally, given the potential for the transport of certain pollutants along with air moisture during the condensation process, performing final treatment stages, monitoring the concentration of metal ions (such as Na^+ and Ca^{2+}) and disinfection with Ultraviolet (UV) radiation are mandatory [6, 8, 13].

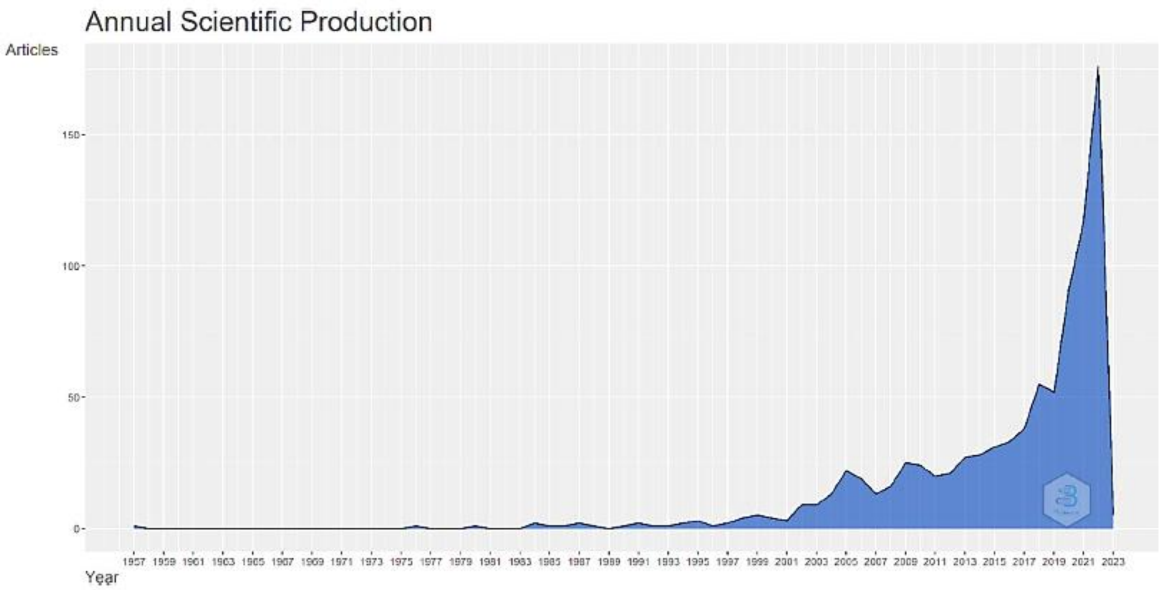

***Fig. 1.** Annual number of publications on atmospheric water harvesting. Data extracted from the Scopus database [8].*

2. Methodology

Given the extensive body of research in the field of Atmospheric Water Generation (AWG) and the necessity of classifying diverse methods, the present study has been conducted using a systematic review approach based on archival and literature-based research. The fundamental objective of this investigation is to perform a comparative analysis and scrutiny of four key technological axes, including:

1. *Active refrigeration techniques*
2. *Vapor concentration processes*
3. *Passive techniques*
4. *Novel and enhanced approaches*

The process of identifying and collecting resources was conducted using specialized keywords across reputable scientific databases. The selection criteria for articles and data were based on three key indicators:

- *Functional Evaluation: Analysis of the daily water production rate.*
- *Energy Indices: Investigation of Specific Energy Consumption (SEC).*
- *Climatic Adaptability: Operational capability across a wide range of atmospheric conditions, from saturated regions (80% humidity) to ultra-arid environments (humidity below 20%).*

Finally, the data extracted from empirical studies and industrial models were subjected to both qualitative and quantitative analysis, and the findings were synthesized and compiled in the form of comparative tables.

3. Results and Discussions

Biomimicry: Inspiration from Biological Structures

Throughout the evolutionary process, nature has developed optimal solutions for moisture extraction in harsh climatic conditions. Two prominent examples include:

- *Namib Desert Beetles: This organism utilizes a hybrid mechanism; its elytra (wings) are equipped with hydrophilic spots to capture micron-sized fog droplets, surrounded by hydrophobic regions to direct the accumulated droplets toward the insect's mouth [3].*
- *Spider Silk: The water collection process in spider webs is based on Laplace pressure (the pressure differential between the interior and exterior of a curved surface), which leads to spontaneous dew condensation on the silk fibers [8].*

3.1. *Thermodynamic Foundations and Environmental Parameters*

Understanding the process of atmospheric water extraction requires an analysis of the interaction between physical atmospheric variables. The amount of water vapor in the air is a function of relative humidity, ambient temperature, and total atmospheric pressure (equivalent to 101.325 kPa) [8].

- *Relative Humidity (RH): This index is defined as the ratio of the mass of water vapor per unit volume of air at a specific temperature to the maximum mass of vapor that the air can hold at saturation at that same temperature. In essence, RH describes the saturation level of the air-vapor gas mixture [13].*
- *Dew Point: In a constant-pressure cooling process, the temperature at which the condensation phase begins is called the dew point, which is equivalent to the saturation temperature. A relative humidity of 100% implies that the ambient temperature aligns with the dew point. From an AWG system design perspective, high RH indicates that the ambient temperature is close to the dew point, thereby reducing the specific work (energy consumption) required to initiate the condensation process [8, 13].*

3.2. *Effects of Electric Fields and Wettability on Condensation Mechanisms*

Microscopic analyses reveal that the application of an electric field perpendicular to the surface (Z-axis) leads to the orientation of water molecule dipoles (hydrogen in the direction of the field and oxygen against it). According to documentation, at field strengths exceeding 0.06 V/Å, water molecules transform from a spherical structure to a columnar configuration, resulting in a sharp decline in heat flux [14]. In fact, the condensation process on surfaces is the result of the competition between electric field forces and surface attraction forces. Alterations in surface wettability modify the attraction *potential and determine molecular distribution; specifically, the condensation rate is directly proportional to surface wettability and inversely proportional to electric field intensity [14].*

Furthermore, based on the expansion of the Kelvin equation, the presence of strong electric fields can facilitate the condensation process by increasing the liquid's boiling point and decreasing the saturated vapor pressure. The critical field strength for polar fluids such as water is estimated at approximately 6×10^8 V/m. Additionally, capillary condensation occurs only when the contact angle is significantly less than 90°; otherwise, the concavity of the liquid surface and the resulting increase in vapor pressure inhibit the progress of condensation [15].

