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A Review on The Progress in Water Production from Air by Using Solar Driven Technology

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Abstract

The utilization of solar energy for water production offers a sustainable and environmentally friendly solution, particularly in desalination and atmospheric water generation. Solar power is an efficient system for driving pumps and heating, which means it is most appropriate in areas that are remote and off-grid, including regions in cases of natural disasters. These include desiccant materials, hybrid absorbent systems, and nanomaterials, all enhancing efficiency in water production. For instance, with an efficiency cycle of 91.5% at 20°C, a system using SWS can generate between 3 and 5 tons of water in a day for every 10 tons of dry SWS. Another example is the metal-organic framework, MOF 801, where sorbents provide 2.8 liters of water per kilogram capacity at 20% relative humidity. Advanced systems, such as parabolic solar concentrators, depict a water production rate of 2.32 liters per square meter per day. The decreasing costs of solar technology add further value to its competitiveness as a cost-effective alternative to systems currently using fossil fuel. Future research areas shall also focus on integration with more renewable energy sources, cost reduction in materials, and study on the socio-economic impact of such systems across diverse regions. All these developments are potentially promising in contributing to water scarcity reduction across arid and resource-starved regions of the world.

Keywords: Atmospheric water generation (AWG), vapor concentration sorbent sorption (VCSS),Selective Water Sorbents (SWS),Metal-Organic Frameworks (MOF), phase change material (PCM).

Nomenclature

Nomenclature	
AWG	Atmospheric Water Generation
VCSS	The Vapor Concentration Sorbent Sorption
SWSs	Selective Water Sorbents
MOFs	Metal-Organic Frameworks
ACF	Active Carbon Felt
PCM	Phase Change Material
PCLG	Poly(E-Caprolactone-Co-Lactide-Glycolide)
NBHA	Nanostructured Biopolymer Hygroscopic Aerogel
AWH	Atmospheric Water Harvesting
ACF-CaCl2	Activated Carbon Fiber-Calcium Chloride
ACF-LiCl	Activated Carbon Fiber-Lithium Chloride.
TSS	Tubular Solar Still
ANFIS	Adaptive Neuro-Fuzzy Inference System
DS-HCBSS	Double-Slope Half-Cylindrical Basin Solar Still
LDS	Liquid Desiccant System
SGDBS	Solar Glass Desiccant Box Type System
HDH	Humidification Dehumidification
EES	Engineering Equation Solver
CFD	Computational Fluid Dynamics
WHO	World Health Organization
TEGs	Thermoelectric Generators

1. Introduction

Freshwater is a vital resource essential for human survival and well-being. However, the world is facing a fresh water crisis due to increasing demand, pollution, and mismanagement of this finite resource [1][2]. Pollution is a major contributor to the freshwater crisis, along with increasing demand and mismanagement. Industrialization, urbanization, and agriculture have all contributed to the contamination of freshwater sources. Toxic chemicals, fertilizers, and pesticides from these activities can seep into rivers, lakes, and groundwater, making the water unsafe for human consumption and environmental health [3][4]. The modern world is also facing the challenge of plastic pollution, which is having a significant impact on freshwater systems. Climate change is another factor that is contributing to the fresh water crisis. Rising temperatures and changing rainfall patterns are affecting the availability and quality of freshwater, and the frequency and intensity of natural disasters, such as droughts and floods, are also increasing. To address the fresh water crisis, it is essential to implement effective water management policies, reduce pollution, and encourage the adoption of clean energy

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alternatives. It is also essential to raise awareness about the importance of freshwater and the need to conserve and protect this vital resource for future generations [5][6][7][8][9][5].There are several ways to produce water using renewable energy sources as shown in Fig. 1, including:

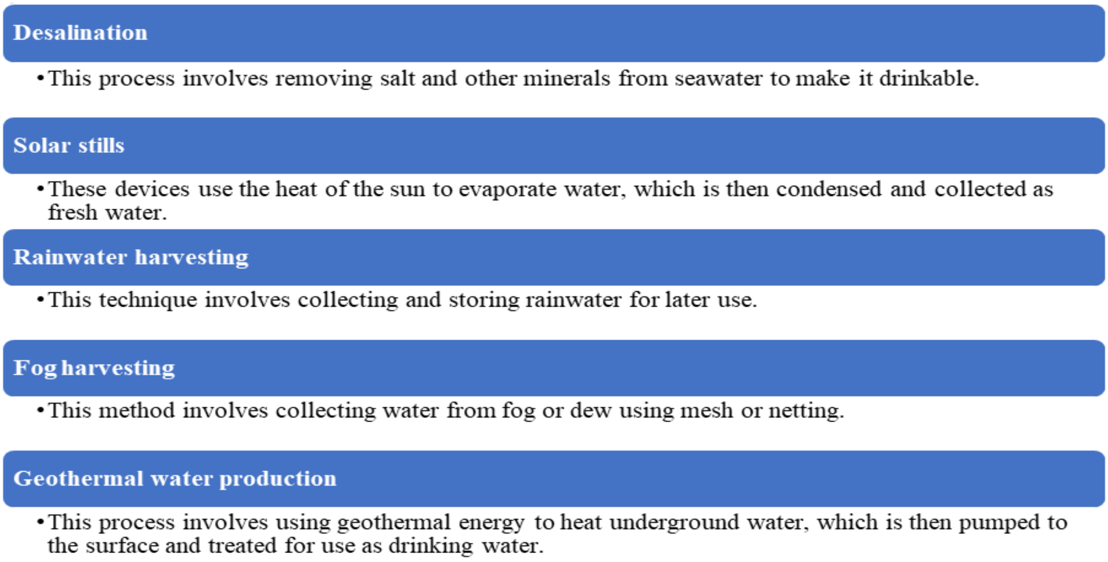
Overall, renewable energy technologies can play an important role in producing clean, safe water for communities around the world [10][11][12][13][14][15][16][17].

Solar energy is a green, sustainable energy source that has many applications. One of the most frequent applications of solar energy is creating electricity by using solar panels[18][19][20][21]. Solar panels capture sunlight and transform it into electricity, which can be used to run homes, businesses, and other facilities. Solar energy can also be used for making water from air by using a method called humidification-dehumidification. In this method, solar energy is used to warm air, making it rise and cool as it goes up. As the air cools, the water vapor in it changes into liquid, and the resulting water is gathered. This method can be used to produce water in areas with low moisture or where traditional water sources are scarce[22][23][24]. Various processes use solar energy to create water from the air. The methods that use sun energy for generating water from air are shown in Fig. 2.

Atmospheric water generation refers to the process of extracting water from the air using energy. One way to do this is through the use of solar energy. This can be done through the use of several devices. This study focuses on innovations in extracting water from the air using solar energy, investigating the working principles, performance, and limitations of various technologies, including systems that utilize salt-based thermal energy storage and electrical cooling to condense atmospheric moisture, as well as hybrid approaches combining solar thermal and photovoltaic components for water extraction. Potential applications include providing potable water for drinking and cooking in homes located far from traditional water sources, serving as a source of clean water for outdoor activities like camping and trekking, and supplying water in regions impacted by drought or flooding.

2. Harnessing Solar Light for Thermal Energy

Solar energy can be used as a heat source for atmospheric water generation (AWG), which involves obtaining water from the air through various methods[25][26][27].For it carries a lot of heat because of the hotness of the sun, it can be utilized in various ways[28][29][30][31]. The following sections consider the potential for harvesting solar heat using different materials and applications to produce water.



Desalination

- This process involves removing salt and other minerals from seawater to make it drinkable.

Solar stills

- These devices use the heat of the sun to evaporate water, which is then condensed and collected as fresh water.

Rainwater harvesting

- This technique involves collecting and storing rainwater for later use.

Fog harvesting

- This method involves collecting water from fog or dew using mesh or netting.

Geothermal water production

- This process involves using geothermal energy to heat underground water, which is then pumped to the surface and treated for use as drinking water.

Figure 1. Producing water using renewable energy sources.

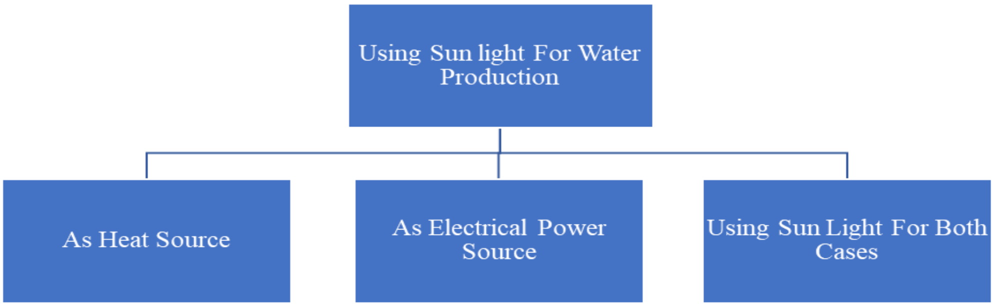


Figure 2. Using solar energy for atmospheric water generation.

2.1. Influence of Sorbent Material Characteristics

Desiccant materials are substances that capture water vapor from the air and retain it in a dry state. They are used in various applications to control humidity and prevent moisture-related issues, such as corrosion, material degradation, and water generation. In the vapor concentration sorbent sorption (VCSS) process, materials absorb water vapor from the air, which is then released by heating the material and collected as liquid water. This method is effective in producing fresh water from air, though performance may vary depending on moisture and heat levels. Sorbents like silica gel, zeolites, and certain polymers each have distinct properties, making them more or less suitable for specific applications. A sorption humidifier is needed to facilitate this process by using sorbent materials that absorb water vapor from the air and release it upon heating, typically with an electric heater or solar thermal system. The released water vapor is then condensed into liquid form using a condenser or cold surface. These materials are chosen for their moisture absorption capacity and compatibility with their intended applications. Desiccant materials also have uses in air conditioning, heating systems, gas purification, and water treatment, and are critical in atmospheric water generation systems [32][33][34][35][36][37]. Adsorption is when a substance, usually a gas or liquid, sticks to the surface of a solid. This occurs when the molecules of the adsorbate (the substance being adsorbed) are attracted to the surface of the adsorbent (the substance doing the adsorbing). The attractive forces can be chemical, physical, or a combination of both[38][39][40]. Desorption is the reverse process, in which the adsorbate is released from the surface of the adsorbent. This can occur when the attractive forces between the adsorbate and adsorbent are weakened or broken, or when the adsorbate is driven off the surface by a change in temperature, pressure, or some other external condition [41][42][43][44].

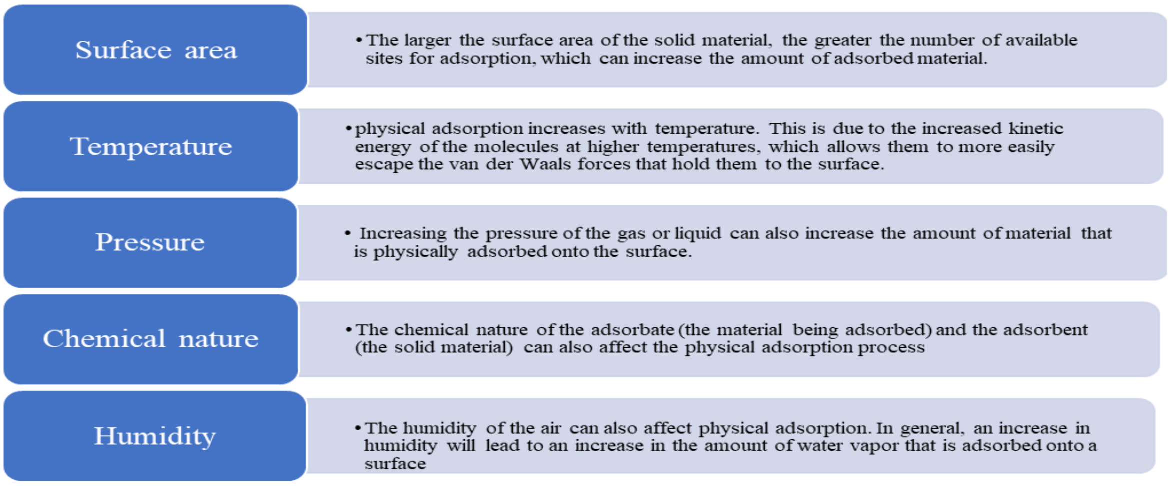
The process of water generation using sorption material called vapor concentration sorbent sorption (VCSS) process. As the material becomes saturated, it releases heat. The saturated material is then heated above the dew point, releasing water vapor which is condensed into liquid. The desiccated material is then cooled and recharged for repeated cycles. VCSS is effective in regions with high humidity but limited freshwater, where other methods like desalination are less practical or economical. The process's efficiency is affected by factors like air humidity, sorbent material properties, and system design [48][49][50][51].

Within the VCSS process, air is circulated through a sorption material bed, where the material absorbs water vapor from the air. The sorption material can be a chemical compound or a natural material, such as a type of clay, that has a high affinity for water. As the sorption material absorbs the water vapor, it becomes saturated with water and releases heat[52][53][54][55].

The sorption material that has taken in water vapor is then warmed up to a temperature that is above the point where the water vapor turns into liquid, making the water change into gas and is gathered as a liquid. The water-depleted sorption material is then cooled and recharged with water vapor, allowing the VCSS process to be repeated.

VCSS is a promising technology for producing water in areas where other methods, such as desalination, are not practical or cost-effective. The effectiveness of the VCSS process relies on both the sorption material employed and the humidity level in the air.

The physical adsorption process can be influenced by various factors, such as:



Surface area
- The larger the surface area of the solid material, the greater the number of available sites for adsorption, which can increase the amount of adsorbed material.

Temperature
- physical adsorption increases with temperature. This is due to the increased kinetic energy of the molecules at higher temperatures, which allows them to more easily escape the van der Waals forces that hold them to the surface.

Pressure
- Increasing the pressure of the gas or liquid can also increase the amount of material that is physically adsorbed onto the surface.

Chemical nature
- The chemical nature of the adsorbate (the material being adsorbed) and the adsorbent (the solid material) can also affect the physical adsorption process

Humidity
- The humidity of the air can also affect physical adsorption. In general, an increase in humidity will lead to an increase in the amount of water vapor that is adsorbed onto a surface

Figure 3. Variables influencing the physical adsorption processes [45][46][47].

The VCSS process involves several steps as shown in Fig. 4:

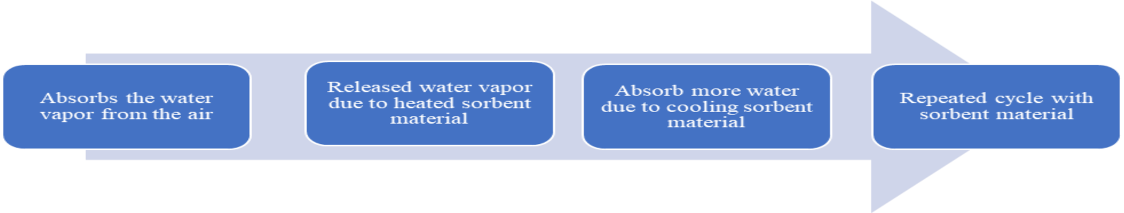


Figure 4. The VCSS Steppes.

VCSS systems can work non-stop or in cycles and can use different energy sources. How well VCSS systems work is influenced by many factors such as the moisture and heat level of the air, the kind and characteristics of the material that takes in water vapor, how well heat and mass move, and how the system is designed and run. VCSS devices can be used to generate water in outdoor environments, buildings, and industrial processes, and can be powered by solar, wind, or fossil fuel energy sources [56].

