Review of sustainable methods for atmospheric water harvesting

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Abstract

The scope of this paper is to review different types of sustainable water harvesting methods from the atmospheric fogs and dew. In this paper, we report upon the water collection performance of various fog collectors around the world. We also review technical aspects of fog collector feasibility studies and the efficiency improvements. Modern fog harvesting innovations are often bioinspired technology. Fog harvesting technology is obviously limited by global fog occurrence. In contrast, dew water harvester is available everywhere but requires a cooled condensing surface. In this review, the dew water collection systems is divided into three categories: i) dew water harvesting using radiative cooling surface, ii) solar-regenerated desiccant system and iii) active condensation technology. The key target in all these approaches is the development of an atmospheric water collector that can produce water regardless of the humidity level, geographical location, low in cost and can be made using local materials.

1. INTRODUCTION

Globally, the number of people lacking access to water is 2.1 billion, while 4.5 billion people have inadequate sanitation and clean water source [1]. The latter, has led to risk of infected by diseases, such as cholera and typhoid fever and other water-borne illnesses. As a result, the world has witnessed 340 000 children under five die each year from diarrheal diseases alone [1]. Clearly, water scarcity is an issue requiring urgent action. The situation is exacerbated by climate change causing rainfall patterns to change with some areas already experiencing prolonged droughts.

Worldwide, many methods have been used to harvest water such as through water desalination, ground water harvesting and rain water collection and storage. Obviously, for these to work liquid water must already be available, but when such supplies are limited, harvesting atmospheric water becomes essential. Therefore, not surprisingly, it is now receiving considerable attention from researchers worldwide. This paper reviews this work, discussing the various water harvesting technologies and their performance, both theoretical and experimental. Commercialized atmospheric water harvesting technologies are also described. We hope this review will help new workers wishing to enter

this important field by providing introduction to state-of-the-art technologies and inspire them to develop their own ideas for innovative and sustainable atmospheric water harvesting technology. We believe that general readers, with an interest in the welfare of 'water poor' people, will also find this paper useful by showing how emerging water harvesting systems can contribute to improve living standards.

Figure 1 shows how atmospheric water harvesting technologies may be classified. The first category is harvesting water from fog, i.e. a visible cloud water droplets or ice crystals that are suspended in the air at or near the Earth's surface [2]. It normally occurs due to added moisture in the air or falling ambient air temperature. Methods may be usefully divided into 'traditional' and 'modern'.

The second collection category is the collection of water vapour. While fog is visible to our naked eyes, water vapour is invisible and is generated by the evaporation of liquid water or the sublimation of ice. When water vapour condenses on a surface cooled temperature below the dew point temperature of the atmospheric water vapour, 'dew water' will be formed [3]. While fog water harvesting system are more related to traditional concept using a mesh-like structure, there are various technologies related to dew water harvesting technique. The early studies involved passive systems
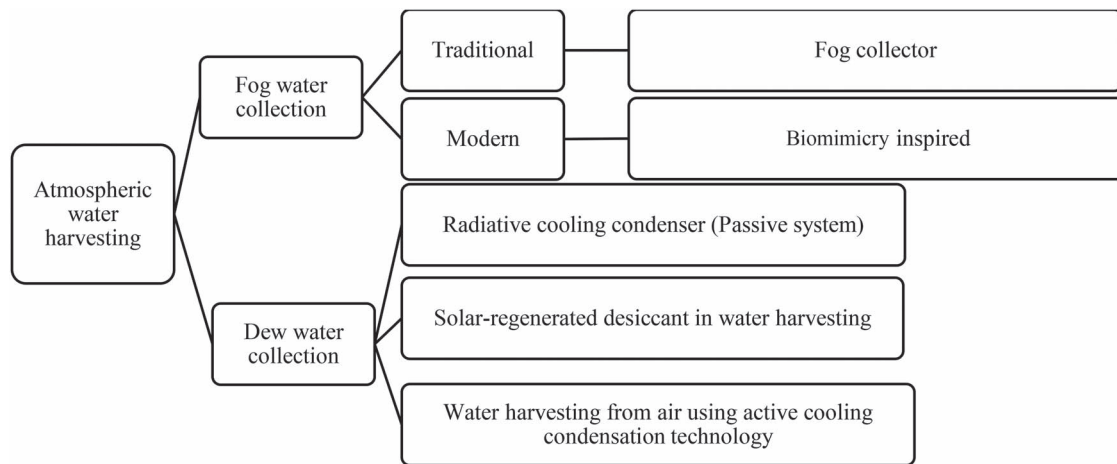
Figure 1. *Categories of atmospheric water harvesting techniques.*

using radiative condenser, but their low efficiencies resulted in, researchers introducing solar-regenerated desiccant methods to enhance the moisture sorption and desorption, however, still has not proved on its own to be sufficient. Thus, research in dew water harvesting also covers integration with active cooling condenser technology that covers the use of typical vapour compression air conditioning system and most recently, thermoelectric cooler. Due to the high in efficiency of active cooling condenser systems, at the end of this paper, readers will be presented with selected commercially available technology on water harvesting technology involving active cooling condensing system.