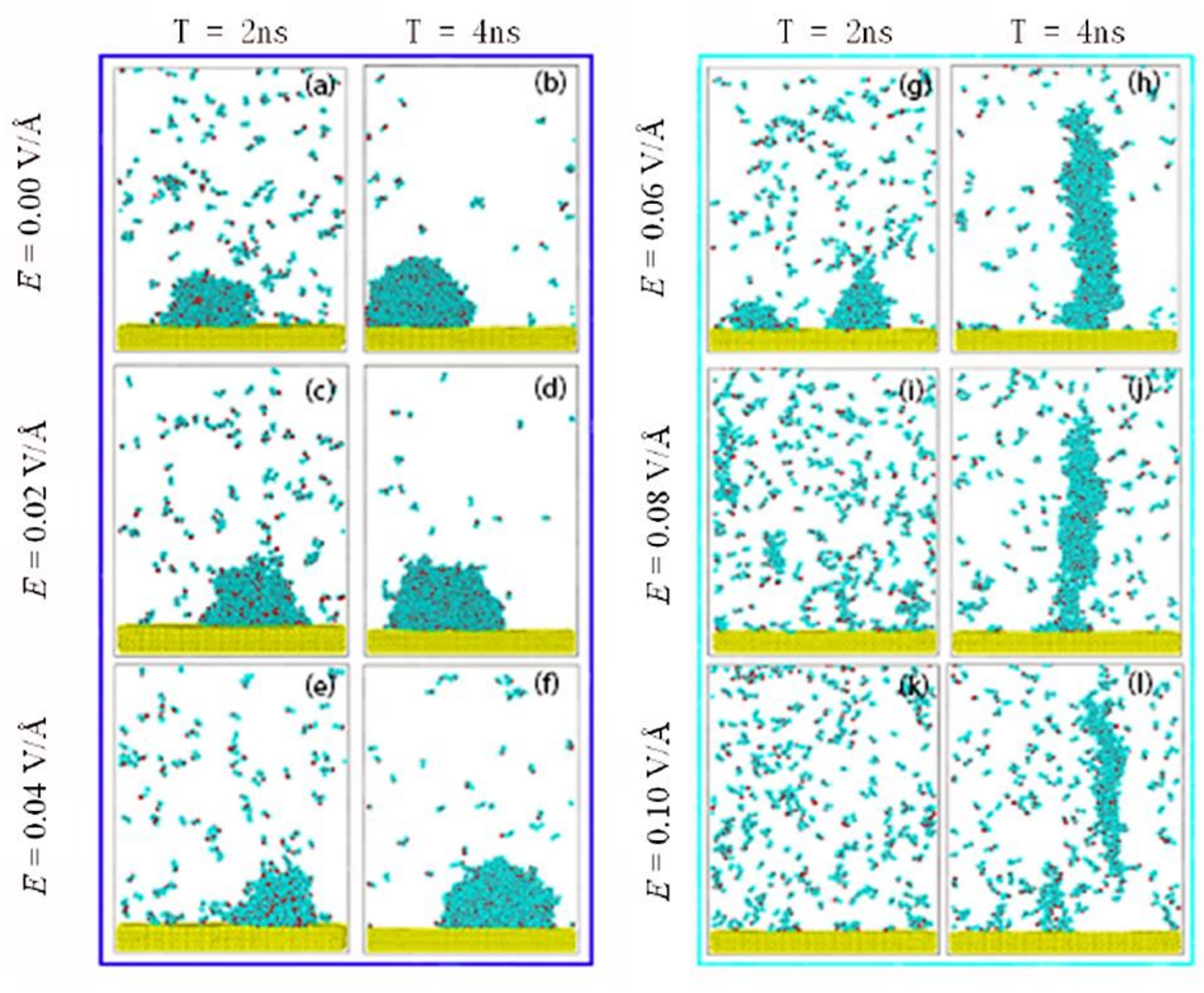

Fig. 2. *Snapshots of water molecule condensation on the surface at 2 ns and 4 ns under an electric field [14].*

3.3. *Classification of Atmospheric Water Generation (AWG) Strategies*

Technologies developed for extracting atmospheric moisture can be categorized into four general classes based on the sorption mechanism and energy consumption level [3]:

1. *Active Refrigeration Techniques: These systems rely on high electrical power consumption to reduce the surface temperature below the dew point, thereby forcibly facilitating the condensation process.*

2. *Vapor Concentration Techniques: This approach is based on the use of sorbents or selective membranes, which serve to separate and pre-concentrate water vapor molecules prior to the condensation stage.*
3. *Passive Techniques: These methods include fog harvesting and dew harvesting, which operate without the need for an external energy source, relying solely on the natural potential of the climate at high relative humidity (RH).*
4. *Hybrid Approaches: This strategy focuses on integrating two or more of the aforementioned mechanisms to enhance overall system efficiency and reduce operational costs through synergistic effects.*

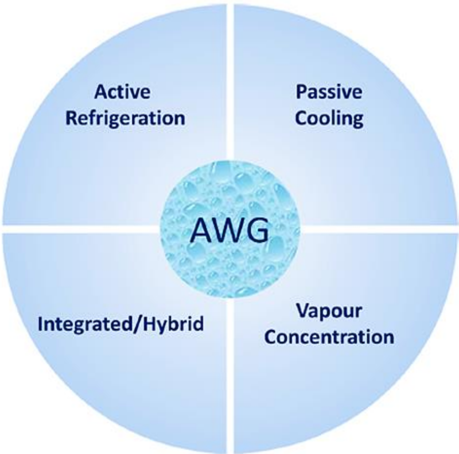

Fig. 3. *Atmospheric Water Generation (AWG) Technologies [3].*

3.3.1. *Active Refrigeration Techniques*

In this system, the water extraction process requires the ambient air to be first cooled sensibly until it approaches the dew point, followed by the removal of latent heat to facilitate the phase change from vapor to liquid [3].

3.3.1.1. Vapor Compression Refrigeration (VCR) or Vapor Compression Cycle (VCC)

This technology, designed based on conventional refrigeration and air conditioning cycles, consists of four main components: a compressor, a condenser, an expansion valve, and an evaporator.

- *Operational Mechanism: Humid air is directed toward the evaporator coils by a fan. As the air temperature drops below the dew point at the evaporator surface, the condensation process initiates.*
- *Climatic Limitations: In conditions where the relative humidity (RH) is below 30%, the dew point temperature typically drops below 0°C. In such scenarios, the formation of a frost layer on the evaporator acts as a thermal resistance, significantly impeding the system's performance [3, 16].*
- *Energy Optimization: To enhance efficiency, the cold exhaust air can be utilized for pre-cooling the inlet air, thereby reducing the overall cooling load [3].*

Patel et al. conducted an empirical study investigating the performance of a VCR-based AWG system across various Indian cities using a climatic chamber (equipped with an electric heater and humidifier). This chamber enabled the simulation of diverse atmospheric conditions in a laboratory environment. Their findings confirmed that these devices exhibit maximum efficiency in hot climates with high relative humidity [3].