The researchers concentrated on enhancing the VCSS process to maximize water production from atmospheric air using solar energy, as illustrated in Fig. 5. Table 1 presents the sorption material employed in the VCSS process and the corresponding water yield under different conditions.

2.1.1. Single sorbent

Aristov et al. [57] developed a system for producing water from the atmosphere using composite sorbent material and solar-powered technology. These materials, known as selective water sorbents (SWSs), can take in water vapor from the air. The process has two steps: at night, the SWSs capture water from the air, and during the day, they let go of the water and change it into a liquid using a cold surface as seen in Fig. 6. This water can then be used. The researchers tried different kinds of SWSs, such as SWS-1L, SWS-1A, SWS-1C, and SWS-2L. They discovered that the system could make 3-5 tons of fresh water for every 10 tons of dry SWS in a day.

Calcium chloride ($CaCl_2$) is a salt known for its ability to absorb moisture from the air via a phenomenon known as deliquescence. When exposed to humid air, $CaCl_2$ absorbs water vapor, creating a solution. The quantity of water generated is contingent on both the humidity of the air and the concentration of $CaCl_2$ in the solution [58][59][60].

Hamed [61]investigated the utilization of $CaCl_2$ as an absorbent for extracting water from atmospheric air. The study involved a thermal process with the following stages:

1. Isothermal absorption of water vapor from the air.
2. Constant concentration heating of the sorbent material.
3. Constant pressure regeneration of the sorbent.
4. Constant concentration cooling of the sorbent.

The findings indicated that the highest cycle efficiency, reaching 91.5%, was achieved when the ambient temperature was 20°C.

Li, R [62] worked on a method that uses a material composed of a hydrogel and a salt that dissolves in water to capture water from the air is called harvesting water from the air using anhydrous salt with sunlight. Salts that dissolve in water, like calcium chloride, sodium hydroxide, and potassium carbonate, are very attracted to water and easily take it in from the air, even when the air is not very moist. In the study, material made of $CuCl_2$, $CuSO_4$, and $MgSO_4$ anhydrous salts produced 0.27, 0.40, and 0.45 g/g of water, respectively.

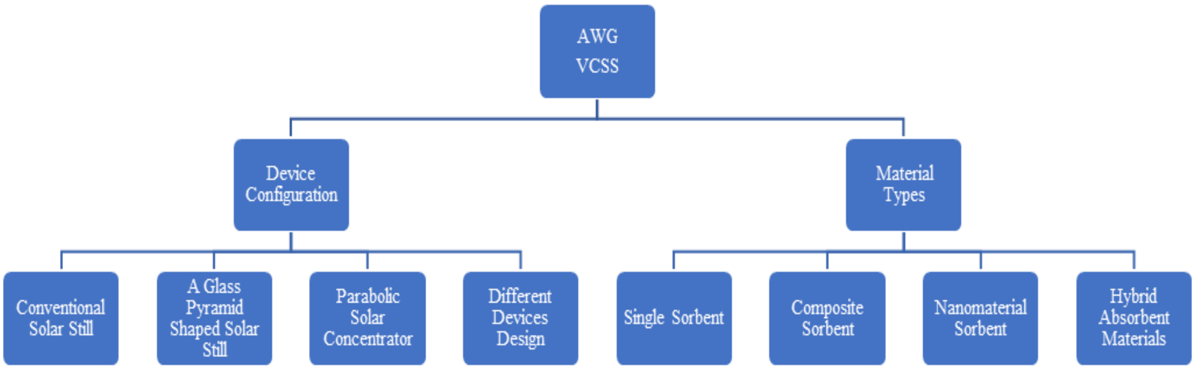


Figure 5. Classifications of VCSS system works.

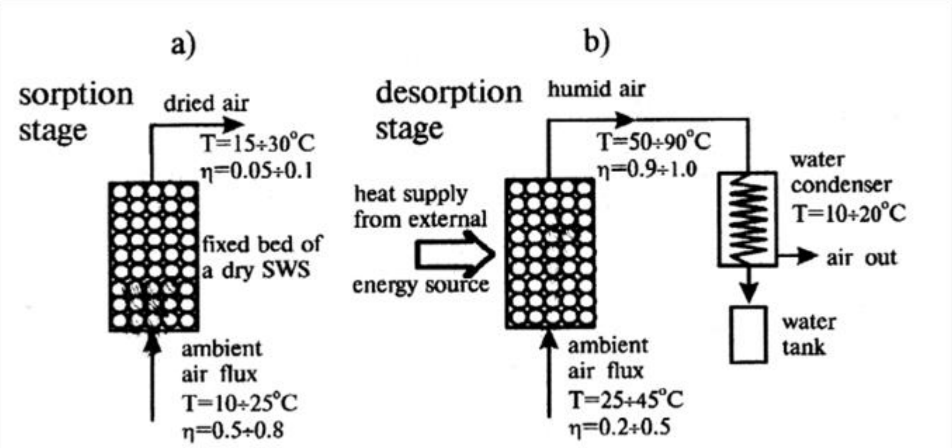


Figure 6. The general scheme of the water production from the atmosphere using composite sorbent material [57].

2.1.2. Composite sorbent

Composite solid sorbents are materials that can be utilized in solar-powered systems to generate fresh water from various sources such as seawater, brackish water, and contaminated water. These materials take in water vapor from the air and let it go when warmed up by solar energy. Silica gel is a type of composite solid sorbent that is often used in water production systems that use solar power because it has many small holes that let it take in a lot of water vapor. There are also other materials like activated carbon, zeolites, and metal-organic frameworks (MOFs) that can be used as composite solid sorbents in water production systems that use solar power because they have many small holes and can take in water vapor [63][64][65].

A new composite adsorbent material has been created by Ji et al. [66]. A material composed of calcium chlorides, created from aqueous CaCl2 solutions of 20%, 25%, 30%, and 35% concentrations, is used to produce water through solar energy. The apparatus, depicted in Fig. 4, exposes 0.1 kg of the adsorbent material to the surrounding air, enabling it to adsorb water vapor from the atmosphere. The results indicate that for daily radiation levels of 15.5, 18.9, and 17.8, the water production was 1.26, 1.39, and 1.34 kg/m^2, respectively. As shown in Fig. 7, the device is illustrated.

Wang et al. [67] investigated the use of composite solid sorbents to produce water from the air using solar energy. The study examined the use of mixtures, made of a mineral matrix and soft, bendable particles dipped in silica solution, to capture water from the air by filling the tiny spaces between material molecules with water molecules. The results indicated that the ACF matrix had the highest water absorption rate from the air at 0.65 g/g.

The goal of Bui et al.[54] was to extract water from air characterized by a low relative humidity of 20%, employing a metal-organic framework material identified as MOF 801 [Zr6O4(OH)4(fumarate)6]. The MOF 801 powder was subjected to 150 C using natural sunlight, and the resulting water was collected via condensers connected to a cooling apparatus. This setup successfully produced 2.8 L/kg of MOF.

The article by Larisa G et. al [68] explores the use of metal-organic frameworks (MOFs) to obtain potable water from the air. MOFs are porous, crystalline materials that have a high surface area and can selectively adsorb particular molecules as shown in Fig. 8.

An advantage of using MOFs for water extraction is that they can perform effectively at low relative humidity levels, making them suitable for arid regions. Additionally, MOFs are highly selective and can remove impurities from the water, resulting in high quality water.

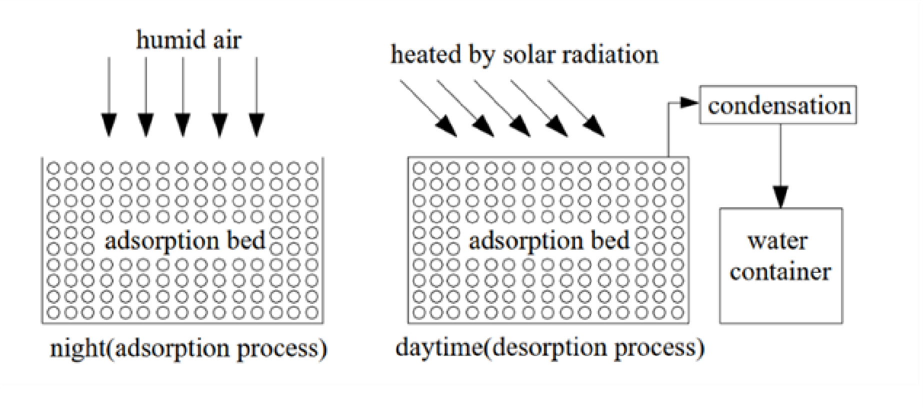


Figure 7. Diagram of the solar-driven water generation using composite adsorbent material techniques from air[66].

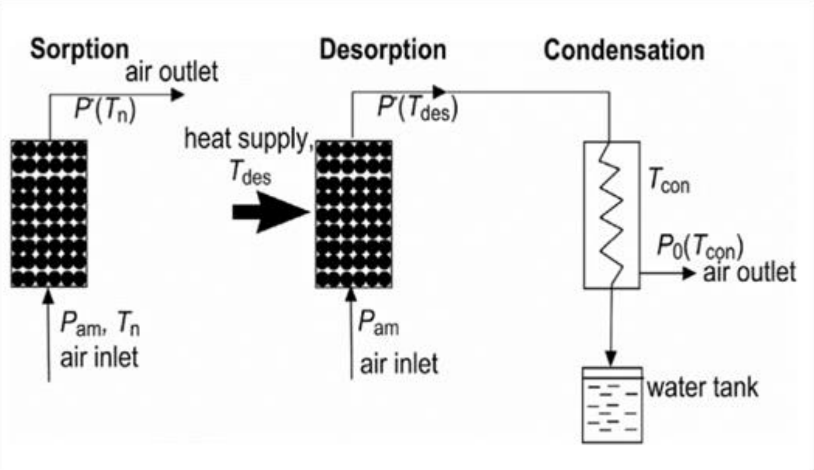


Figure 8. General scheme of using metal-organic frameworks process for water generation[68].

2.1.3. Hybrid sorbent material

Hybrid thermal water absorbent materials are materials that can absorb and release water vapor when the temperature changes. These materials are commonly used in systems for generating water from the atmosphere (AWG), which involve extracting water from the air by utilizing various technologies [69].

A hybrid thermal water absorbent material is a combination of a polymer that absorbs water vapor and a phase change material (PCM) that stores and releases heat. It absorbs water vapor from the air and releases it as fresh water when heated. The PCM stores the heat of sorption for desorption [70][71][72]. Other hybrid thermal water absorbent material combines a water-absorbing polymer with a metal-organic framework or a zeolite. These materials also absorb and release water vapor based on temperature changes and can be used to generate water from the atmosphere [73][74].

Li et al.[75] used a new method that involves absorbing and releasing water from the air, the researcher created a flexible hybrid material that can produce fresh water. The materials are made of a deliquescent salt and hydrogel, which can capture water even in dry conditions. Some examples of these materials are calcium chloride, sodium hydroxide, and potassium carbonate. The researcher tested the material in the field and found that 35 g of dry hydrogel could generate 20 g of water in 2.5 hours under sunlight.

2.1.4. nano material

Wang [76] used nano enabled photothermal material to improve the energy efficiency of solar-powered water production by evaporation and distillation. These materials can absorb and convert sunlight into heat very well, making them suitable for solar-powered water production. The researcher created different types of nanoenabled photothermal materials, such as nanoparticles, nanofibers, and nanostructured surfaces, using various methods such as chemical vapor deposition, electrospinning, and sol-gel methods. These materials can produce clean water in small devices that only use solar energy and can help solve water scarcity problems. [77][78][79][80][81][82]. The next Fig. 9 shows how nanomaterial can extract water from the air using solar energy.

The solar spectrum at sea level exhibits a range from 280 to 2500 nm. Scientists have explored the use of nanomaterials as photothermal agents for solar water evaporation and distillation. These materials can effectively absorb a wide array of wavelengths within the solar spectrum, contributing significantly to the harnessing of solar energy[83][84][85][79][86].

Table 1. Types of sorbent material for water generation using solar energy.

Research	Single, composite, and Hybrid	Research focus	Result
[57] Aristov, Y.I., et al.	Single sorbent	were SWS-1L cacl2 (23.7%), SiO2 , SWS-1A cacl2 (25.9%), Al2O3 SWS-1C cacl2 (24.5%), C SWS-2L libr (30.8%), SiO2	Water production for the day were 3–5 tones per 10 tons of the dry SWS.
[61] Hamed	Single sorbent	Using CaCl2 and working thematically and clarify the thermal process for AWG	Cycle efficiency 91.5% when the ambient temperature was 20 °C
[62] Li et al.	Single sorbent “anhydrous salt”	calcium chloride (CaCl2), sodium hydroxide (NaOH), and potassium carbonate (K2CO3)	CuCl2, CuSO4, and MgSO4 of anhydrous salt (g/g) 0.27, 0.40 , and 0.45 with water production in (g/g) 0.21, 0.30, and 0.35, respectively.
[66] Ji et al.	Composite sorbent	Using CaCl2 solutions with (20%, 25%,30%, 35%) in mass concentration	Daily radiation level of 15.5, 18.9, and 17.8, the water production was 1.26, 1.39, and 1.34 kg per square meter, respectively.
[67] Wang et al.	Composite sorbent	Matrix of mineral and soft, flexible particles that are immersed in a silica solution	water absorption rate from the air at 0.65 g/g (g of water per gram of ACF).
[54] Bui et al.	Composite sorbent	Metal-organic framework-801 (Zr6O4(OH) 4 (fumarate) 6) MOF 801 materials	Water harvesting was 2.8 L of water per kilogram of MOF
[68] Gordeeva, L.G., et al.	Composite sorbent “metal-organic frameworks”	Ability to absorb moisture which were MIL-101(Cr), Co2Cl2(BTDD), and MIL-101(Cr)eso3h. MIL-160 and CAU-10(pydc).	They exchange 0.34e1.6 g/g under conditions of the considered regions.
[75] Li et al.	Hybrid absorbent materials	Effect of PAM-CNT-CaCl2 hydrogel, a material made of polyacrylamide and carbon nanotubes,	Produce 20 g of fresh water within 2.5 hours.

Researchers have delved into the application of diverse nanomaterials as photothermal agents, utilizing their capacity to absorb light and transform it into heat through the movement of mobile carriers within their crystals. Carbon-based materials, including carbon black, carbon nanotubes, graphene, and graphene oxide, are favored options due to their extensive light absorption, stability, lightweight, and cost-effectiveness [87][86][88][89][90][91][92][93]. Recent progress in solar evaporation has unveiled its versatility for various applications such as zero liquid discharge desalination, reduction of wastewater volume, and extraction of salt or heavy metal [93]. Bimetallic nanocomposites, featuring specially crafted nanostructures, have demonstrated potential for enhanced light harvesting. An interfacial heating approach can expedite the response to sunlight and diminish the heating of the bulk water body [94][95].

Wang et al. [96] have pioneered the development of a novel material named PCLG, comprising hydrogel, to augment the efficiency and viability of atmospheric water harvesting systems. The PCLG exhibits a remarkable water-absorbing capacity and incorporates a meticulously designed honeycomb structure that enhances heat and mass transfer, as depicted in Fig. 10. Testing has revealed that the PCLG-based harvester can collect 2.9 L of water per square meter per day under natural sunlight.

The researcher created a new method for producing fresh water with solar energy. The method uses a solid material called solar-powered nanostructured biopolymer hygroscopic aerogel NBHA that can capture water from the air, even in low humidity and low sunlight conditions. The device harvested 6.6 g of water in 8 hours of weak sunlight (natural sunlight of 0.10-0.56 kW/m^2).