2. ATMOSPHERIC FOG HARVESTING

2.1. Fog collector inspired by traditional concept

Illustrated in Figure 2, the traditional fog collecting method is very simple, comprising a mesh exposed to the atmosphere over which the fog is driven by the wind. Two posts on guy wires are used to support the mesh and cables to suspend the mesh. Water droplets trapped by the mesh accumulate and drain under gravity into the channels of the water collection system. Collectors can be usefully classified as standard fog collectors (SFCs) and large fog collectors (LFCs) [2]. SFCs are typically used in a small scale exploratory studies to evaluate the amount of water that can be collected for a specific condition. The collector has a typical size of (1×1) m² surface with a base of 2 m above the ground [4]. LFCs, typically 12 m long and 6 m high has mesh covers the upper 4 m of the collector giving ~48 m² of water collection area. They are mainly used for actual harvesting installation. For maximum efficiency, fog collectors should be positioned perpendicularly to the prevailing wind. Typically, LFSs produce 150 l to 750 l of water a day depending on the site [5]. Reported in 2011, the cost for a unit of 48 m² fog collectors is US$400 meanwhile, the 1 m² SFCs cost from US$100 to US$200 to build depending on the country and the materials [5].

Commercially available, Raschel-weave high-density polyethylene mesh, commonly used for shading crops in hot climates, has
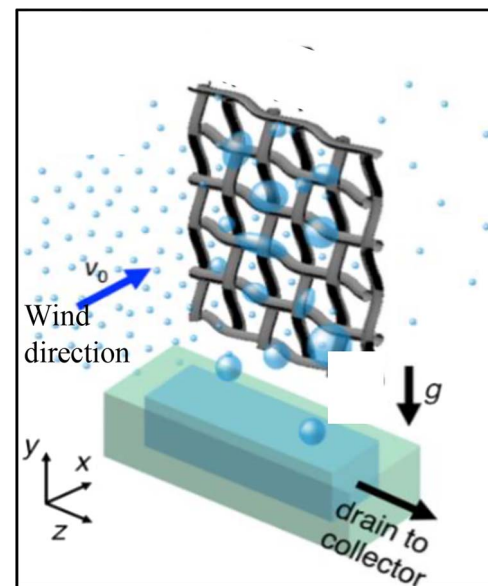

Figure 2. *The basic concept of fog collector. Adapted with permission from [6] Copyright (2013) American Chemical Society.*

been a popular collector material, although other weaves such as aluminet shade net have subsequently been investigated [7]. Illustrated in Figure 3, the standard Raschel mesh is black in colour, with treated UV-resistance and has 35% shade coefficient S [8]. Shade coefficient S is the portion of the fog collector's area that is capable of capturing fog droplets and can be expressed using the following equation [9]:

$$S = 1 - f, \qquad (1)$$

where f is defined as the ratio of mesh openings area to the total screen area.

Along the longitudinal direction, the mesh filament is tied up continuously, meanwhile transversely, we can see that the filaments are not continuous but knotted to the longitudinal one [8]. A leading developer of fog harvesting technology based on
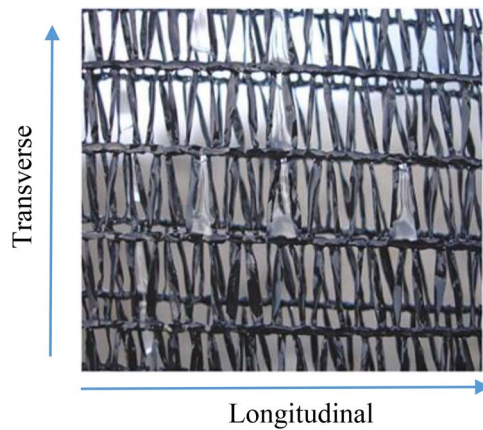
Figure 3. *An example of Raschel mesh used in a project by Fog Quest [10].*

Figure 4. *The examples of robust materials. Left: is a robust material with a stainless mesh, co-knitted with poly material. Right: a 3D net structure (1 cm thickness) of poly material [2].*

Raschel-weave shading mesh is the non-profit registered Canadian charity, FogQuest, (www.foqguest.com), which 'is dedicated to planning and implementing water projects for rural communities in developing countries'. Their first fog water harvesting experience dates from 1987. In addition to innovative fog collectors, they have also included rainfall collectors to make optimum use of natural atmospheric sources of water.