On an operational scale, the implementation of this system in an Abu Dhabi hotel resulted in a 19% reduction in total water supply costs. Although early versions of this technology utilized CFC refrigerants (ozone-depleting substances), they have been replaced by eco-friendly refrigerants in recent years. Furthermore, companies such as Rainmaker and Eolewater have successfully integrated VCC systems with wind turbines to produce 1500 liters of water daily at 24°C and 45% RH, achieving a process with zero greenhouse gas emissions [8].

Table 1. *Summary of research works on Vapor Compression Refrigeration (VCR) systems [3, 8, 16].*

system &company or model	Temprature ℃	Relatve Humidity (RH) %	Water harvesting rate (WHR) (Kw~Kg)	Unit power consumption (UPC)	Refrence
VCC_1	35	20-40	0.13-2 Kg h^{-1}	0.18-2.08 KW h Kg^{-1}	Yang[8]
VCC_2/Southern Iran	60	69-94	0.92-1.08 Kg h^{-1}	0.22-0.3 KW h Kg^{-1}	Zolfagharkhani et al[8]
VCC/hotel in Abu Dhabi	35	60	Summer:425/Winter:104 Kg h^{-1}	8.47 KW h Kg^{-1}	Magrini et al[8]
VCC_3/Compressor power:1035W	19.4,26.7	—	1.5 Kg h^{-1}	0.69 Kw h Kg^{-1}	Luo et al[8]
VCC_4/Two evaporator	—	70-90	1.5-4.2 Kg h^{-1}	0.64 Kw h Kg^{-1}	Zhang et al[8]
VCC	40	—	250 Kg h^{-1}	4.2 Kw h Kg^{-1}	Elattar et al[8]
VCC/wind power Eolewater	25	45	62 Kg h^{-1}	—	Nazarova et al[8]
VCC/wind power Rainmarker	15	30	312.5 Kg h^{-1}	—	Sol´ıs-Chaves et al[8]
VCR	35	95	1.78 L h^{-1}	0.75 Kw h L^{-1}	Patel et al[3]
VCR	33	24	0.33 L h^{-1}	1.76 Kw h L^{-1}	Talib et al[3]
VCR/Maithri Aquatech	29.4	80	40 L day^{-1}	0.7 Kw	https://www.maithriaqua.com/[16]
VCR/VayuJal Technologies	30	70	30 L day^{-1}	0.5 Kw	https://vayujal.com/[16]
VCR/AirOWater	—	70	25 L day^{-1}	0.5 Kw	https://www.airowater.com/[16]
VCR/Akvo	30	80	50 L day^{-1}	0.65 Kw	https://akvosphere.com/[16]
VCR/Clean Water Generator	30	65	30 L day^{-1}	0.45 Kw	https://www.cleanwaterproblem.com/[16]
VCR/Aeronero	30	80	20 L day^{-1}	0.25 Kw	https://aeronero.life/[16]
VCR/Aguae	30	80	20 L day^{-1}	0.47 Kw	https://www.aguaer.com/[16]
VCR/Aryav	30	80	30 L day^{-1}	0.3 Kw	https://aryaveco.com/[16]
VCR/Accairwater	30	80	30 L day^{-1}	0.45 Kw	https://www.accairwater.com/[16]
VCR/Vayuneer	30	80	30 L day^{-1}	0.3 Kw	https://www.vayuneer.com/[16]
VCR/Innovaqua	28	90	30 L day^{-1}	0.45 Kw	https://www.innovaqua.org/[16]
VCR/Watergen	26.6	60	30 L day^{-1}	0.4 kw	https://www.watergen.com/[16]
VCR/Genaq	30	80	20 L day^{-1}	0.35 Kw	https://www.genaq.com/[16]
WaterMaker India	25-32	80	25 L day^{-1}	0.4 Kw	https://watermakerindia.com/[16]

3.3.1.2. Thermoelectric Cooling (TEC)

Thermoelectric cooling systems operate based on the Peltier Effect; when an electric current pass through the junction of two dissimilar conductors, heat absorption (cooling) occurs on one side while heat rejection (heating) occurs on the other.

- *Advantages: These devices are characterized by the absence of chemical refrigerants, compact structure, negligible maintenance costs, and vibration-free/silent operation.*
- *Challenges: The primary limitation of this technology is its low Coefficient of Performance (COP) and relatively high energy consumption. Research indicates that the thermal efficiency of these systems can be enhanced by employing advanced heat sinks and applying hydrophobic coatings on the cold side [3, 17].*

In the field of small-scale systems, Kazim et al. experimentally evaluated a solar-powered TEC-AWG prototype equipped with an aluminum cone on the cold section [3]. Furthermore, Michael et al. introduced a technology known as MOHA, which utilizes corona discharge and electrospray mechanisms for the electrostatic separation of moisture. This method, supported by the U.S. Army Corps of Engineers, is capable of extracting latent heat without the need to cool the entire volume of the passing air. This feature enables the technology to maintain high efficiency in environments with a humidity range of 20% to 80% (such as the Mojave Desert).

Experimental results by Michael et al. indicate that by precisely tuning the cooling power, the electrospray technique can increase the water extraction rate by up to five times. Additionally, to ensure the quality of the produced water and control the Total Organic Carbon (TOC) index on an industrial scale, the use of stainless-steel condensers and Teflon separators is recommended. Moreover, the implementation of multi-stage separators, alongside increasing the heat exchange surface area, is recognized as an effective strategy for improving the final efficiency of moisture collection [18].

Table 2. *Summary of research works on Thermoelectric Cooling (TEC) systems [3, 16].*

system &company or model	Temprature ℃	Relatve Humidity (RH) %	Water harvesting rate (WHR) (Kw~Kg)	Unit power consumption (UPC)	Refrence
TEC_1	30	90	0.024 kg h^{-1}	7.5 Kw h Kg^{-1}	joshi et al[16]
TEC_2	35	75	0.026 Kg h^{-1}	2.5 kw h kg^{-1}	Tajeddini et al[16]
TEC/solar distillation	25-34	70-90	1.01-1.41 Kg h^{-1}	0.39-0.58 Kw h kg^{-1}	jradi et al[16]
TEC_3	24	67-92	0.0112-0.0251 Kg h^{-1}	2.23-5.21 Kw h Kg^{-1}	Liu et al[16]
TEC_4	26.5	70	0.00875 Kg h^{-1}	1.56 Kw h Kg^{-1}	Pontious et al[16]
TEC	16-20	100	WGR improved by 30% with hydrophobic coating and16–18% with cleaning	—	Hand et la[3]
TEC	24.3	90	24 mL h^{-1}	52.3 W	Liu et al[3]
TEC	24.29	67.8	20 mL h^{-1}	58.2 W	He et al[3]
TEC	31	75	20 mL h^{-1}	70 W	Kadhim et al[3]
TEC	45	75	26 mL h^{-1}	20 W	Eslami et al[3]
TEC	22-35	60-90	0.82 L h^{-1}	30 W	Irshad et al[3]

3.3.2. *Passive Techniques (Passive Cooling)*

These methods are considered an economical option due to their simple structure and negligible operational costs, primarily relying on Radiative Cooling or specific mechanical configurations [3].