[97] Another method for making water with solar energy is solar semiconductor condensation. This method uses a semiconductor material that absorbs sunlight and converts it to heat, increasing the temperature of the material. This makes water vapor in the air condense on the semiconductor surface and form water droplets that can be collected as fresh water [98][49][99][100].

The researcher also developed a solar semiconductor condensation wall water intake system for irrigating crops in desert areas. The system uses 5G network technology and big data analysis to adapt to the desert environment and climate. The system can improve the water use efficiency in agriculture and help solve water scarcity problems in desert regions [101]. The system is expected to generate 138.3 g of water per hour, and produce 28,800 kWh of power over 20 years. The system includes photovoltaic panels, a suction system to bring in moist air, a condensing system using semiconductor refrigeration to cool the air and condense moisture, and a water collection system to store the condensed water. The system is made up of four main parts: photovoltaic panels, a suction system, a condensing system, and a water collection system.

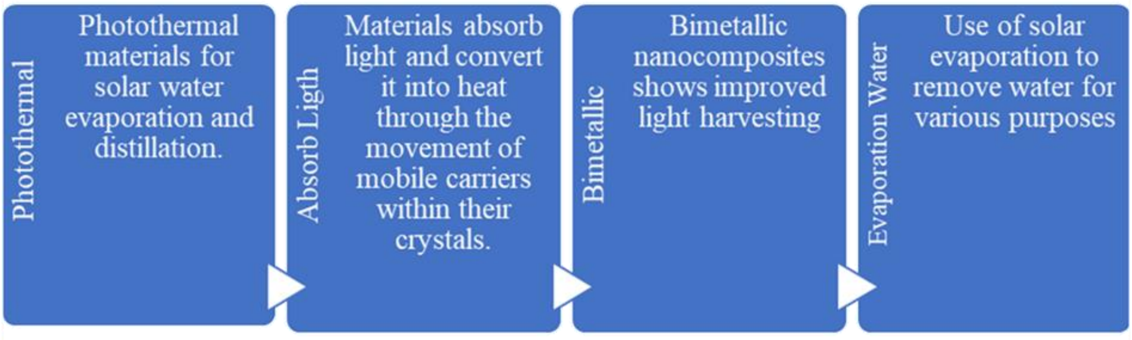


Figure 9. Extraction of water from air using solar energy and nanomaterials.

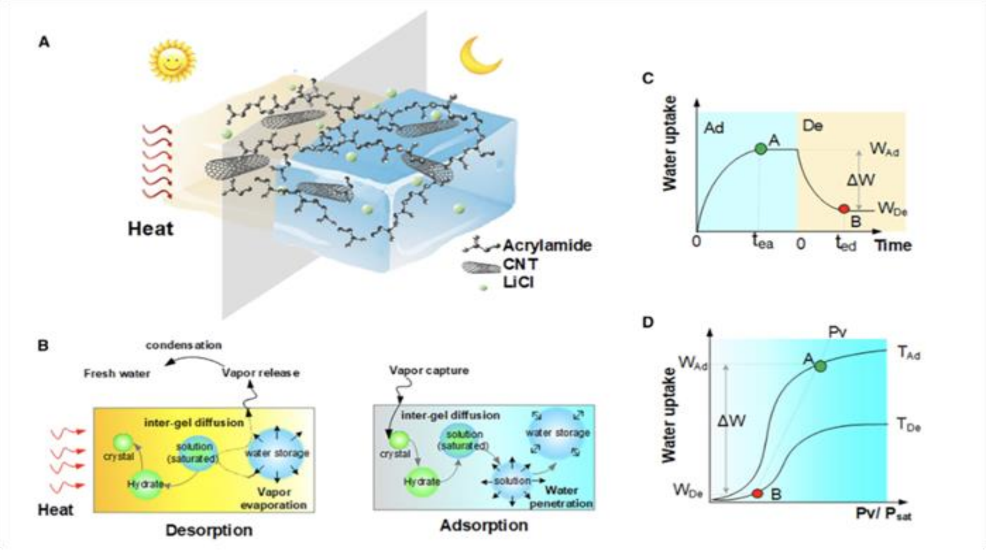


Figure 10. Working principles of the PCLG-based AWH process[96].

2.2. Effect of Device and Material

The effectiveness of devices and materials in producing water through absorption will vary based on multiple factors including the properties of the devices or material and the conditions in which they are used. Material with high surface area or high porosity tends to be more effective in absorbing water vapor from the air, resulting in higher water production. Conversely, materials with low surface area or low porosity tend to be less effective in absorbing water vapor, resulting in lower water production. Additionally, humidity and temperature of the air also play a role in the rate of water production through absorption.

2.2.1. Conventional Solar Still

One advancement in solar still technology involves adding salts and other materials to absorb moisture that isn't evaporated during the regular condensation process[102][103][104]. Table 2 outlines the characteristics and specifications of the solar stills used for this enhanced condensation process.

Hall, R.C. [105] A proposed method to obtain water from the atmosphere involves absorbing it into an absorbent material and then separating it using a solar-type still. the system's operation is shown in Fig. 11. The researcher tested different materials for their ability to absorb water, such as sodium hydroxide, lithium chloride, sulfuric acid, calcium chloride, ethylene glycol, and Di propylene glycol. The results showed that sodium hydroxide absorbed the most water, with 0.76 g of water per gram of liquid. Lithium chloride absorbed 0.65 g of water per gram of liquid, followed by sulfuric acid and calcium chloride, both absorbing 0.52 g of water per gram of liquid. Ethylene glycol absorbed 0.41 g of water per gram of liquid, and Di propylene glycol absorbed the least water, with only 0.09 g of water per gram of liquid.

H.E. Gad et al. [106] aimed to devise a system for generating fresh water from the atmosphere. This proposed system involves the synergistic use of a desiccant and a solar collector. The process involves absorbing water vapor from the air during the night, followed by utilizing solar heat during the day to rejuvenate the desiccant and transform the water vapor into a liquid state. The system exhibits the capacity to produce approximately 1.5 L of fresh water per square meter per day.

Hamed, A.M. et al. [107] A system that generates fresh water from the atmosphere by combining a desiccant and a solar collector was created and tested, as depicted in Fig. 13. The system has an average output of 1 L of fresh water per square meter per day. The thermal process of water generation is shown in Fig. 14.

LaPotin, A., et al. [108] introduced an adsorption-based solar-thermal atmospheric water harvesting (AWH) system designed to generate water in arid regions. To enhance efficiency, a dual-stage AWH device was created, employing optimized transport and utilizing the latent heat of condensation from the upper stage to sustain a temperature gradient between the two stages, as depicted in Fig. 15. This device, utilizing commercial zeolite, underwent outdoor testing under natural sunlight and demonstrated successful regeneration, yielding a daily water production of approximately 0.77 L/m^2.

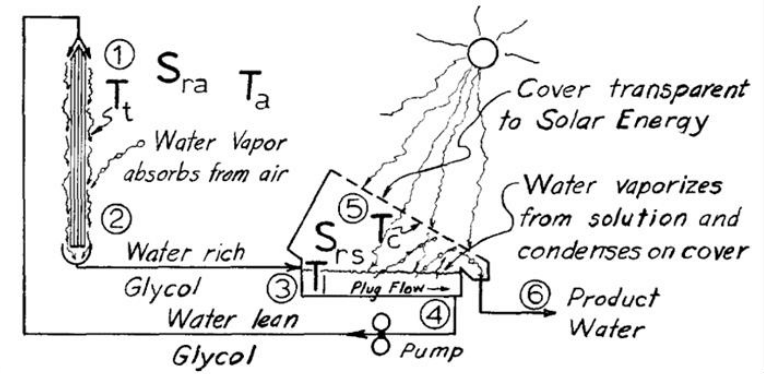


Figure 11. The diagram of composition for ethylene glycol with lines of constant relative humidity for AWG[105].

Figure 12. Image of desiccant and a solar collector used for AWG[106].

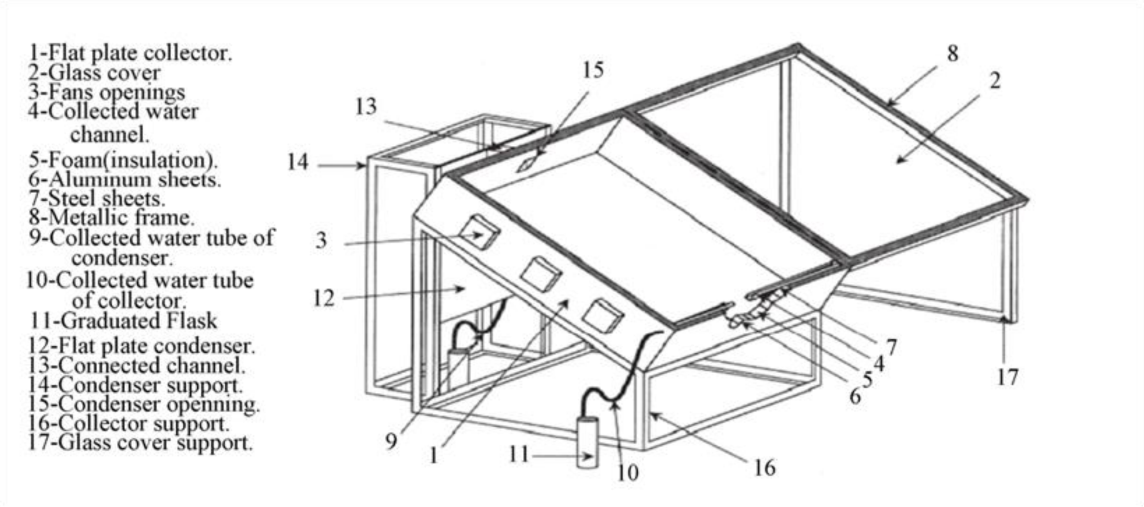


Figure 13. Schematic diagram of solar desiccant collector works to recover water from air[107].

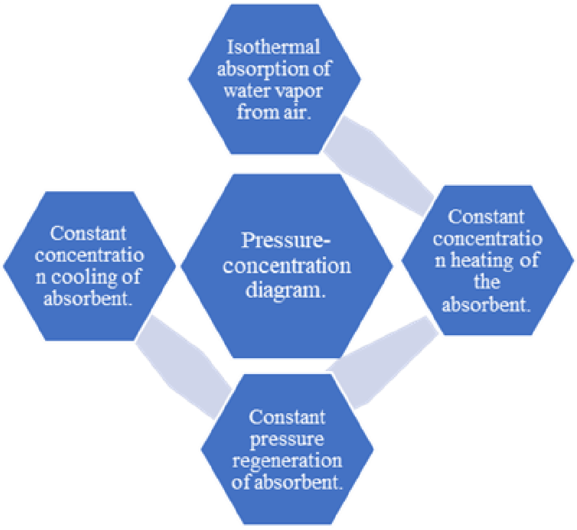


Figure 14. Thermal processes depicted on the vapor pressure-concentration diagram pertain to the absorbent in operation.

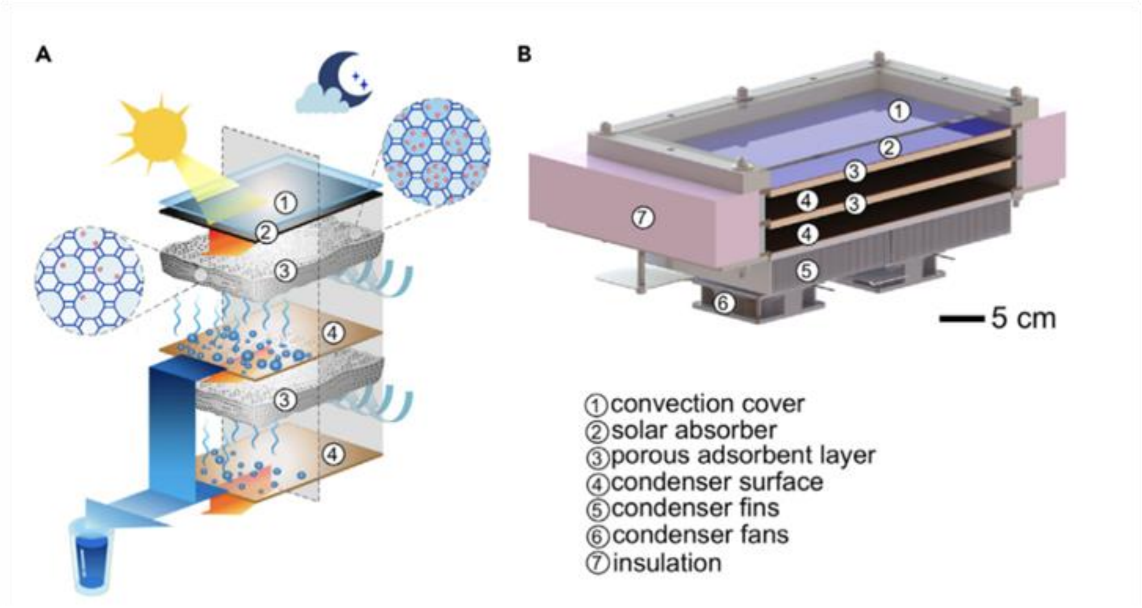


Figure 15. Dual-stage AWH. (a) The diagram shows how the dual-stage AWH works. (b) The diagram shows the details of the prototype of the dual-stage AWH device[108].

Prasadet al.[109], devised a moisture recovery system based on solar still, employing orange silica gel as the adsorbent desiccant to harvest clean water from the atmosphere. The silica gel underwent charging with air overnight and was then subjected to an average solar radiation of 720 W/m2 the subsequent day through a solar still-based recovery unit. The system demonstrated its effectiveness by producing 940 mm of fresh water per 15 kg of desiccant per day. This underscores its efficiency and cost-effectiveness in generating potable water from the ambient air, particularly in regions with scarce water resources.

In a parallel study, Kabeel, A [110], investigated the utilization of a sandy bed solar collector system for extracting water from the air in a simulated desert environment within an Arab country. The system underwent testing at various tilt angles, and a theoretical model was developed for performance analysis. Results showed that the system produced 1.2 L/ m^2 day.

2.2.2. Pyramid Solar Still

The researcher used a device that uses solar energy to get water from the air. The device is shaped like a pyramid and made of glass. The glass traps solar energy and turns it into heat. The heat warms up the air inside the device, making the water in the air turn into droplets on the glass. The droplets are then collected and stored for later use. This device can make drinking water or water for irrigation in places where water is hard to find [111][112][113][114][115][116]. Table 3 shows the techniques using Pyramid Solar Still.

The researcher tested how well a glass pyramid-shaped device with multiple shelves can get water from humid air. The researcher used two devices, each with different kinds of beds on the shelves, as shown in Fig. 16. The researcher soaked both devices with a solution that had 30% Calcium Chloride. The results showed that the bed made of cloth soaked up more solution (9 kg) than the bed made of saw wood 8 kg, and the device could make 2.5 L/m^2 day of water with this method. The device with four glass sides and multiple shelves made more water (90-95% more) than a device with horizontal and corrugated beds [117].

Table 2. Types of sorbent material for water generation using Conventional solar still.