3.3.2.1. Dew Harvesting

The process of dew formation is a function of environmental parameters such as atmospheric temperature, humidity levels, wind speed, and cloud density. By designing surfaces with low solar *absorptivity and high infrared emissivity, the cooling power required for condensation can be achieved, even during daylight hours [3, 5].*

Chen et al., in their studies, achieved a significant temperature reduction of 42 ℃ over a 24-hour cycle. This achievement was realized using a selective emitter composed of alternating layers of silicon nitride (Si_3N_4), silicon (Si), and aluminum (Al) [4]. To optimize performance and minimize convective heat loss, the emitter was housed within a vacuum chamber. Additionally, to facilitate radiative heat exchange and provide protection against environmental factors, a transparent window made of zinc selenide (ZnSe) was utilized. Finally, by integrating a vertical shield and a reflective funnel, the absorption of direct solar radiation on the emitter surface was minimized to ensure the continuity of the condensation process throughout the day [3].

Table 3. *Summary of research works on dew harvesting [5].*

system &company or model	Temprature ℃	Relatve Humidity (RH) %	Water harvesting rate (WHR) (Kw~Kg)	Unit power consumption (UPC)	Refrence
DH/Styrene foam panels	—	—	0.6 L m^{-2} h^{-1}	—	Sharan et al[5]
DH/Epoxy/SiO2 grooves	—	—	0.2 L m^{-2} h^{-1}	—	Bintein et al[5]
DH/Polymer flat surfaces	—	100	0.2 L m^{-2} h^{-1}	—	Jin et al[5]
DH/Patterned copper	—	50	1.1 L m^{-2} h^{-1}	—	Hou et L[5]
DH/Nanostructured Teflon AF and PTFE surfaces	—	98	0.72 L m^{-2} h^{-1}	—	Gerasopoulos et al[5]
DH/Porous coating layer	—	—	0.13 L m^{-2} h^{-1}	—	Xu et al[5]
DH/Rough Duralumin Alloy Plates	—	70	0.15 L m^{-2} h^{-1}	—	Trosseille et al[5]
DH/Needle-Shaped Black Silicon	—	70	0.1-0.27 L m^{-2} h^{-1}	—	Liu et al[5]

3.3.2.2. Fog Harvesting

Fog is defined as a collection of micron-sized water droplets with an approximate diameter of 10 µm suspended near the Earth's surface. Standard fog collection systems primarily consist of vertically oriented meshes known as Raschel mesh.

- *Dimensional Classification: These systems are designed in two scales: Small Fog Collectors (SFC) for monitoring and exploration, and Large Fog Collectors (LFC) with an approximate area of 48 m^2 for operational use, yielding a daily production of 150 to 750 liters [17].*
- *Modern Optimization: Enhancing the performance of these meshes is achievable through the application of nano-coatings on the mesh wires and precise engineering of pore spacing, which prevents the aerodynamic deflection of droplets upon impact [3, 19].*

Cruzat and Jerez-Hanckes utilized a mechanism of injecting electric charge into fog droplets to overcome their aerodynamic deflection in the vicinity of wire networks. By establishing a radial electric field between an internal (copper) electrode and an external collector, the resulting electrostatic force overcomes the drag force, directing the droplets directly toward the collection surface. This approach increases the water extraction rate by up to 60% compared to conventional collectors [3].

In a similar vein, Maher and Kripa employed ion emitters to induce corona discharge at voltages exceeding the threshold limit (V_c), thereby charging the fog droplets and driving them toward a grounded collector. Laboratory findings indicated that at a voltage of 10 kV, the power consumption is only 40 W/m^2. The water recovery rate in power plant cooling towers using this method reaches 5000 L/m^2 per day, which, with a negligible energy consumption of 0.2 kWh/m^3, is evaluated as significantly *more economical than processes such as Reverse Osmosis (RO). In addition to meeting potable and agricultural needs in arid regions, this technology is applicable for improving horizontal visibility on roads and at airports [19].*

On an operational scale, successful international projects have been commissioned, including a 600 m^2 facility in Morocco that, over a six-year period, achieved a yield of 17 gallons of water per square meter per day [8]. Additionally, the Warka Tower structure, featuring a 10-meter-high bamboo and polyester framework, possesses a production capacity of 50 to 100 liters of water per day. In the design of these structures, fabric canopies are utilized at the lower section of the collector to prevent the re-evaporation of collected water [8, 17].

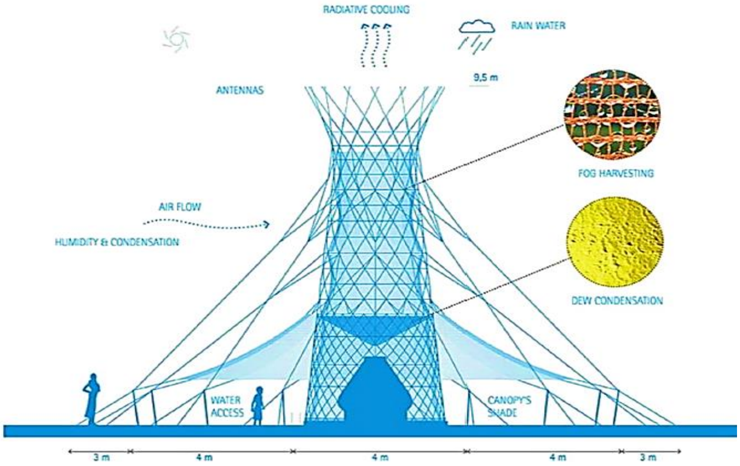

Fig. 4. *Concept of the bamboo tower for atmospheric water harvesting through fog [17].*

Table 4. *Summary of research works on fog harvesting [5, 17].*

system &company or model	Temprature °C	Relatve Humidity (RH) %	Water harvesting rate (WHR) (Kw~Kg)	Unit power consumption (UPC)	Refrence
FH/35 LFCs	Winter dry season	–	(6300/4-6 monthes) 200 L da	–	Hu et al[5]
FH/Four LFCs were added in the 2000s,and four more in 2011	–	–	–	–	Jaén et al[5]
FH/60 fog nets	–	–	100 L day^{-1}	–	https://www.naturphilosophie.co.uk...[5]
FH/Locally created collector	–	–	100 L day^{-1}	–	Larrain et al[5]
FH/SFC fog collector	–	–	61 L day^{-1}	–	Larrain et al[5]
FH/25 LFCs	Dry winter period	–	4.5 L day^{-1}	–	Schemenauer et al[17]
FH/Eiffel collector LFC	During the pick fog season	–	2650 L day^{-1}	–	Lummerich et al[17]
FH/Harp collector LFC	During the pick fog season	–	200 L day^{-1}	–	Lummerich et al[17]
FH/Diagonal Harp collector LFC	During the pick fog season	–	94.21 L day^{-1}	–	Lummerich et al[17]

3.3.3. *Water Vapor Concentration and Sorption Technologies*

Unlike refrigeration-based methods, this approach does not require the direct cooling of vast volumes of air; instead, it focuses on the separation and accumulation of vapor molecules within an intermediate phase (sorbent material or membrane).

3.3.3.1. Sorption-based Methods

These systems operate based on a two-stage cycle consisting of adsorption (typically during the night) and desorption (utilizing solar thermal energy during the day) [8].

- *Physical Adsorbents: Compounds such as silica gel and zeolites are known for their strong bonding with water molecules; however, their regeneration process requires high operating temperatures (exceeding 160°C) [10, 13].*
- *Hygroscopic Salts: Materials like LiCl and $CaCl_2$ possess high absorption capacities, but challenges such as particle agglomeration and equipment corrosion limit their application [10].*
- *Metal-Organic Frameworks (MOFs): These porous structures have created a fundamental paradigm shift in water harvesting from ultra-arid atmospheres. For instance, the MOF-303 compound exhibits high efficiency even at extremely low humidity (10%), and the produced water meets potable standards without the need for secondary treatment [8].*

Kim et al. developed a system based on MOF-801 to address the challenge of water production at low relative humidity (20%), capable of producing 2.8 L of water per kilogram of adsorbent in a daily cycle. The desorption temperature of this material is estimated at approximately 65°C, which is easily supplied by flat-plate solar collectors; thus, MOF-801 is considered an ideal candidate for hot and arid climates such as North Africa [3]. Furthermore, a strategy integrating MOFs with passive radiative cooling has been introduced, where the use of high-emissivity copper foam reduces the ambient temperature by 3 K and increases the effective relative humidity by 5% to 7%. This hybrid system operates with a thermal efficiency of 14% under critical conditions (10% to 40% RH and sub-zero dew points) [10].

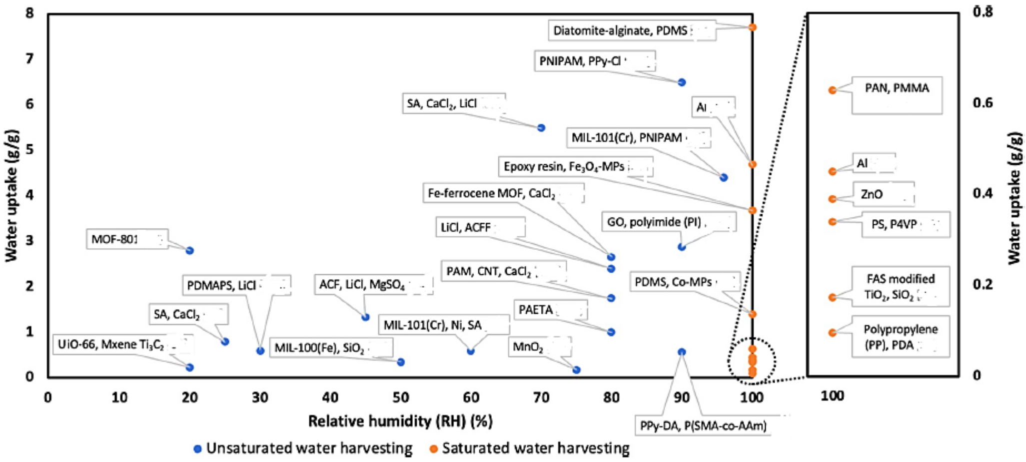

***Fig. 5.** Summary of water harvesting capacity of AWH materials [2].*

3.3.3.2. Membrane Separation

This technology utilizes polymeric membranes with selective permeability, where the transport rate of water vapor is up to 20,000 times higher than that of air. This method possesses the potential to reduce energy costs by 50%, although membrane fouling remains a technical challenge [7, 20].

Bergmair et al. proposed an AWG model utilizing selective membranes that reduces energy demand by more than 50%. The driving force for permeation in this system is the partial pressure differential between the inlet stream and the permeate side, managed by a condenser and a vacuum pump. This model is capable of producing 9,190 liters of water daily with an energy intensity of 583 MJ/m^3; in contrast, non-membrane processes under similar conditions extract only 4,450 liters with an energy intensity of 1,202 MJ/m^3. Additionally, the membrane acts as a primary filter, enhancing the physical quality of the water [3].

This technology is evaluated as highly efficient for regions such as the Negev Desert, which lack surface resources but possess favorable dew points (16.3°C). Simulations indicate that in a configuration with 5,000 m^2 of membrane and a pressure of 25 mbar, 9.19 m^3 of water can be produced daily with a power consumption of 62 kW. In this scenario, 87.4% of the power is dedicated to the condensation process, indicating high system efficiency [20]. Although a portion of the energy (5.4 kW) is consumed by the vacuum pump to manage non-condensable gases, the overall savings compared to conventional systems (with consumptions of 270 to 500 kWh/m^3) are quite significant [11, 20].

***Table 5.** Summary of research works on sorption and membrane-based systems [3, 5, 8].*

system & company or model	Temprature ℃	Relatve Humidity (RH) %	Water harvesting rate (WHR) (Kw~Kg)	Unit power consumption (UPC)	Refrence
S/CS/Al-Fum/SA/ Passive	25	33	1.95 $L_{H2o}\ Kg_{CAS}^{-1}\ day^{-1}$	1.57 $Kw\ h\ L_{H2o}^{-1}$	Tao et al[8]
S/$CaCl_2$/Passive	—	—	0.63 $Kg\ m^{-2}\ day^{-1}$	Solar	Talaat et al[8]
S/LiCl/$MgSO_4$/ACF composite/Passive	Cold semi-arid	35	0.92 $g_{water}\ g_{adsorbent}^{-1}$	—	Ejeian et al[8]
S/MOF-801/Passive	20	30	0.25 $L_{water}\ Kg_{MOF}^{-1}\ day^{-1}$	Solar	Kim et al[8]
S/MOF-801($Zr_6O_4(OH)_4(fumarate)_6$)/Passive	25	20	2.8 $L_{water}\ Kg_{MOF}^{-1}\ day^{-1}$	Solar	Kim et al[8]
S/MOF-801-graphite mixture/Passive	25	15	100 $gr_{water}\ Kg_{MOF}^{-1}\ day^{-1}$	Solar	Fafhieh et al[8]
S/Zeolite (AQSOA Z01)/Active	25	15-20	0.77 $L\ m^{-2}\ day^{-1}$	Solar	Lapotin et al[8]
S/Lithium chloride in silica sol/Active	31	66-93	0.67 $g_{water}\ g_{sorbent}^{-1}\ h^{-1}$	Solar	Wang et al[8]
S/LiCl@rGO-SA/Active	—	15-30	2120 $mL_{warer}\ Kg_{sorbent}^{-1}\ day^{-1}$	Solar/0.95-1.05 $Kw\ m^{-2}$	Xu et al[8]
S/MOF-801/Active	—	17-32	3.5 $L_{H2o}\ Kg_{MOF}^{-1}\ day^{-1}$	1.67-5.25 $Kw\ h\ L_{H2o}^{-1}$	Almassad et al[8]
S/MOF-303/Active	27	10	0.7 $L_{water}\ Kg_{MOF}^{-1}\ day^{-1}$	—	Hanikel et al[8]
S/MOF-303/Active	27/ In desert	32	1.3 $L_{water}\ Kg_{MOF}^{-1}\ day^{-1}$	—	Hanikel et al[8]
S/HCS-LiCl@SiO_2/Active	25	60	1.6 $Kg_{water}\ Kg_{sorbent}^{-1}$	Solar/1 $Kw\ m^{-2}$	Li et al[8]
S/$CaCl_2$	26	70	910 $gr\ m^{-2}$	Solar	William et al[8]
S/Licl@MOF	30	30	0.3 $gr\ gr_{Composite}^{-1}$	Solar	Xu et al[8]
S/Silica-based $CuCl_2$	17	20	0.25 $gr\ gr_{Composite}^{-1}$	Solar	Alsaedi[8]
S/Zeolite 13-$CaCl_2$-MWCNT	30	35	0.5 $gr\ gr_{Composite}^{-1}$	Solar	Chan et al[8]
S/Zeolite 13	30	—	0.09 $gr\ g_{rComposite}^{-1}$	Solar	Chan et al[8]