Researcher	Year	Technique/ device	Focus on	Sorbent materials	Result
[105] R.C. Hall	1966	Absorbent using a solar-type still with different sorbent materials	Using different materials for water generation with solar still device	NaOH, LiCl, H_2SO_4, $CaCl_2$, $C_2H_6O_2$, and $C_6H_{14}O_3$	Result (0.76,0.65,0.52, 0.52,0.41, and 0.09) g Water / g Liquid
[106] Gad et al.	2001	Stored solar energy and used a thick corrugated layer of cloth	Using stored solar energy to drive the desiccant material and extract water from the air	CaCl2	Produce Approximately 1.5 L of Fresh Water Per Square Meter Per Day
[107] Hamed et al.	2011	Solar still	Application of solar energy to heat a sandy bed impregnated	Cacl2	Produce An Average Of 1 L of Fresh Water Per Square Meter Per Day
[108] LaPotin et al.	2021	Dual-stage AWH device	Dual-stage configuration for solar-thermal adsorption-based AWH with optimized heat and mass transport to increase the daily water harvesting productivity	Adsorption-Based AWH Uses Adsorbent	Daily Water Production of Approximately 0.77 L/m^2
[109] Prasad, A.R., et al.	2022	The system consists of a solar still	Examine a method for recovering drinkable water from the ambient air using a solar recovery system based on desiccant	Silica Gel	The System Was Able to Produce 940 mL of Fresh Water Per 15 g of Desiccant Per Day,
[110] Kabeel	2004	Using a sandy bed solar collector system	Three different tilt angles: 15, 20, and 25 degrees	Sandy Bed	Produce Approximately 1.2 L of Fresh Water Per Square Meter of Glass Cover Per Day

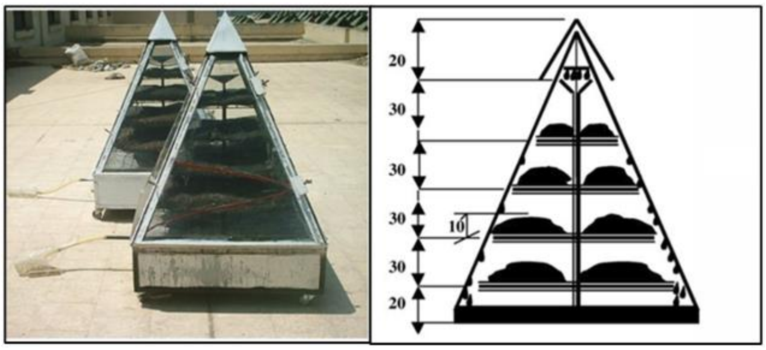


Figure 16. (a) Image of the utilized system. (b) Pyramid with open glass covers during the night time[117].

William, G.E. et al. [118] conducted a study on a system utilizing a combination of a desiccant and a solar collector for the production of fresh water from atmospheric air. The system operates by absorbing water vapor from the air during the night and subsequently employing solar energy to regenerate the desiccant, transforming the water vapor into a liquid state during the day. To enhance efficiency, a trapezoidal prism solar collector with four fiberglass sides and a multi-shelf bed (desiccant carrier) was designed and built. This construction aimed to augment the bed surface area within the collector, thereby increasing absorption and evaporation surfaces. Fig. 17 illustrates the test rig used in the experimental work. The findings revealed that the total evaporated water for the cloth and sand beds could reach 2.32 and 1.23 L/m^2 day, respectively.

The researcher suggested a system that can get water from the air by using solar energy. The system makes water vapor turn into droplets on the sides of a solar collector and then collects the droplets as fresh water. The researcher wanted to see how different conditions affect the system. The results showed that the system could make about 3.02 L of water per day for each square meter of the collector in spring in Alexandria [119].

2.2.3. Parabolic Solar Concentrator

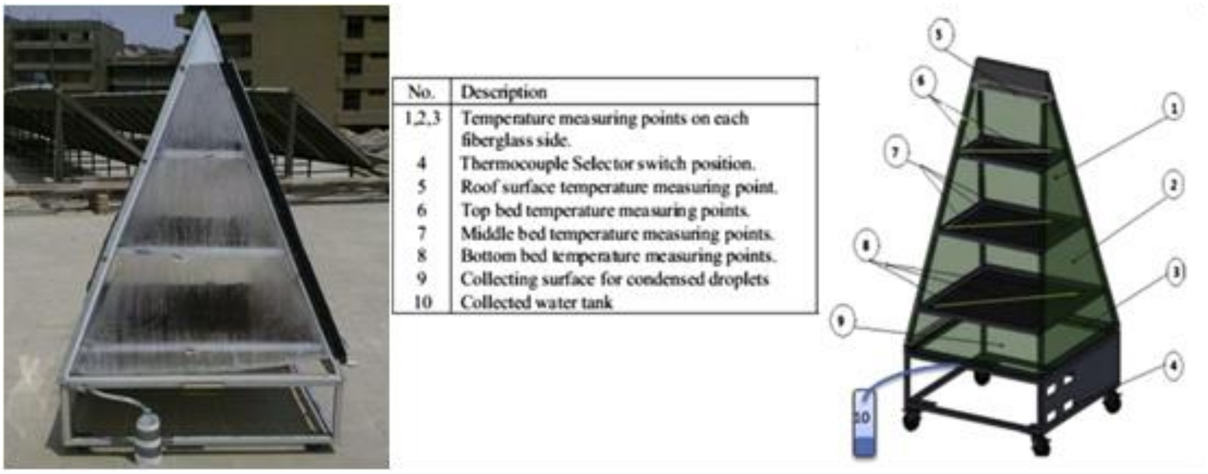
A parabolic solar concentrator is a device that uses mirrors or lenses to direct and focus sunlight onto a small area, resulting in a high level of heat and light intensity[120][121]. This concentrated energy can be utilized for various applications, such as generating electricity via photovoltaic cells or producing steam for use in thermal power plants[122][123][124]. Table (4) shows the techniques using a parabolic solar concentrator.

A use of parabolic solar concentrators is to create water from the air using the method of humidification and dehumidification. This process uses the focused sunlight to heat a fluid, that fluid is then used to humidify the air. The air is then cooled and dehumidified, and the water vapor is collected and purified[125].

1. Parabolic solar concentrators have several benefits for water production, such as:
2. They can function continuously as long as there is adequate sunlight.
3. They can be employed in regions with low humidity or in circumstances where access to fresh water is restricted.

They have the capability to be highly effective as they can focus sunlight onto a small area to generate high levels of heat and light intensity.

Wang, J., et al. [126], developed two solar-powered devices for extracting fresh water from the atmosphere using the sorption cycle. The first, an open-type concept machine, was designed to produce 320 g of water with a 0.77 m^2 solar collector area. This system utilized 2250 g of ACF-CaCl2 composite sorbent and featured a roll-up sorbent bed structure. The second device, an improved semi-open-type model, is illustrated in Fig. 18.



No.	Description
1,2,3	Temperature measuring points on each fiberglass side.
4	Thermocouple Selector switch position.
5	Roof surface temperature measuring point.
6	Top bed temperature measuring points.
7	Middle bed temperature measuring points.
8	Bottom bed temperature measuring points.
9	Collecting surface for condensed droplets
10	Collected water tank

Figure 17. (a) Photograph trapezoidal prism solar collector. (b) Schematic diagram of the test rig[118].

Table 3. Types of sorbent material for water generation using Pyramid Solar Still.

Researcher	Year	Technique/ device	Focus on	Sorbent materials	Result
[117] Kabeel	2007	Glass pyramid-shaped	Two pyramids were used with different types of beds on the shelves	Cacl2	Produce 2.5 L/m^2 using this approach
[118] William et al.	2015	Trapezoidal prism solar collector with four fiberglass sides and a multi-shelf bed (desiccant carrier)	Designed and constructed to maximize the bed surface area inside the collector and increase the absorption and evaporation surfaces	Cacl2	Total evaporated water for the cloth and sand beds could reach 2.32 and 1.23 L/ m^2 day
[119] Mohamed et al.	2017	A trapezoidal prism solar collector	Evaluate the effect of different operating conditions (initial desiccant concentration, initial mass of solution, and host materials)	Cacl2	The total produced water in spring was approximately 3.02 L/ m^2 day.

The researcher created a new system that can harvest water from the air in very dry places using solar energy. The system uses a tube-shaped device that collects solar energy with a curved mirror, as shown in Fig. 19. The device uses a strong material, such as calcium chloride, that can make water evaporate even in very dry conditions. The device made 0.51 L of water for each kilogram of calcium chloride, with a thermal efficiency of 24.61% and a water production cost of $0.15. The researcher found that the system made more water and used less energy than the tube-shaped device without the mirror, and also reduced the water production cost by 25% [127].

Essa, F., et al. [128], have developed an innovative method for harvesting drinking water from the air using sunlight. The system employs a highly hygroscopic silica gel desiccant within a double-slope half-cylindrical basin solar still (DS-HCBSS) to extract water from the atmosphere.

To enhance performance, the DS-HCBSS was modified with four longitudinal fins inside, increasing its surface area. Both the basin liner and fins were covered with a layer of silica gel, as depicted in Fig. 20. With the silica gel desiccant, the productivity of the DS-HCBSS saw a 72% improvement with longitudinal fins and a 166% improvement with longitudinal fins combined with gravels. The highest accumulated productivity, reaching 400 mL/m^2, was achieved with the DS-HCBSS utilizing silica gel, longitudinal fins, and gravels.

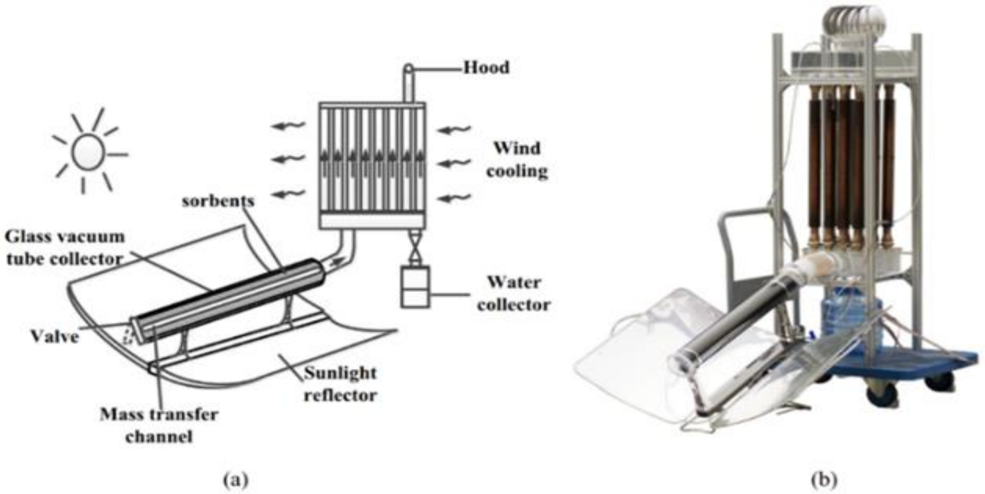


Figure 18. (a) Working diagram of the solar power system of AWH. (b) Photograph of the device[126].

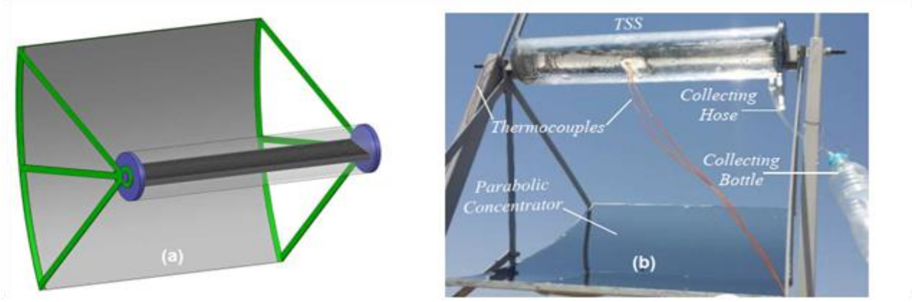


Figure 19. A tube-shaped device testing rig. (a) Three-dimensional computer-aided design (3D-CAD) representation and (b) Photograph of the system[127].

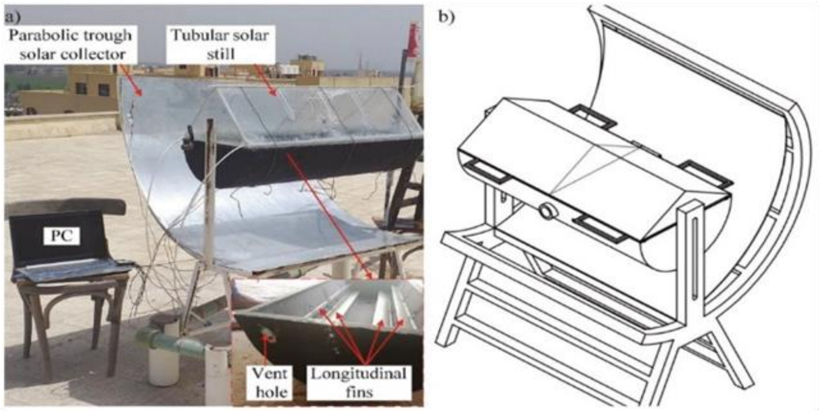


Figure 20. Hygroscopic silica gel desiccant within a double-slope half-cylindrical basin solar still (a) A photograph of the system. (b) A schematic diagram[128].

The researcher used three materials (LiCl/sand, CaCl2/sand, and LiBr/sand) that had 37% salt and sand to make water from the air. The material absorbed water from the air at night and released water during the day using a curved mirror that collected solar energy. The mirror was 1.54 m2 in size. The researcher found that the three materials made different amounts of water: LiCl/sand made 90 mL/day, CaCl2/sand made 115 mL/day, and LiBr/sand made 73 mL/day [129].

Audah et al. [130] aimed to optimize the liquid desiccant system using solar energy for supply cooling and fresh water generation of buildings. Fig. 22 shows a diagram of a liquid desiccant (CaCl2) system (LDS) that uses parabolic solar concentrators as a solar heat source for the system and the condensing water will be taken from the air leaving the regenerator. Where the moist air is directed towards the desiccant liquid in more than one stage, where the water molecules present in the air are absorbed through the exchanger between the air and the desiccant liquid. the result shows the maximum water production using this system is 2797 mL/hour where an air flow rate of 1.205 kg/s inAugust.

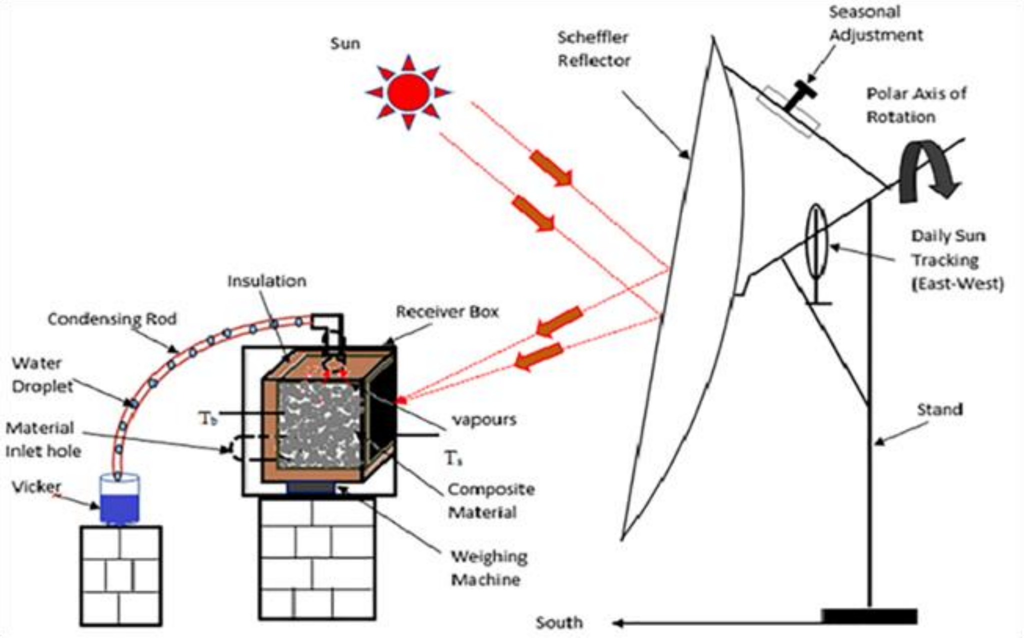


Figure 21. Schematic ofabsorbed water system working principle[129].