Table 5. *Continued.*

S/PPSD	—	40	0.43 gr $gr_{Composite}^{-1}$	Solar	Ni et al[8]
S/SD	—	40	0.05 gr $gr_{Composite}^{-1}$	Solar	Ni et al[8]
S/MOF-801	22	18	0.33 L_{warer} Kg_{MOF}^{-1} h^{-1}	Solar	Terzis et al[8]
S/MOF-Co_2Cl_2BTDD	25	30	0.82 g_{H2o} g_{MOF}^{-1}	400 Kw h m^{-3}	Rieth et al[8]
S/Polymer-MOF, MIL-101(Cr)	30	90	6 gr_{water} $kg_{P\text{-}MOF}^{-1}$	1 Kw m^{-2}	Yilmaz et al[8]
S/MIL-101(Cr)	—	40	3.1 L_{water} m^{-2} day^{-1}	—	Mulchandani et al[8]
S/Mil-125(Ti)-NH_2	11	20	0.32 g_{water} g_{MoF} day^{-1}	Solar	Silva et al[8]
S/UiO-66 MOFs	25	40	0.054 g_{water} g_{MOF}^{-1}	Solar	Trapani et al[8]
S/Zr-MOF-808	22	70	8.66 L_{H2o} Kg_{MOF}^{-1} day^{-1}	—	Logan et al[8]
S/MIL-160(Al) MOF	30		0.305 g_{water} g_{MOF}^{-1}	—	Silva et al[8]
S/MOF-derived nanoporous carbon	—	30	0.18 L_{water} Kg_{carbon}^{-1} h^{-1}	Solar/1 Kw m^{-2}	Song et al[8]
S/MIL-100(Fe)	150	—	86.8 L day^{-1}	—	Silva et al[5]
S/P-SG & P-SG-L	40	10	1.70 g g^{-1}	—	Ma et al[5]
S/Carbon fibre felt (ACFF)–silica sol–$LiCl_3$	31	63	7.7 Kg	—	Wang et al[5]
S/$CaCl_2$ nanocrystals	15	80	2.685 g_{H2O} g_{CaCl2}	—	Hu et al[5]
S/ASLi30	51	30	0.42 kg_{water} $kg_{adsorbent}^{-1}$	—	Wang et al[5]
S/GO–SSNF	—	30	0.69 g g^{-1}	—	Kim et al[5]
S/Cr-soc-MOF-1	25	70	1.95 g g^{-1}	—	Towsif et al[5]
S/Aluminum Fumarate	25%	—	0.33 g g^{-1}	—	Teo et al[5]
S/AQSOA-Z01 zeolites	25 & 60	—	0.23 g g^{-1}	—	Kayal et al[5]
S/$AlPO_4$-LTA	10 & 15	—	0.37 g g^{-1}	—	Krajnc et al[5]
S/Calciumchloride + vermiculitesaw wood	—	—	195 mL kg^{-1} day^{-1}	—	Kumar et al[5]
S/Calcium chloride and cloth	—	—	3.02 L day^{-1} m^{-2}	—	Mohamed et al[5]
S/Calcium chloride and black cloth	—	12	Minimum 230 mL m^{-2} day^{-1}	—	Elashmawy[5]
S/30% Calcium chloride and black cloth	—	16	0.51 L kg^{-1}	—	Elashmawy et al[5]
S/LITHIUM BROMIDE ANHYDROUS (LiBr)	—	—	73 mL day^{-1}	—	Srivastava et al[5]
S/Calcium chloride and black cloth	—	—	272–750 g day^{-1}	—	Fathy et al[5]
S/carbon felt + LiCl	—	85	14.7 Kg	—	Wang et al[5]
S/Layered structure MnO_2	—	23 Dew point	0.07 kg_{water} $kg_{sorbant}^{-1}$	—	Wang et al[5]
S/Functionalized carbon nanotube (FCNT)	—	40	5.6 g_{water} $g_{sorbent}^{-1}$	—	Entezari et al[5]
S/LiCl- inside nanocarbon capsule's void core	—	60	1.6 kg_{water} $kg_{sorbant}^{-1}$	—	Yang et al[5]
S/ACF (LiCl, $CaCl_2$, and $LiNO_3$)	25	20	1.18 g_{water} $g_{sorbant}^{-1}$-LiCl	—	Zhang et al[5]
S/PDMAPS	65	—	28 g	—	Aleid et al[5]
S/Alginate-chained hydrogel	—	—	5.6 g	—	Entezari et al[5]
S/Pyramidal solar still for CaCl2 (4-shelves)	15	—	1-2 L	—	Kabeel et al[5]
S/$CaCl_2$ single-basin solar still	—	40	1 L m^{-2} day^{-1}	—	Hamed et al[5]
S/$CaCl_2$ ACF sorbent	70-80	—	0.32 kg_{water} and 2.25 kg_{ACFCA}	—	Wang et al[5]
S/[$ZrO_4(OH)_2$(fumarate)$_6$] air-cooled sorbent-based device-(MOF)-801	—	40	0.21 L	—	Kim et al[5]
S/Adsorption-Desorption in Liquid Sorbent	—	80	2.8 L m^{-2} day^{-1}	—	Krajnc et al[5]
S/COF-432	30&35 adsorption & desorption	40&30 adsorption & desorption	0.33 g g^{-1}	—	Nguyen et al[5]
S/Hydrogel(hygroscopic)	25	90	4.2 g g^{-1}	—	Krishna et al[5]
S/Cu (II)-ethanolamine hydrogel	25	30	0.14 g g^{-1}	—	Yang et al[5]
S/Co-SHM	25	30	0.11 g g^{-1}	—	Zhang et al[5]
S/IPN- interpenetrating polymer network	25	30	0.18 g g^{-1}	—	Matsumoto et al[5]
S/SMAG	25	30	0.7 g g^{-1}	—	Zhao et al[5]
S/PC-MOF	25	30	0.76 g g^{-1}	—	Yilmaz et al[5]

Table 5. Continued.

S/PC-MOF	25	30	0.76 g g^{-1}	—	Yilmaz et al[5]
S/G-PDDA	25	30	0.13 g g^{-1}	—	Yang et al[5]
S/LiCl@MIL-101(Cr)_51	30	30	0.82 g g^{-1}	—	Xu et al[5]
S/LiCl@HS-200	25	30	0.76 g g^{-1}	—	Yang et al[5]
S/PAM-CNT-$CaCl_2$	25	35	0.69 g g^{-1}	—	Li et al[5]
S/Alg-CaCl	28	33	1.18 g g^{-1}	—	Jia et al[5] & Kallenberger et al[5]
S/ACFP30	25	70	1.62 g g^{-1}	—	Wang et al[5]
S/Saturated LiBr solution	25	30	0.34 g g^{-1}	—	Gordeeva et al[5]
S/Saturated LiCl solution	25	60	1.79 g g^{-1}	—	Yang et al[5]
S/[Pyrrol][Ac]	29	57	0.45 g g^{-1}	—	Chen et al[5]
S/[DEA][Fo]	29	57	0.4945 g g^{-1}	—	Chen et al[5]
S/[DEA][Ac]	29	57	0.6545 g g^{-1}	—	Chen et al[5]
S/HCS-LiCl nano sorbent	22	60	1.6 $kg_{water}\ kg_{sorbent}^{-1}$ in 10 h	Solardesorptio/30 min/1 Kw m^{-2}	Li et al[3]
S/ACF-LiCl, ACF-$CaCl_2$,ACF-$LiNO_3$ composite sorbent	25	70	2.9 (ACF-LiCL) $g_{water}\ g_{sorbent}^{-1}$	—	Entezari et al[3]
S/ACF-CaCl2, ACF-LiCl	30–33	65–85	0.32 kg_{water}(2.25$kg_{ACF-CaCl2}$) & 11.2 kg_{water} (40.8 $kg_{ACF-LiCl}$)	—	Wang et al[3]
S/CaCl2 liquid desiccant	31 & 41	87–92	1.15 $L_{water}\ m^{-2}\ day^{-1}$	—	Gandhidasan et al[3]
S/LiCl/Sand,$CaCl_2$/Sand,LiBr/Sand	Semi-arid	HR=7.6–13.8 g Kg^{-1}	90/115/73m$L_{water}\ day^{-1}$ 5.5/4.5/4.5	—	Srivastava et al[3]
S/MOF-303/G	18–25	30–50	174 $g_{water}\ kg_{sorbent}$	—	Fathieh et al[3]
S/MOF-801	23.5	39	0.52 $L_{water}\ h^{-1}\ kg_{sorbent}^{-1}$	—	Terzis et al[3]
S/PGF	Arid and contaminated	15	0.14 $g_{water}\ g_{sorbent}^{-1}$	—	Yao et al[3]
S/Composite hydrogel sorbent (PAM-CNT$CaCl_2$)	22–26	35	0.74 $g_{water}\ g_{sorbe}^{-1}$	—	Li et al[3]
S/$CaCl_2$ solution with graphene oxide aerogel	25	70	2.89 kg $m^{-2}\ day^{-1}$	—	Wang et al[3]
S/(1-ethyl-3-methylimidazolium acetate) CFM	25	80	2.8 $L_{water}\ m^{-2}\ day^{-1}$	—	Qi et al[3]
S/Agricultural wastecorn stalk	—	20–80	0.5–1.8 $kg_{water}\ kg_{material}^{-1}$during 8h	—	Gong et al[3]
S/G-PDDA aerogel	20	60	4.25 $L_{water}\ kg_{sorbent}$ during 12h	—	Yang et al[3]

3.3.4. Integrated and Hybrid Approaches

Recent research focuses on integrating AWG technologies with other industrial processes and renewable energy sources. These strategies include combinations with Reverse Osmosis (RO) systems, energy recovery from flare gases in refineries, or utilizing the exhaust air stream from fuel cells to enhance water extraction rates.

- *Solar Chimney Power Plants: Ming et al. proposed a modified solar chimney model for freshwater production. In this design, black helical tubes absorb and store radiant energy during the day and re-emit it at night, creating a continuous buoyancy flow. This phenomenon leads to moisture condensation on porous surfaces installed at the top of the chimney. In addition to water production, this structure is capable of harvesting electrical energy from the airflow and fluid motion using wind and hydraulic turbines.*
- *Water Recovery in Thermal Power Plants: In another study, Ghosh et al. investigated the potential of fog harvesting from the exhaust streams of power plant cooling towers. Simulation results for a 500 MW unit demonstrated that by installing fog collectors at the tower outlet, approximately 40% of the evaporated water can be recovered. The resulting water is of high quality and can be reused as make-up water in the power plant cycle without the need for complex treatment processes. Findings indicate that the efficiency of this method is twice that of natural fog collectors; unlike seasonal weather phenomena, this source is consistently available as long as the power plant is operational [3].*