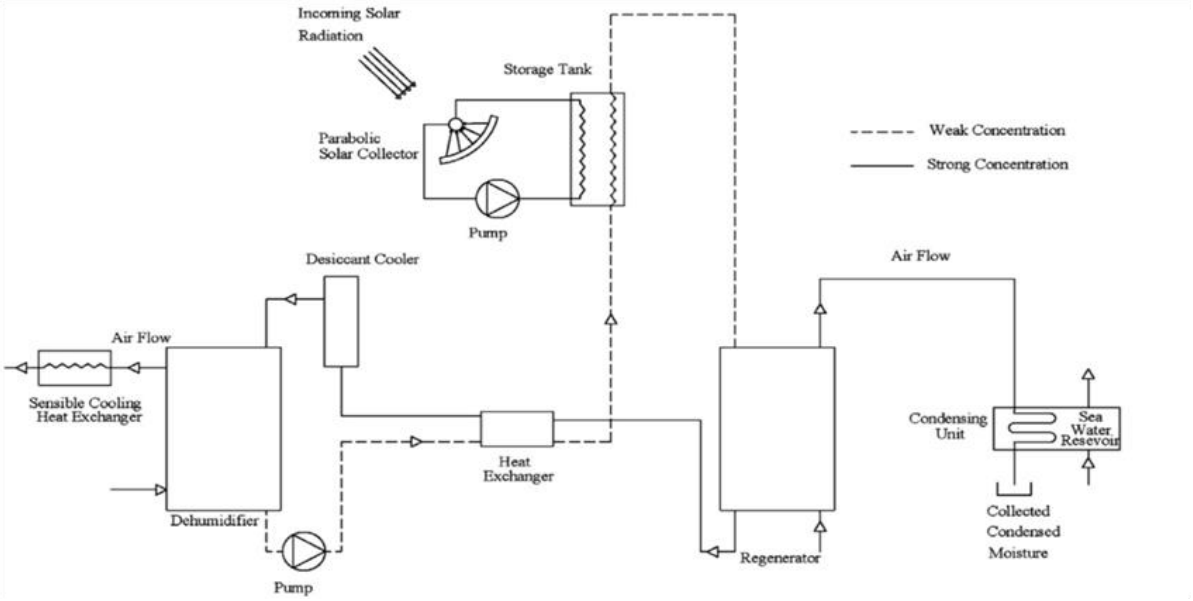


Figure 22. Depicts the solar-powered liquid desiccant system (LDS)[130].

Table 4. techniques utilizing parabolic solar concentrators with various types of sorbent materials.

Researcher	Year	Technique/ device	Focus on	Sorbent materials	Result
[126] Wang, j., et al.	2017	Parabolic solar concentrator	Two solar-driven appliances are to extract fresh water from the atmosphere based on one open type concept machine, and one improved semi-open type device	ACF-LICL sorbents	Generated 9000 g of water using a 4 m^2 solar collector and 40800 g of consolidated ACF-LICL sorbents
[127] Elashmawy, m. And f. Alshammari	2020	Parabolic solar concentrator	Uses a tubular solar still (TSS) activated by a parabolic solar concentrator	Cacl2	Produce 0.51 l /kg of calcium chloride
[128] Essa, f., et al.	2020	Parabolic solar concentrator	Conducted to evaluate the performance of the solar still with this modification	Silica gel desiccant	Accumulated productivity of 400 ml/m^2 was achieved with the DS-HCBSS using silica gel
[129] Srivastava, s. And a. Yadav	2018	Parabolic solar concentrator	Using a parabolic solar concentrator with composite material to generate water from atmospheric air and calculating coast of water production each day	Composite material (LiCl/sand, cacl2/sand, and libr/sand)	Three composite materials were 90 mL/day, 115 mL/day, and 73 ml/day
[130] Audah et al.	2011	Parabolic solar concentrator	Optimization of the liquid desiccant system using solar energy for supply cooling and fresh water generation	Liquid desiccant (cacl2) system (LDS)	Maximum water production using this system is 2797 ml/hour

2.2.4. Different Devices Design

Various methods and designs were employed to enhance salt absorption and achieve maximum productivity, as detailed in Table 5.

Talaat, M., et al. [131], devised and evaluated a portable device designed to collect water from the atmosphere using solar energy and a Calcium Chloride solution as a desiccant. The device, depicted in Fig. 23, consists of a double-faced conical-finned absorber and a double-faced conical transparent surface, mounted on a telescopic stick and base. This design elevates the absorber's temperature, leading to the evaporation of absorbed vapor from the solution and its subsequent condensation on the surface. Tested at various times throughout the year, the device demonstrated an accumulated productivity ranging from 0.3295 to 0.6310 kg/m^2 day.

Ibrahim, N.I., et al. [132], conducted a study to investigate water extraction from a solar cooling system utilizing a lithium bromide absorption chiller and a fan coil unit, with varying ratios of fresh air. Optimal conditions for peak performance were identified, revealing that the highest collector efficiency was achieved at a flow rate of 0.3 kg/s, a collector surface area of 28 m^2, a temperature of 45 degrees Celsius, and a fresh air volume ratio of 50%. Under these conditions, the generator's useful energy reached 14.8 kW, and the water production rate was 8 L/h.

Mulchandani, A. et al. [133], analyzed to assess the potential of capturing water from the atmosphere using solar-based materials and devices. Utilizing Monte Carlo simulations and geospatial mapping, the study evaluated water capture capacity across the United States. Results indicated the possibility of capturing 4-8 L of water per square meter of system footprint per day during spring and summer. This analysis highlights the significance of location and season in determining atmospheric water capture potential, emphasizing the importance of selecting appropriate materials and optimizing system design for maximizing water harvesting.

Hanaa M. Farghally et al. [134] proposed and evaluated a method for extracting potable water from the atmosphere in remote areas using solar energy and a standalone photovoltaic system. The system utilizes solar thermal energy to heat the air and solar photovoltaic energy to power a fan in the water production system. A MATLAB/SIMULINK mathematical and simulation model was developed, with results indicating higher water extraction in areas with high humidity and solar radiation.

Fathy et al. [135] conducted experiments to test a solar-powered device designed for water production from the air. The device employs a solar vapor absorption process, featuring an absorber made of black cotton cloth impregnated with a calcium chloride solution. The compact and portable device, illustrated in Fig. 24, has a transparent PVC cover that can be folded for convenient transportation and storage. The experiments aimed to estimate the mass transfer coefficient and cloth thickness for the absorber and ensure homogeneity in the solution inside the absorber.

A research by Dorzhiev et al. [136] aimed to provide a sustainable solution to the problem of limited water supply in arid regions by extracting humidity from the air using Silica Gel desiccant materials. The desiccants are heated using solar energy to vaporize the adsorbed water and then cooled below the dew point to condense into fresh water as shown in Fig. 25. The new design was able to heat the Silica Gel to around 85°C and produce 70 to 100 mL of water from 1000 g of Silica Gel.

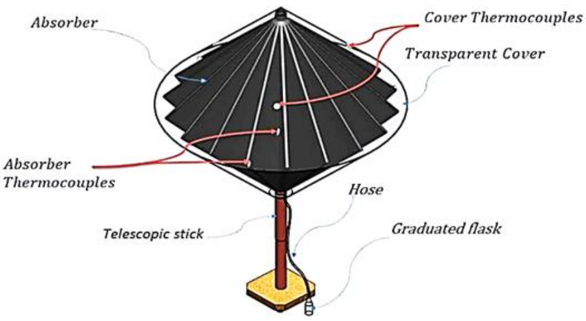


Figure 23. Schematic diagram of the double-faced conical-finned absorber system[131].

The researcher used adsorption and a little solar energy to get water from the air. The researcher used 20.5 kg of silica gel beads that were 3 mm in size. The beads absorbed water from the air for 10 hours until they were full. Then, the researcher used hot water from a heat exchanger to make the beads release water. The water was collected by a condenser with a fan. The researcher made 2318 g of water and used 4583 Wh of heat. [137] The researcher also used a tubular solar still to make water from the air. The tubular solar still was a clear cylinder with a black basin under it. The cylinder acted as a condenser for water vapor from the inside. The cylinder was curved to get more sunlight and heat the black basin. The researcher used a material called CaCl2 anhydrous to absorb water from the air inside the tubular solar still. The researcher studied how air speed affected water production from low humid regions. Fig. 26 shows the tubular solar still.

The result shows the maximum water generation at 4 m/s air speed was 467 ml/m2 day with a thermal efficiency of 25 %

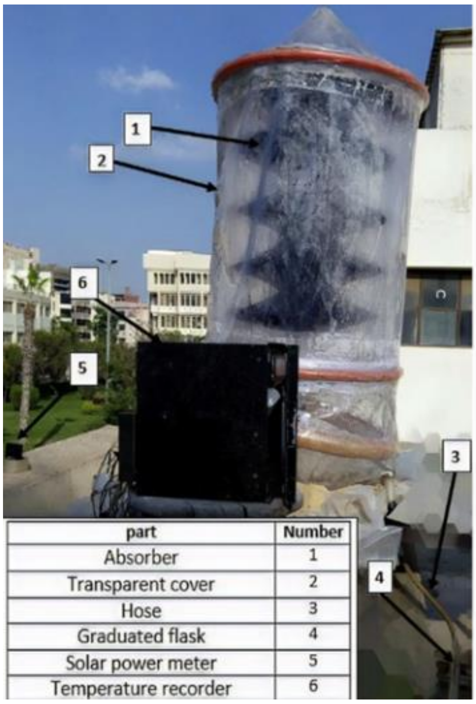


Figure 24. Photograph of the solar vapor absorption device[135].

Figure 25. Experimental device of extraction water in the arid region using Silica Gel[136].

Figure 26. 3D-CAD of the test rig of tubular solar still absorption modules[137].

Table 5. Types of sorbent material for different device designs.

Researcher	Year	Technique/ device	Focus on	Sorbent materials	Result
[131] Talaat, M., et al.	2018	The device consists of a double-faced conical-finned absorber and a double-faced conical transparent	Fabricate and design a double-faced conical-finned absorber device for water generation.	Cacl2	Productivity ranging from 3295 to 6310 g/m^2/day.
[132] Ibrahim, N.I., et al.	2016	Evacuated tube solar collector	The effects of flow rate of the fluid in the collector, solar insolation, fresh air volume ratio.	LIBR	Maximum values (0.73 and 6.6 l/h) at noon
[133] Mulchandani, A., P Westerhoff	2020	Solid desiccant-based device	The potential for capturing water from the atmosphere using solar-based material and devices was analyzed using Monte Carlo simulations and geospatial mapping.	Sio$_2$ and metal-organic frameworks (MOFS)	Capture 4-8 l of water per square meter of system footprint per day across the United States
[134] Farghally et al.	2020	Sorption bed and condenser	The system uses solar thermal energy to heat the air and solar photovoltaic energy to power a water production system fan.	System that contains cacl2	Maximum amount of water extracted From air is 0.8 l/h
[135] Fathy et al.	2020	Black cotton cloth impregnated with a solution of calcium chloride	Test a device that can produce water through the process of solar vapor absorption	Cacl2	The amount of water produced ranged from 272 to 750 g per day
[136] Dayakar et al.	2019	Rectangular black box	Providing a sustainable solution to this problem by extracting water present In the air in the form of humidity	Silica gel, SiO_2.	Produce 70 to 100 ml of water from 1000 g of silica gel
[137] Elashmawy, M.	2020	Using tubular solar still	Effect of the air speed on the performance of desiccant (cacl2 anhydrous) moistureabsorption inside tubular solar still	Cacl2 anhydrous	Maximum water generation at 4 m/s air speed was 467 ml/m^2 day

Kumar et al. [138][139][140][141][142][143] conducted a research on generating water from atmospheric air using a Solar Glass Desiccant Box Type System (SGDBS) as outlined in Table(6). The device is made up of several components:

1. FRP container: which created from fiber reinforced plastic for a water collection tray with a slight slope had been used, that condensates on the glass
2. glazing: for water condensation at the top of the device
3. wire mesh tray: for holding the solid desiccant material.
4. water measuring cylinder: which indicates the quantity of the water collected
5. composite desiccant material: using different desiccant materials according to their case.
6. connecting pipe.

A water collection tray is provided for the condensed water, as seen in Fig. 27. The experiments were conducted in India at 29°58' North latitude and 76°53' East longitude. The device operates by extracting moisture from the air using a saline substance and then using solar energy to evaporate the water and the absorbent material, with the output being condensed on the glass at the top of the device.

1. Using solar energy with CaCl2/saw wood for water production from atmospheric air was investigated experimentally by Kumar, M. and Yadav A. [138]. The experimental part was the consciences of the desiccant box.

   It’s found that using CaCl2/saw having 60% CaCl2 in the saw wood could produce water of about 180 mL/kg per day which is equal to 500 ml/m^2 day from 2.8 kg of the composite desiccant material.

2. In a research, Kumar, M. and Yadav A. [139], a device called (SGDBS) was utilized for the production of water. The device employed the use of three different desiccant materials, namely Silica gel, activated alumina, and Molecular sieve, which are insoluble and non-toxic. The results showed that the water production rates for Silica gel, activated alumina, and Molecular sieve were 160, 20, and 35 mL/kg day respectively
3. 3. Solar Glass Desiccant Box Type System (SGDBS) was used by Kumar, M. and Yadav A. [140].

A new composite desiccant material made of CaCl2/Vermiculite/Saw wood was used to generate water from the air. The brine of CaCl2 was combined with a host matrix material such as saw wood and vermiculite. The saw wood and vermiculite consist of flat layers that provide ample space for storing large amounts of salt material, like CaCl2. The amount of water produced by this novel composite desiccant material was 195 mL/kg day.

4. Kumar, M. and Yadav A. [141] in an experiment, five new samples were created using an aqueous solution of CaCl2 with concentrations of 16%, 23%, 28%, 33%, and 37% respectively, mixed with floral foam. It was found that the highest water production occurred at a CaCl2 concentration of 37% with a rate of 0.35 mL/cm3 day
5. M. Kumar and A. Yadav[142] the effectiveness of Silica gel was observed to be superior compared to other materials in extracting water from air under similar conditions. Kumar et al. [142] implemented an integrated air-drying system by extracting water from the air using silica and changing the properties of the solar air drying device (CGDBS). Where the researcher changed from…
    1. The angle of incidence of the sun.
    2. Use glass of different thicknesses.
    3. Using monochromatic glass as opposed to using double glazing.
    4. The effect of the air gap between the glass and the water vapor absorbent material.

Where experimental results showed that it is possible to obtain maximum water from atmospheric air when using Silica gel which is equal to 200 mL/kg day.

6. In a study, Kumar, P.M [143] examined the effectiveness of using a solar recovery system with orange silica gel as a desiccant to extract potable water from the atmosphere. The silica gel adsorbed water molecules from the air at night and during the day, the solar recovery system extracts the water from the saturated silica gel. The results showed that the system can produce 0.98 L day efficiently and cost-effectively.

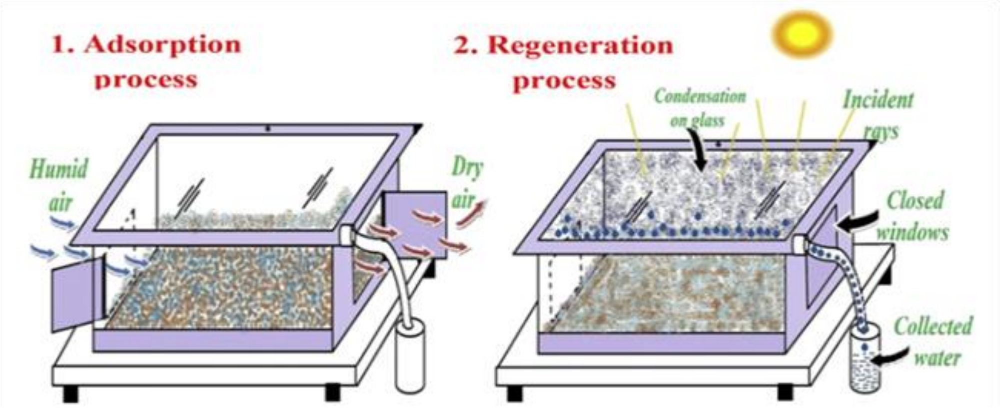


Figure 27. Schematic diagram for solar glass desiccant-based system (SGDBS) [138].

Table 6. experimental work by Kumar et al. for AWG using (SGDBS).

Research	**Device**	**Idea**	**Desiccant Materials**	**Result “water production”**
[138] Kumar, M. and Yadav A.	Solar Glass Desiccant Box Type System (SGDBS).	Different CaCl$_2$ concentrations in saw wood (10, 20, 30, 40, 50, and 60)%	CaCl$_2$/saw wood	180 mL/kg day
[139] Kumar, M. and Yadav A.	Solar Glass Desiccant Box Type System (SGDBS).	Different material types.	Silica gel, activated alumina, and molecular sieve	160, 20, and 35 ml/kg day, for Silica gel, activated alumina, and molecular sieve, respectively.
[140] Kumar, M. and Yadav A.	Solar Glass Desiccant Box Type System (SGDBS).	Concentrations of CaCl$_2$ in Vermiculite/Saw wood (16, 23, 28, 33 and 37) %.	CaCl$_2$/Vermiculite/Saw wood material	195 ml/kg day.
[141] Kumar, M. and Yadav A.	Solar Glass Desiccant Box Type System (SGDBS).	Concentrations of CaCl2 in CaCl2/floral foam (16, 23, 28, 33 and 37) %.	CaCl2/floral foam	Maximum at 37 % concentration of cacl2. 0.35 ml/cm^3 day.
[138][142] M. Kumar and A. Yadav	Solar Glass Desiccant Box Type System (SGDBS).	Changing parameters of (SGDBS) device using silica gel	Silica gel	200 ml/kg day.
[143] KumarP.M., et al.	Solar Glass Desiccant Box Type System (SGDBS).	Behavior of orange silica gel for water adsorption	orange silica gel	98 ml/kg day

VCSS systems have some drawbacks, such as lower energy efficiency compared to other AWG technologies, high energy consumption, and high cost for installation and maintenance [144]. Additionally, the use of sorbent material in VCSS systems may have negative environmental effects, as some of these materials come from non-renewable resources or may be harmful to the environment.

2.2.5. Solar Chimney

Other methods used for water production use cooling surfaces for the condensation process such as Solar chimneys[145]. A solar chimney is a passive solar heating and ventilation system that uses the natural convection of air to draw in outside air and ventilate a building. It consists of a vertical shaft or chimney that is placed on the roof of a building and surrounded by a large, transparent solar collector. The solar collector absorbs sunlight and heats the air inside the chimney, causing it to rise and create a natural draft. Solar chimneys can be used to extract water from the air in a process called dehumidification. In this process, air is drawn into the base of the solar chimney and heated by the sun's energy absorbed by the solar collector. As the air is heated, it rises up the chimney and passes through a dehumidifier, which removes moisture from the air. The moisture is collected as liquid water, while the dry air is vented out the top of the chimney. Solar chimney dehumidification systems can be an effective way to produce fresh water in arid or humid regions where traditional water sources are scarce. They can be powered by renewable energy sources such as solar or wind energy, making them a sustainable and environmentally friendly option. However, solar chimney dehumidification systems may be expensive to implement and may not be suitable for all locations and climates [146][147].

Kashiwa et al. [148] worked on water production from atmospheric air by using Solar Cyclone. Fig. 28 shows the Solar Cyclone device Fig. 28 which contains greenhouse with a central chimney that channels an atmospheric updraft and a converging-diverging nozzle 500 m high with a separator placed in the nozzle at the flow path between the greenhouse and chimney and swirl vanes to drive the air into the conversion – diversion nozzle. Sunlight is used for energizing and "heating" the air by furnishing a portion of the separation in the greenhouse and channeling the heated air in a chimney updraft. The flow in the nozzle decreases the temperature which condensates the wet air for producing water at the separator due to the centrifugal action. The result shows the water production is directly proportional to the length of the solar chimney.

Ming et al. [149] worked on water generation from atmospheric air using a solar chimney power plant. A station has been proposed that operates on the base of the solar chimney with twisted black tubes filled with hot water, which works to warm the air entering the chimney and maintains the relative humidity of the air, corresponding to the ambient humidity, as shown in Fig. 29.

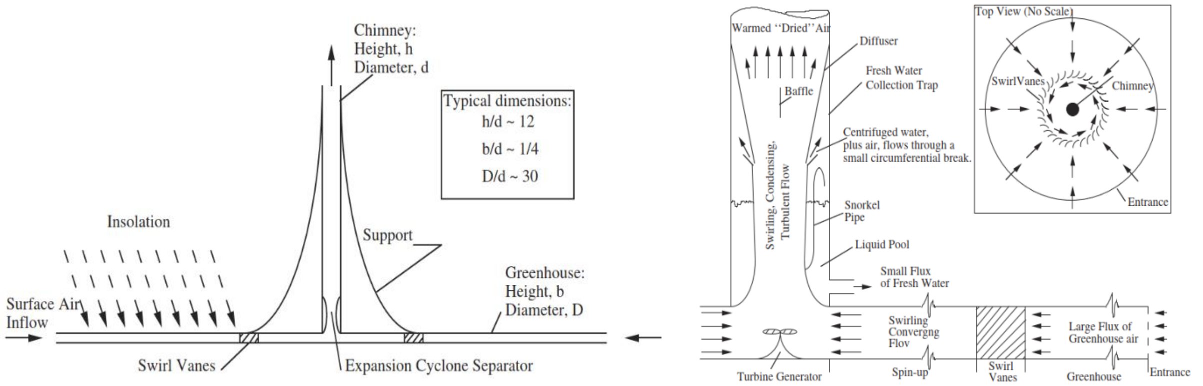


Figure 28. Water production process by Solar Cyclone device[148].

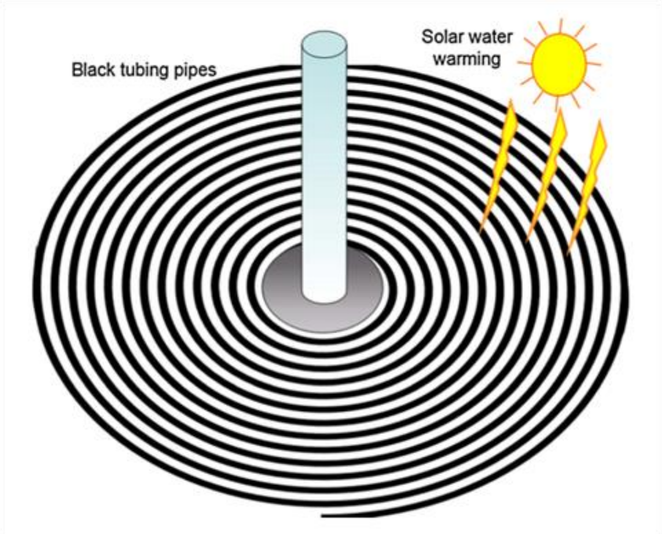


Figure 29. SCPP variant system with a coil of black tube working as the solar collector[149].

Relatively moist air enters the chimney with a shower of warm water in the lower part of the tower, and because of this procedure, a difference in the density of the incoming and outgoing air leads to the air flowing to the top of the tower by convection, and thus the heat will be thrown out in a sequence so that the water settles on the wall and collecting. The result shows water production per year 2.74 *109 m^3 at Chongqing where domestic water is billion cubic meters 1.81.

3. Solar Energy for Electrical Power

Using solar energy to generate electricity to power a device that extracts water from the air is a viable option[150][151][152]. This technology is known as a solar-powered atmospheric water generator (AWG) and it works by using solar panels to generate electricity which is then used to power a system that cools the air and condenses the water vapor into liquid form. This process can be used to generate clean, safe drinking water in areas where water is scarce.

3.1. Refrigeration system

Refrigeration systems are an essential component of atmospheric water generation systems, as they provide the cooling needed to condense the water vapor from the air[153][154]. These systems can be powered by a variety of energy sources, including electricity, natural gas, and renewable energy sources such as solar or wind energy[153].

Overall, atmospheric water generation systems can be an effective way to produce fresh water in areas where water is scarce or not easily accessible. However, they may be expensive to implement and maintain, and may not be suitable for all locations and climate [155][156].

Center et al. [157] presented experimental study of atmospheric water generation and rain water purification by using solar power energy. The [157] aimed at establishing a cheap atmospheric water generation system as shown in Fig. (30).The system consists of car air-condition used as dehumidifier device for water production by replacing devices such as the car compressors replaced by 1.5 horsepower compressor. The water production was 18.3 L/20 hr. at average relative humidity of 69.2%. Within power consumptions of 2 kWh/L of water production.

Aye et al. [158] worked on modeling and simulation of atmospheric water generation by using a solar chilled system. It aimed for extracting water by cooling condensation which uses electricity to drive the compressor. The solar power PV system was applied to supply the system with enough electricity. Fig. 31 shows the block diagram of the system, where water generation is dependent on environmental properties “temperature and relative humidity” and the amount of electricity supplied by PV panel for the operation compressor and compressor efficiency to generate enough cooling for water condensate in the evaporator. The result showed that the maximum water production from the air was 36.6 L/ day in august.

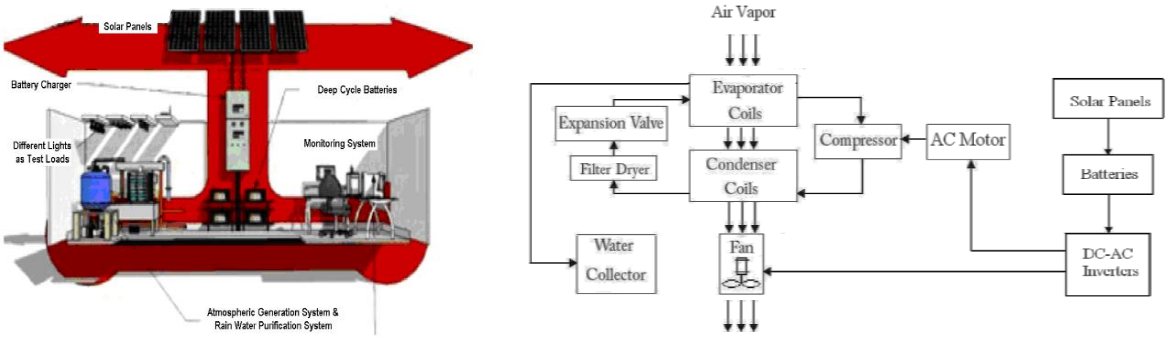
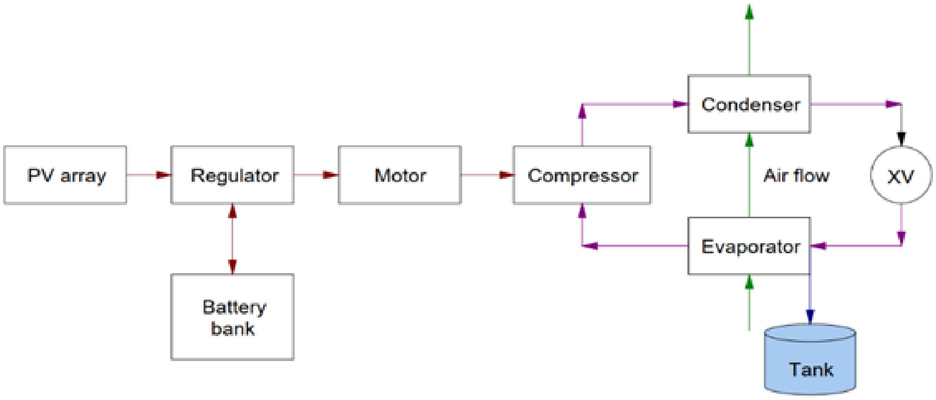


Figure 30. Refrigeration systems for AWG a) test rig of water production, b) block diagram of dehumidifier device[157].



XV = Expansion valve for pressure reduction

Figure 31. Schematic diagram of a PV driven AWG[158].

Yıldırım et al. [159] studied the design parameter effect on water production using humidification dehumidification (HDH) desalination powered by solar energy.

A theoretical study was conducted on the effect of design parameters and environmental effect as shown in Fig. 32 on the amount of water produced using the theory of dehumidification in the atmosphere of Antalya, Turkey. It is noticed that clean water directly affects the heating of the fresh water and that heating the air does not have a significant effect on the productivity of potable water, and whenever there is a greater flow of air, there exists a positive effect on the water productivity, but there is a limit to the amount of distraction flowing, otherwise in the case of high flow The air will reduce the water yield.

Elattar et al. [160] studied new hybrid air conditioning fresh water generation using humidification–dehumidification process powered by solar energy. [118] worked theoretically by A mathematical model grounded on thermodynamic analysis and using EES software and C++ to clarify the parameter design effect of the proposed system on cooling and freshwater productivity. Fig. 33 shows the schematic diagram of the proposed system where the device.

The result shows that increasing the ambient temperature, relative humidity, and different temperatures between the system and surroundings will increase water productivity, cooling capacity, and power conception of the system. the COP of the system increases with increased ambient relative humidity, decreasing ambient temperature, air flow rate, and temperature difference across the heating system. Also, the proposed system had high COP and water production compared with the basic system.

Alahmer et al. [161] used solar energy as a power source for the generation of fresh water from the air. They Experimentally found that the water production was dependent on intensifying the water vapor from the air. The device consists of the following stages:

1. Electrostatic filter to remove particulate matter in the air.
2. The moist air passes into a condenser that relies on the principle of air cooling to reduce the ability of the air to hold water vapor, which causes the air to condense.
3. Germs in the water are killed by passing the resulting water with ultraviolet rays for 30 min.
4. The mixture is passed to a sediment sieve to get rid of the chemical suspensions contained in the liquid.
5. Filter the water through the filtering membrane.
6. The product is poured into the reservoirs.

The process is repeated to obtain a sufficient quantity suitable for human use. The factors affecting the water yield are temperature, relative humidity, air volume, and the capacity of the refrigeration machine. The refrigeration machine is powered by environmentally friendly energy by relying on solar energy to extract enough heat to form water droplets as shown in Fig. 34.

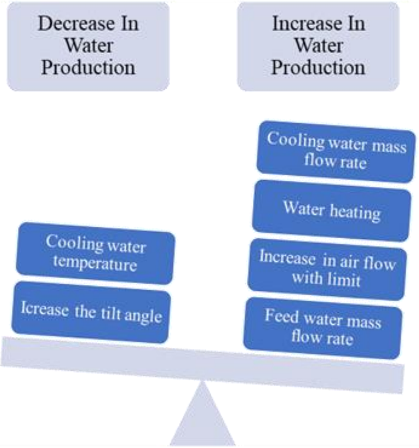


Figure 32. Parameter design condition on fresh water production.