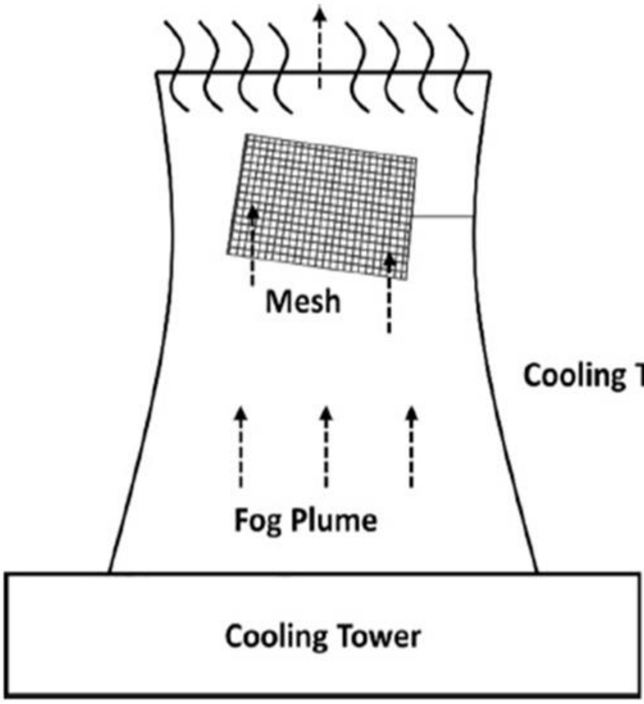

Fig. 6. *Fog harvesting from cooling tower plumes [3].*

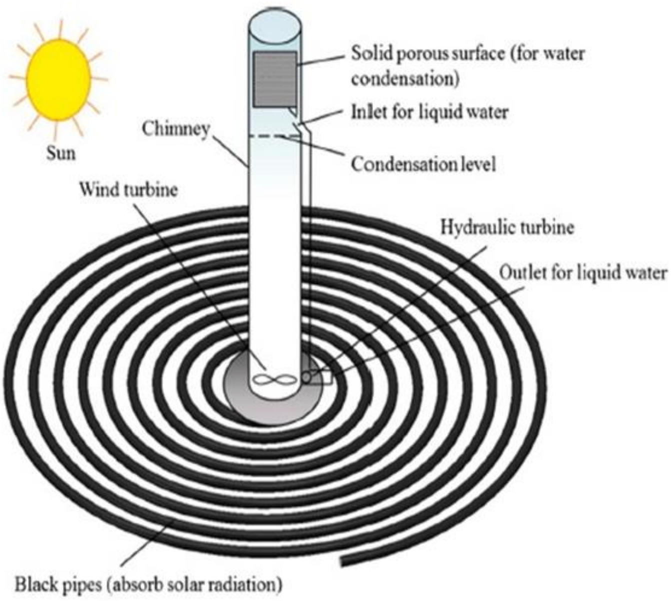

Fig. 7. *Modified solar chimney power plant [3].*

Table 6. Summary of recent approaches in atmospheric water generation [3].

system &company or model	Temprature ℃	Relatve Humidity (RH) %	Water harvesting rate (WHR) (Kw~Kg)	Unit power consumption (UPC)	Refrence
IH/Tubular Solar Still-AWG silica gel	28–40	45-62	400 $mL\ m^{-2}$	—	Essa et al[4]
IH/Tubular Solar Still -AWG $CaCl_2$	29–36	12	467,230 $mL\ m^{-2}\ day^{-1}$ (fan or not)	—	Elashmawy et al[4]
IH/Tubular Solar Still -AWG $CaCl_2$	Low humid desert	16	0.51 $L_{water}\ kg_{desiccant}^{-1}$	—	Elashmawy et al[4]
IH/Trapezoidal Solar Still-AWG$CaCl_2$	24–26	60–89	2.320, 1.235 $L_{water}\ m^{-2}\ day^{-1}$	—	William et al[4]
IH/Trapezoidal Solar Still-AWG $CaCl_2$	28	26.5	1.06 $L_{water}\ m^{-2}\ day^{-1}$	—	Elashmawy et al[4]
IH/Biomass gasification powered AWG	Indian climate	—	1.2 $L_{water}\ kg_{biomass}^{-1}$	—	Chaitanya et al[4]
IH/Waste natural gas-powered AWG	Warm humid climate	—	12.6 $L_{water}\ m_{gas}^{-3}$	—	Ozkan et al[4]
IH/VCR based AWG with multiple desiccant wheels	40	RH=5 g kg_{dryair}^{-1}	32.5 $L\ h^{-1}$	0.794 $KW\ h\ L^{-1}$	Tu et al[4]
IH/Fuel cell-VCR-AWG hybrid system	27	60	—	0.2 $KWh\ L^{-1}$	Kwan et al[4]

4. Conclusion

The selection of an optimal strategy for atmospheric moisture extraction is a function of precise climatic variable analysis and mapping the "water-energy nexus." Despite technological advancements over the last decade, a single universal solution capable of addressing all challenges in this field has yet to emerge [3]. The key findings of this research are summarized as follows:

- *Active Systems: Technologies based on the Vapor Compression Cycle (VCR) possess the highest water production rates compared to Thermoelectric (TEC) systems due to their superior cooling capacity and airflow management. However, high energy intensity and functional dependency on hot and humid environments challenge their efficiency in cold and arid regions [3]. These units are operational across a wide range of scales, from domestic applications to agricultural water supply [17].*
- *Passive Extraction (Fog and Dew): Classical challenges, such as the aerodynamic deflection of fog and the clogging of mesh networks, have been largely mitigated today through modern surface engineering approaches. Harvesting fog from the exhaust streams of power plant cooling towers offers significant potential for scalable water production and the recovery of 40% of evaporative losses [3]. Beyond providing water resources, this method is effective in improving road visibility and restoring vegetation in arid regions.*
- *Sorption and Membrane Technologies: Systems based on sorbent materials, particularly Metal-Organic Frameworks (MOFs), represent a sustainable solution for diverse climates due to their ability to operate at critical humidity levels (below 20%) without the need for high-grade energy sources [3]. Simultaneously, the employment of selectively permeable membranes in hot regions with high vapor pressure offers the potential to reduce energy consumption by more than 50%.*

Future Outlook and Recommendations

Based on the comprehensive analysis of current Atmospheric Water Generation (AWG) technologies, several strategic directions are proposed for future research to bridge the gap between laboratory prototypes and industrial-scale applications:

- *Synergy of Electric Fields and Advanced Materials: While this review highlighted the individual potential of electric fields and Metal-Organic Frameworks (MOFs), a promising frontier lies in their integration. Future studies should investigate how external electric fields can be tuned to accelerate the adsorption-desorption kinetics within porous MOF structures, potentially lowering the thermal energy required for water release.*
- *Bio-inspired Surface Engineering: Future designs for fog and dew harvesting should move beyond conventional meshes toward hierarchical, "omni phobic" surfaces. Inspired by the Namib Desert beetle and spider silk, engineering surfaces with asymmetric wettability can facilitate spontaneous droplet shedding, effectively addressing the challenge of aerodynamic clogging and re-evaporation.*
- *Optimization of Hybrid Architectures: The transition toward "Hybrid Systems"—such as coupling Vapor Compression Cycles with selective membranes—represents a vital strategy for energy optimization. Research should focus on minimizing the "energy-water nexus" cost by utilizing waste heat from industrial processes or power plant cooling towers as a driving force for moisture pre-concentration.*
- *Economic and Field-Scale Validation: To move toward commercialization, future work must shift from controlled climatic chambers to long-term field tests in diverse environments. A standardized framework for calculating the Levelized Cost of Water (LCOW) and Return on Investment (ROI) is essential to demonstrate the economic competitiveness of AWG against traditional desalination, especially in landlocked arid regions.*
- *Smart Integration with Renewable Grids: Beyond simple solar-thermal coupling, the development of IoT-enabled AWG units that can adjust their operational mode based on real-time humidity and electricity grid fluctuations (peak/off-peak) will be crucial for sustainable, decentralized water production.*

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