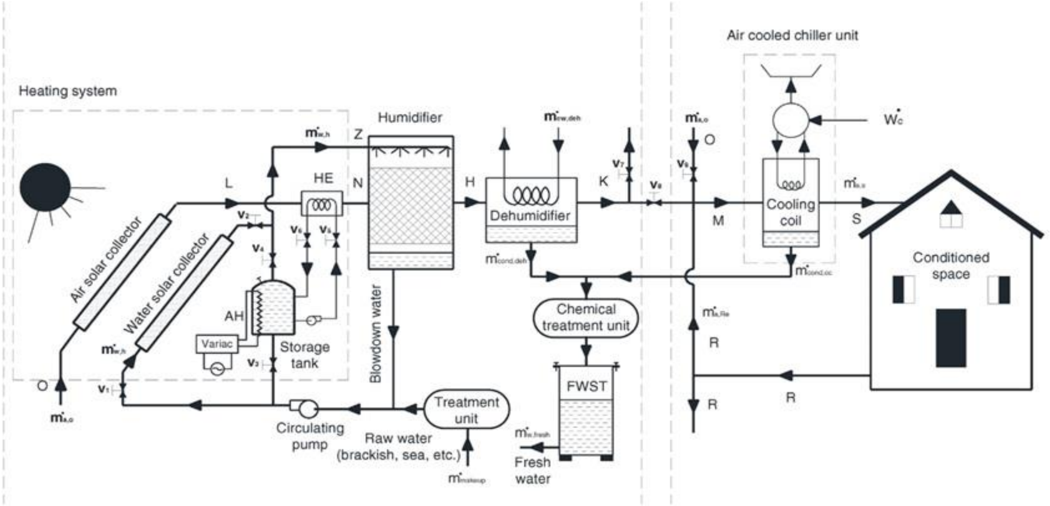


Figure 33. Proposed system schematic diagram[160].

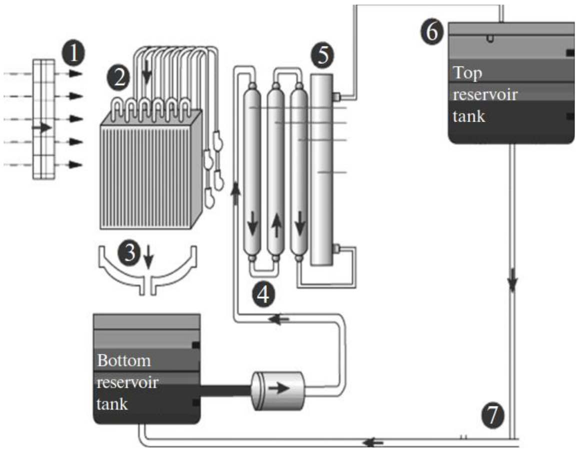


Figure 34. Schematic diagram of the air water generating system[161].

The results showed that the water generation by the device is pure, safe, economical, and acceptably tasting. It can be considered as potable water by filter and disinfected by Ultra Violet Light (UV) technique. The atmospheric water generation was 1722 L/day for a total power consumption of 200 kWh.

Yıldırım et al. [159] conducted a study on a desalination system that uses solar energy to produce fresh water from saline water sources. The system uses a process called humidification–dehumidification (HDH) to extract water from the air, which involves humidifying the air with saline water and then dehumidifying it to produce fresh water. They found that the performance of the HDH unit was significantly influenced by these parameters and that the unit was able to produce fresh water at high efficiency under certain operating conditions. The results of this study suggest that HDH desalination using solar energy could be a promising solution for producing fresh water in arid regions.

[162] This article discusses a study of an atmospheric water extractor, a device used to produce water from the air. The results of field tests on the device were analyzed, and the relationship between various climate parameters and the volume of water extracted was examined. It was found that the difference between calculated and experimental values was within an acceptable range and that the volume of extracted water was most directly dependent on ambient air temperature.

3.2. Thermoelectrical

Thermoelectrical are small in size, noiseless, operate on DC electrical power lightweight, and simple devices working on Seeback and Peltier effect of generation cooling and heating sides for water production from the air by cooling humid air under dew point temperature [163][164][165][166].

To demonstrate the impact of the possibility or capacity of Thermoelectric and the extent to which the value of the productivity and efficiency of the system is utilized to extract water from the air by the action or feeding of solar energy, many researchers have studied the process, theory and numerical effect of the thermoelectrical device according to technologies, cost of water production, and recent development as shown in table (7). Researchers have identified several factors that affect water production in thermoelectric systems, including:

1. Environmental Conditions: The surrounding environmental factors, such as temperature and humidity levels.
2. Device Type: The specific thermoelectric device used and its material properties.
3. Electrical Current: The electrical current supplied to the system, influences water production efficiency.
4. System Design: The design of the dehumidification system, including the number of components, choice of materials, and airflow dynamics.

These factors are illustrated in Fig. 35.

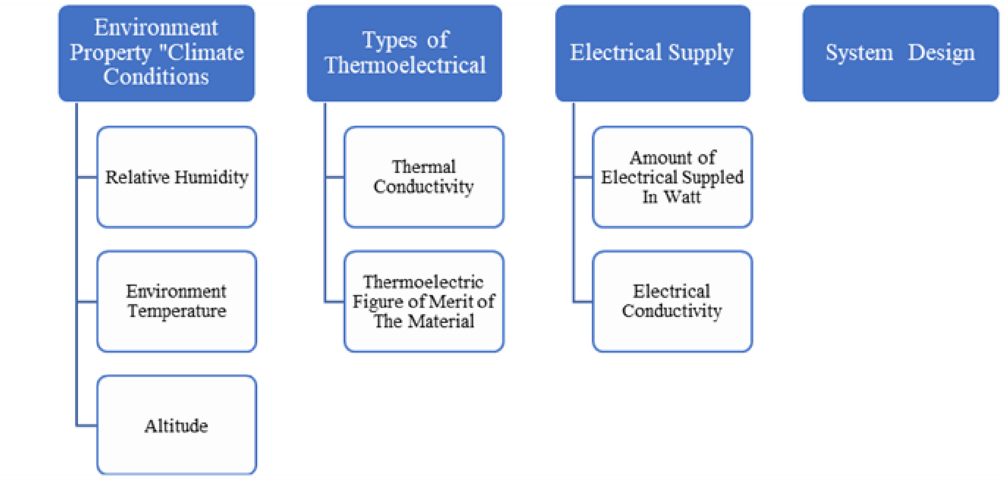


Figure 35. Parameters affecting water production from air.

Vián et al. [167] studied numerical modeling of thermoelectrical dehumidifier, designed and built based on thermoelectric cooling technology, where the thermoelectric effect of heat transfer and phase change of the material was studied through the effect of cooling in the condensation process on solid surfaces with a temperature lower than the dew point temperature. As shown in Fig. 36, the experimental prototype device. The results show that at 12V DC power supply, fan air flow 0.081 m^3/s was 1.4 L/day.

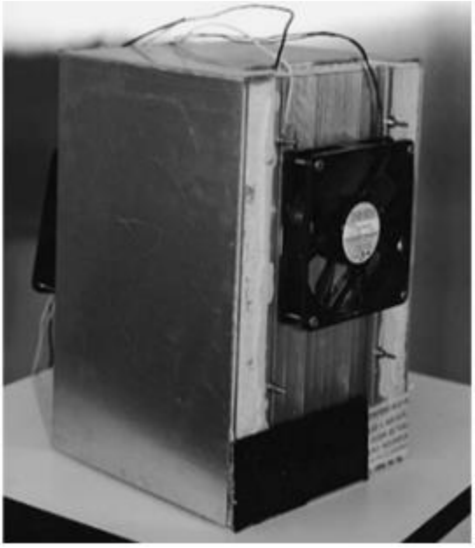


Figure 36. Prototype thermoelectric dehumidifier for water production[167].

Esfe et al. [168]This study investigated the effect of a thermoelectric cooling system (TEC) on water productivity in an air-water generator. By varying the TEC cold surface temperature from 1°C to 12°C, while keeping ambient air at 35°C and 80% relative humidity, the study measured water condensation rates. Results showed that lowering the cold surface temperature increased water vapor condensation, with the highest production rate of 0.323 kg/m^2 hr at 1°C. An 11°C decrease in cold surface temperature resulted in a 36.8% increase in water production.

Milani D. et al.[34] experimentally studied and evaluated the performance of thermoelectrical in a dehumidification system to produce water from air, the research aims tothe viability of using thermoelectric devices in dehumidification process to refrigerate ambient air and provide fresh water from air moisture and using the Psychrometric analysis is used as water production calculations. Two modes of condensation occur dropwise and film condensation heat transfer rate in dropwise condensation is more than 10 times larger than film condensation. The theoretical analysis shows that the cost of generated water is estimated to start from 82 $/1000L depending on climate conditions, where there is an environmental effect of water production from the air as shown in Fig. 37a.

Jradi et al. [169]fabricated integrated Thermoelectric-Photovoltaic system for generating water from atmospheric air, the study is aimed at designing combined system that contains thermal electrical, and solar distiller from production water by dehumidification energized by solar.[169] studied at low humidity regions in Lebanon and they used a robust model for simulation of the dehumidification process. Fig. 37 shows the 3D testing rig with a cooling channel that uses solar energy to operate thermoelectric devices for the cooling process to generate fresh water and operate solar still from the production of humid air with high moisture content. Water production from the system was at least 10 L of fresh water per day.

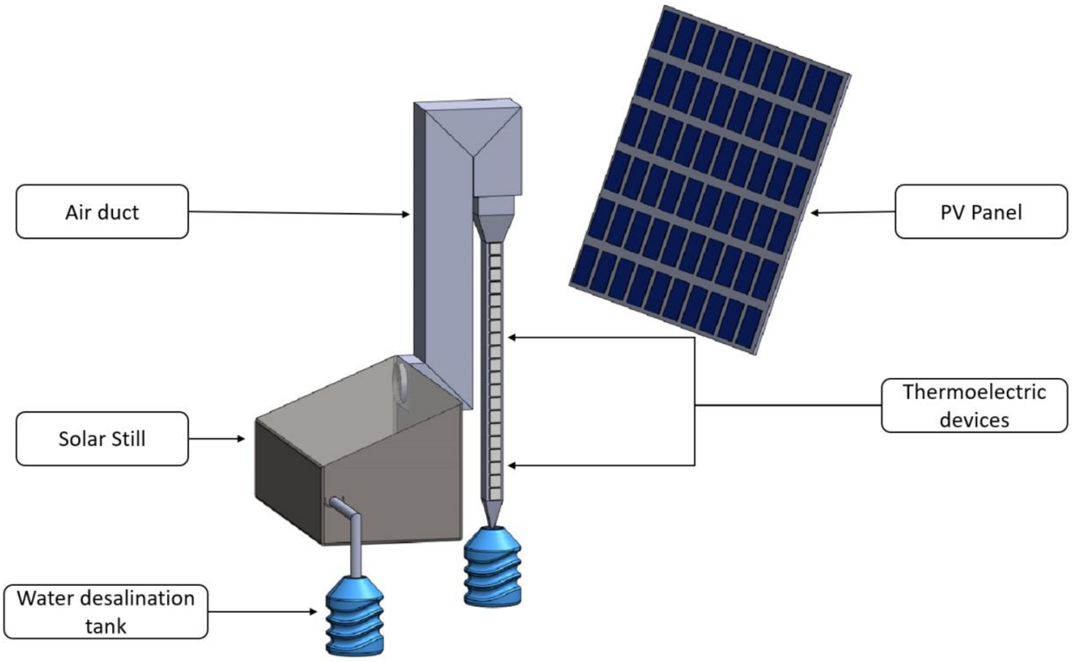


Figure 37. Schematic diagram of the testing rig for water low humid fresh water production[169].

Jradi et al. [170] working on an optimized Solar-Driven Thermoelectric Dehumidification system, by analyzing the effecting parameters on fresh water production of combined techniques solar distiller and solar-driven thermoelectric device. The study focuses on the analysis of the effect of controlling parameters on water generation, which are “ambient conditions, and the electric current input” of the overall system performance. The result showed that the fresh water production of 10 L per day and the optimal operation total energy consumption changed between 5.32 kWh/day in October and 6.73 kWh/day in June, with about 17.26% and 45.25% savings respectively compared to the conventional vapor compression atmospheric water extraction systems.

Muñoz-García et al. [171] fabricated a prototype device for water harvesting for “Yung trees using Peltier modules powered by photovoltaic solar energy”. To overcome the arid climate to preserve the growth of young plants, a device was created that captures water molecules to irrigate the aforementioned crops using solar energy as an energy source "without affecting the environment." The main purpose of the experiment work is to assess the effectiveness of using the thermoelectric device for water production and the best conditions to operate it. There is a relationship between the period of energy supply and the level of water need. In dry areas, high insulation material must be used to avoid heat gain for the surfaces designated for condensation, and the absorption of heat sinks must be increased to gain the largest temperature difference.

Suryaningsih et al. [172] created a thermoelectrical cooler prototype system working on renewable energy “solar driven power” for atmospherically water generation as shown in Fig. 38. Numerical investigation where used “CFD analyzing” to optimize the design process in the flow region. The work was focused on two main objectives: appropriateness for power driven by solar energy resources and submit the minimum quantity of water production. The result shown at a Temperature of 26 C, relative humidity of 69 %, and input power of 125.5 W the fresh water recovery from the atmosphere production was 14.6 L/day.

Kabeel et al. [173] presented a numerical study of a simple design method of water generation recovery from ambient by using thermoelectrical technology. The research was aimed at having a simple effective solution for fresh water harvesting in areas where there is no water. Fig. 39 shows the testing rig system for water generation which is dependent on solar energy as main energy.

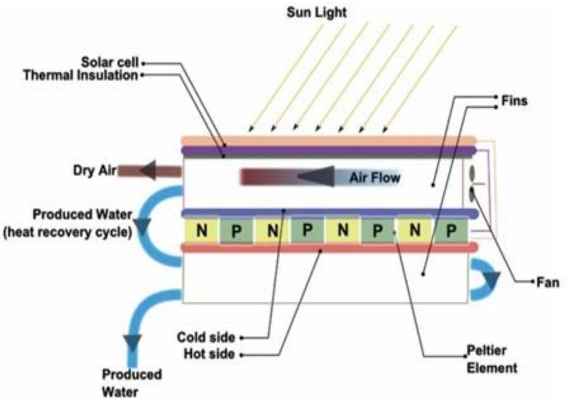


Figure 39. Thermoelectric cooler for water recovery from ambient [173].

The numerical simulation is created using commercial CFD software called Star-CCM+. The parameters studied are the pressure drops, water productivity, influence of ambient temperature, and humidity. The result of the numerical solution of two-phase flow field and condensation inside the dehumidification duct were (3.9, 2.679, and 2.698) L/h m^2 water production at solar power

Joshi et al. [174] studied the fresh water generation using of cooling surface less than dew point temperature by the main of thermoelectric device as shown in Fig. (40). [174] aimed at developing an experimental device for water harvesting from atmospheric air and working in humid regions with “humidity above 60 %”. The result shows the maximum water production is 240 mL/10 h, while the maximum COP observed is 0.437 for an air mass flow rate of 0.011 kg/s and 90% relative humidity.

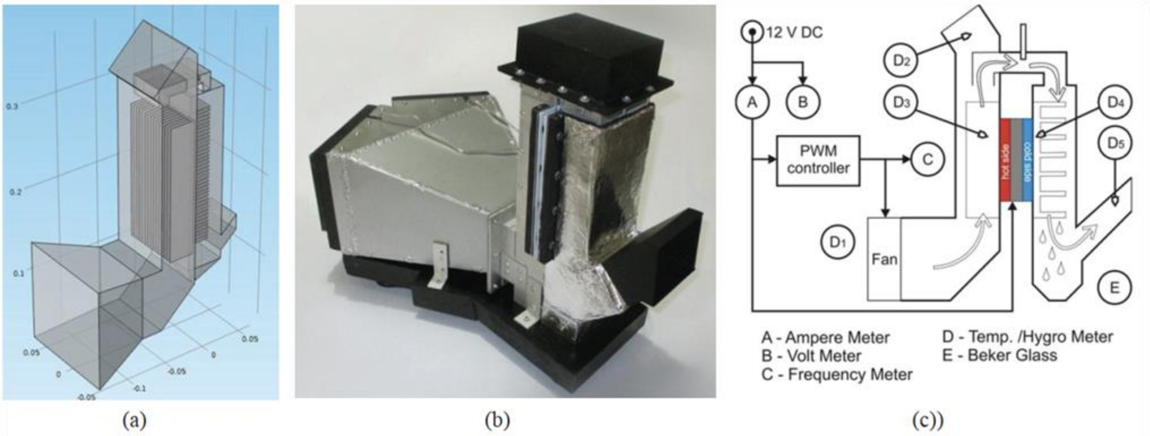


Figure 38. Prototype of thermoelectrical cooler system (a) 3D-CAD of construction experimental prototype (b) photograph of the device (c) schematic of AWG devices parts[172].

[168] This study investigated the effect of a thermoelectric cooling system (TEC) on water productivity in an air-water generator. By varying the TEC cold surface temperature from 1°C to 12°C, while keeping ambient air at 35°C and 80% relative humidity, the study measured water condensation rates. Results showed that lowering the cold surface temperature increased water vapor condensation, with the highest production rate of 0.323 kg/m² hr at 1°C. An 11°C decrease in cold surface temperature resulted in a 36.8% increase in water production.

Atta et al. [175] presented an experimental study of using solar energy and thermoelectrical cooling devices for water production at humid places “close to the sea area”. As shown in Fig. 41 the experimental device consists of a heat exchange unit and air circulation unit, where the PV panel supplies 12 V and a maximum output power of 120 W, of electrical energy for the operation thermoelectrical device. PV panel operates fan “DC 12 V” from blowing moisture air with airflow of 500 cfm. The moisture air is driven first into the hot side of the thermoelectrical device to raise the air temperature and at the same time to cool the hot side of the device. The atmospheric air then drove to the cold side to condense the water moisture. The result shows that fresh water produces 1 L of condensed water per hour during the daylight.

4. Solar Energy for Electrical Power and Heat Generation

Using sunlight as a source of electricity and heat for water production can be an effective way to provide fresh water in remote or arid areas, where water resources are scarce. However, it is important to note that the efficiency of these systems can be affected by factors such as the local climate and the availability of sunlight, and it may not be suitable in all regions or situations.

Milani et al. [176] worked on modeling of water generation of a dehumidification system using solar assisted desiccant. The [176] focused on two purposes which were using solar energy for water production from air and reducing latent heat by pretreatment feed air stream for the air-conditioning unit. Fig. 42 shows the system that worked on the dehumidification process with silica gel for dehumidifying air using PV solar energy. The atmospheric air enters the dehumidifier desiccant wheel at a specific state then the air goes to the heat cooling exchanger for water production. The water-absorbent material releases heat to the surrounding air, making it drier. The role of the wheel is to saturate the air with water vapor to facilitate its extraction by heat exchange. The result shows a small amount of silica gel can generate 5.2 L/day and the water generation per year for London, Sydney, and Abu Dhabi of (10, 13.8, and 18.5) kL respectively.

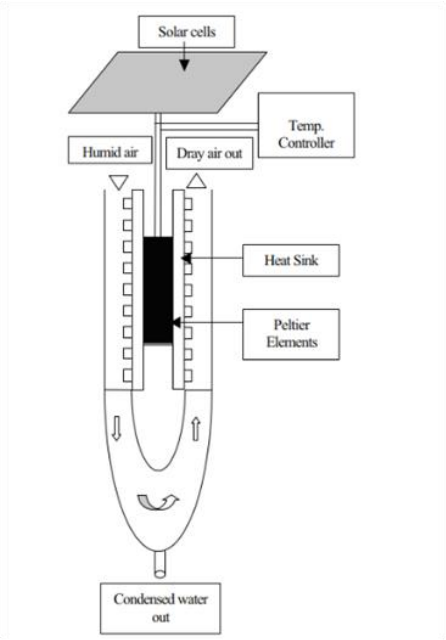


Figure 41. Schematic diagram of the testing rig [175].

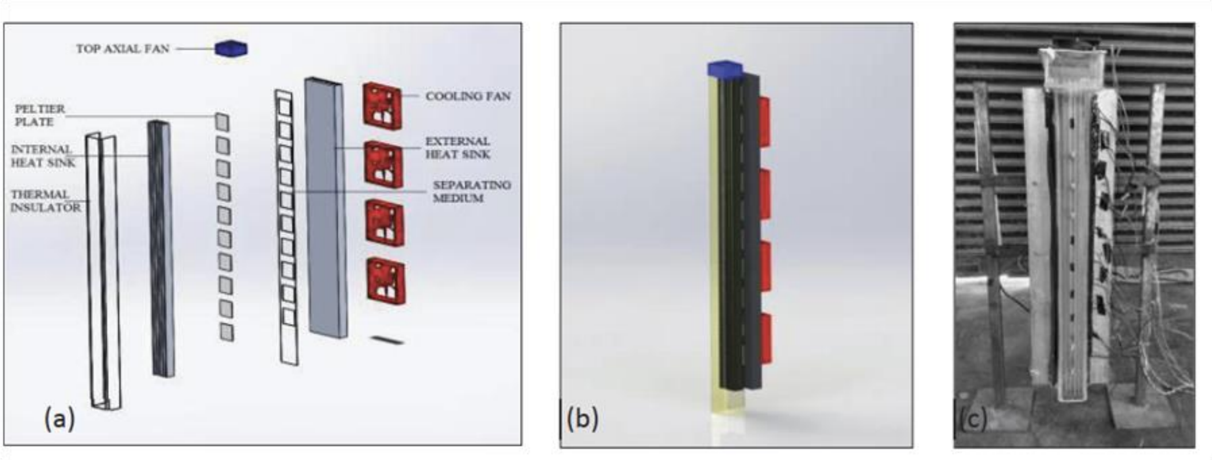


Figure 40. The Experimental testing rig (a) testing rig parts. (b) 3D-CADdevice configuration. (c) image of the testing rig[174].

Table 7. summary of researchers that using thermoelectrical devices for water production

References	Type of Study	Technique	Research focus	Capacity
[167] *Hoán et al.*	Numerical	Calculation model based on electric analogy (AERO), Thermoelectric dehumidifier consists of two stages	Varying the Peltier pellet and air flow supply voltages in the two stages, Study COP and condensed water flow rate performance	Numerical (0.969) L/day Experimental (1.4) L/day
[168] *Esfe et al.*	Numerical	12 numerical samples were evaluated in which the temperature of the thermoelectric cold The surface varies from 1 ◦c to 12◦c	This study is focused on changing thermoelectric cold surface temperature on the water productivity amount from the air which is known as condensation	Maximum water production 0.323 kg/m^2 h
[34] *Milani, D., et al.*	Theoretical	TEC devices offer several attractive features in designing sustainable dehumidification systems	Feasibility of using TEC devices in Dehumidification process to refrigerate ambient air and provide freshwater	The cost of generated water is estimated to start from 82 $/kg depending on climate conditions
[169] *Jradi et al.*	Experimental And Theoretical	Designing a low-power dehumidifying device, which can be driven using renewable energy sources, the solar PV panels, to generate water in the Lebanese humid climate	Parametric analysis of the performance of a solar-driven thermoelectric system to dehumidify air and produce fresh water	10 L/ day
[170] *Jradi, M., et al.*	Experimental and Numerical	The system is combined with a solar distiller humidifying ambient air to enhance distillate output to meet the specified fresh water needs for a residential application	Parametric analysis of the performance of a solar-driven thermoelectric system to dehumidify air and produce fresh water	10 L/ day
[171] *Muñoz-García, M.A., et al.*	Experimental	Non-conventional' method for obtaining water using young trees using Peltier modules powered by photovoltaic solar energy	The system reported herein is to obtain the water required by some dry-climate woody crops to overcome their critical growing stage	10 mL/h
[172] *Suryaningsih, S. and O. Nurhilal.*	Experimental and Theoretical	Using Peltier module TEC1-12706 in parallel, and using Computational Fluid Dynamics (CFD)	The paper presents the method to develop a prototype of an AWG based on a Thermo-electric cooler (TEC)	14.6 L/19 h
[173] *Kabeel, et al.*	A numerical study	The cases have been simulated in 3D using commercial CFD software called Star-CCM+, two-phase flow field and condensation inside the Dehumidification	find a simple and effective solution of water production in remote areas where pure water using a thermoelectric device	3.9 L/h m^2
[174] *Joshi, V., et al.*	Experimental	Cooling channel along with ten thermoelectric modules	Fresh water generator (TFWG) based on the Fundamental of Thermoelectric Cooling Effect by condensing the moisture from the ambient moist air	240 mL/10 h
[175] *Atta, R.M.J.I.J.o.W.R. and A. Environments*	Experimental	Solar PV/battery Thermoelectric dehumidifying systems are the PV cell	A solar water condensation system is built using a TE cooler, solar panels, heat exchange unit for water generation from air	1 L of condensed water per hour during the day light

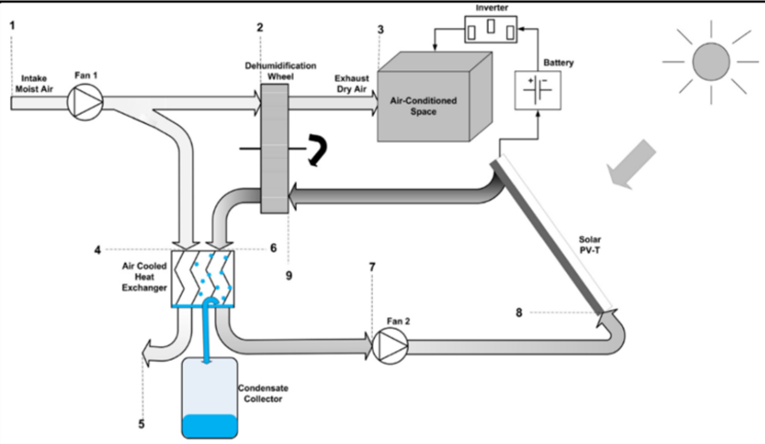


Figure 42. Schematic of Proposed Solar PVT Integrated Dehumidifier[176].

5. Conclusion

A sustainable and environmentally friendly method means the use of solar energy to produce water through electrical and heat generation. This can be used to pump seawater or brackish water, excluding heating. One of the most important advantages in harnessing solar energy for water production is its application in areas that are either far-flung, off-grid, or on-grid. Installation of these panels for this purpose is easy as the requirements are only onsite; hence, no electrical grid is required. This is particularly useful in developing countries or areas affected by natural disasters. The latter could be utilized for either space heating or process heating, and even for electricity generation with the help of a thermoelectric generator. This would enhance the overall efficiency of the system while minimizing the overall production cost.

1. Desiccant materials such as silica gel, zeolites, and polymers are effective in trapping water vapor from the air.
2. Developments in sorbent technologies offer promising methods for water production, such as the Vapor Concentration Sorbent Sorption (VCSS) process, which is effective in high-humidity regions with limited freshwater supply. For example, a system using Selective Water Sorbents (SWSs) can generate 3-5 tons of water daily for every 10 tons of dry SWS, with calcium chloride ($CaCl_2$) achieving a cycle efficiency of 91.5% at 20°C.
3. Composite solid sorbents like silica gel and MOFs, such as MOF 801, can produce 2.8 liters of water per kilogram in low-humidity conditions (20%).
4. Other promising technologies include hybrid absorbent materials that combine polymers with phase-change materials for better water absorption and release.
5. AWG systems are applicable in diverse environments, including arid regions and remote locations.
6. Nanomaterials like nanoparticles, nanofibers, and nanostructured surfaces enhance solar water evaporation and distillation through efficient light absorption and heat conversion.
7. Nanomaterials absorb a broad range of the solar spectrum, maximizing energy capture. Common material types include carbon-based materials (carbon black, nanotubes, graphene) and bimetallic nanocomposites.
8. Combining nanomaterials with technologies like hydrogels and biopolymers improves water harvesting efficiency.
9. A glass pyramid-shaped device with multiple shelves was tested for water extraction from humid air, showing a 90-95% improvement in water production compared to horizontal and corrugated beds.
10. Trapezoidal Prism Solar Collector A system using a desiccant and a trapezoidal prism solar collector achieved water evaporation rates of 2.32 L/m²/day with cloth beds, enhancing absorption and evaporation surfaces.
11. Parabolic solar concentrators focus sunlight to heat fluids for water production through humidification and dehumidification, effective in regions with low humidity.
12. Two solar-powered devices were developed for water extraction, with the semi-open-type model producing 0.51 L of water per kilogram of calcium chloride at 24.61% thermal efficiency.
13. Among tested desiccants (LiCl/sand, $CaCl_2$/sand, LiBr/sand), $CaCl_2$/sand yielded the highest water production at 115 mL/day.
14. An optimized LDS achieved a maximum water production rate of 2797 mL/hour with an air flow rate of 1.205 kg/s in August.
15. A portable device using $CaCl_2$ desiccant showed annual productivity ranging from 0.3295 to 0.6310 kg/m²/day.
16. A tubular solar still using silica gel produced 467 mL/m²/day of water at a 4 m/s air speed with 25% thermal efficiency.
17. These systems extract water from air through dehumidification, effective in arid or humid regions, though costly to implement.
18. The Solar Cyclone device, with a central chimney and converging-diverging nozzle, showed water production proportional to the system’s length.
19. A solar chimney power plant using twisted black tubes filled with hot water generated $2.74 * 10^9$ m³ of water annually in Chongqing, surpassing the city’s domestic water demand.
20. Integration of desiccants with solar collectors enhances water yield through improved moisture capture and release.
21. Compact, noiseless solutions for cooling and condensation, where efficiency is influenced by environmental conditions, device type, electrical current, and system design.
22. The thermoelectric humanizer Influenced by ambient temperature, humidity, thermoelectric device type, electrical current, and system design.
23. Solar-Assisted Desiccant Systems hold promise for water production, especially in sunny regions, though effectiveness varies based on local environmental conditions, limiting applicability in some areas.

- Another advantage of using solar energy for water production is its cost-effectiveness. The cost of solar technology has been decreasing rapidly in recent years, making it a more affordable option than traditional fossil fuel-based systems. Additionally, once the initial investment in solar panels and other equipment has been made, the cost of producing water using solar energy is relatively low, as it requires minimal ongoing maintenance.
- This paves the way for a lot of possible areas for further research. First, it could be with the use of other renewable energy resources, such as wind or geothermal energy, coupled with solar power systems, to complement solar energy and make the water generation systems more reliable. Second, the identification of strategies that further reduce costs in solar-powered water generation for instance, low-cost materials and inexpensive manufacturing processes could make the systems more readily available. Finally, the social and economic impacts of implementing the solar-powered water generation technology across different regions should be assessed with a view to understanding the broader implications and appropriately optimizing their deployment.

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