2.1.1. *Selected projects from the past 30 years to current*

Fog harvesting is common in arid and semi-arid areas close to the ocean where clouds are formed over the sea and pushed by the prevailing winds towards the mainland. The clouds would become fog when they intercept with the surface of highlands near to the sea. There are various fog collector installation, both for research and real applications in different places such as Namib Desert, Africa. The desert is well known for its potential in harvesting water through fog collection. Mtuleni et al. [11] conducted an interesting research to find out the quality of the Namibian fog water. Fourteen SFCs were studied at three Topnaar villages in Namib Desert [11]. The highest water collection was 2.122 l/m² at Klipneus village. In terms of the water quality, after a non-foggy period, the initial rinse of SFCs give turbid, brackish water that contains 1630 mg NaCl [11]. The water was considered as marginally fit for human consumptions. Nevertheless, the subsequent water collected after the initial rinse was found fairly cleaner and has low salt content. In the Coquimbo region of Chile, in 1980s, a research project involving fifty 48 m² fog collectors was conducted [12]. Forty-one new large fog collectors were installed to provide fresh water supply for 100 families benefited, supported initially by the foreign partners and then given over to the local population in the 1990s [12]. However, due to the incompetency of the local non-governmental organisation(NGO) in terms of technical skills, the project was reported degraded. Large fog collectors were also developed from 1995–99 utilized mainly for reforestation and restoration of degraded coastal ecosystems near the town of Mejia, Peru [13, 14]. In Pachamama Grande, Ecuador a large scale project was developed such that 40 LFCs were constructed throughout 1995–97 with the collection efficiencies are
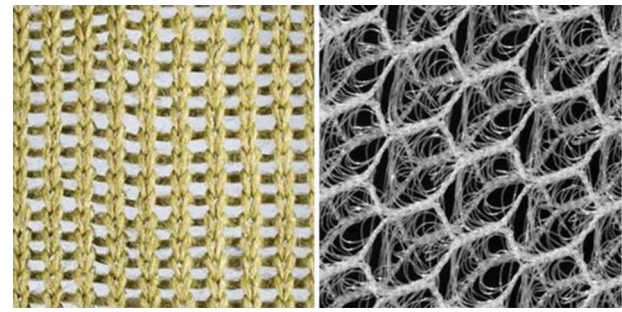
as high as 12 l per square metre per day [15]. Also in the 1990s, in Oman, a major fog collector study was conducted. Daily average collection rates were reported to be as high as 30 l/m². However, the large amount of water collected only happens during monsoon season that occurs about only 2 months in a year. This was considered as a huge limitation to the use of fog collectors in that region [16]. The following Table 1 listed more fog collection projects carried out worldwide.

2.1.2. *Fog collectors design*

For LFCs, the prevailing wind imposes pressures on the mesh which then imposes forces on the supporting structures and finally weakening/break the foundation. Meanwhile, the mesh and other components of LFCs can be damaged by UV radiation and also other environmental factors. Lacking in rational or engineered design process of LFCs being the main reason to the collapse of LFCs under extreme weather. This apparently explains the maintenance issue faced by the local people in managing fog collectors [8]. In order to suit different environmental conditions for examples for very windy sites, robust materials for the fog collectors were made using stronger stainless steel mesh, co-knitted with poly material. See Figure 4 [2].

Various collector designs have also been researched by Lummerich and Tiedemann [22] in a field study on the outskirts of Lima (Peru) to address crucial aspects of economic competitiveness of fog water harvesting. Prior to the field testing, five small scale prototypes with different shapes and materials were tested in selecting the most effective fog collector structure. Following the small scale testing, three different types of large scale fog collector were investigated termed 'Eiffel', 'Harp; and 'Diagonal Harp'. The 'Eiffel Collector' is an example of a 3D collector that is used at places with a rare condition with no unique wind direction associated with the occurrence of fog. In their report, a three-winged screen called astropod was introduced as an improved means to evaluate the amount of water yield by fog water harvesting. The use of astropod allowed the measurement of the favourable wind direction and absolute amount of collected fog at the same time. The fog collector designs and the description are summarized in Table 2.

Table 1. *The selected fog collector projects worldwide.*

State/country	Project	Year	Size/design/cost	Type of application/issues	Water collection	Ref
Falda Verde Mountain, Peru	Locally designed fog collector	1998–2001	1.5 m^2 1 m above the surface	-	100 l (day not stated)	[17]
Alto Patache, Chile	SFC fog collector	1987–2001	-	Primarily for ecosystem and climate research.	6 l per day	[17], [18]
Village of Tojquia in the Western Highlands	35 LFCs	2006–2012	-	High wind speeds are an issue.	Average of 6300 l of water per day in 4–6 months in winter dry season	[2]
Yemen (in the mountains near Hajja, inland from the Red Sea)	25 LFCs	2004	-	Stopped after a year due to insufficient monitoring at community level and issues related to occasional high wind speeds.	4.5 l m^{-2} per day over the 3-month dry winter period	[19]
North West of the island of Tenerife	Four LFCs, in 2000s and four more were added in 2011.	2000s and 2011	-	The water is used for domestic purposes in the Forestry Commission Office, for irrigation for the reforestation of endemic laurisilva species and for prevention of and fight against forest fires.	-	[20]
Lima, Peru	Project- 60 fog nets	2016	'Fog catchers' nylon nets designed. Cost: 500 USD per net	Supply free water to 250 households. The water is not drinkable thus used to sustain small scale farming, wash clothes and to wash households' utensils for poor families.	100 l of water per day, a saving of almost 60% in water usage.	[21]
Tojquia, Guatemala	FogQuest project- 35 large fog collectors (LFCs)	Since 2006 to current (2017)	40 square meters	For community use	Produces an average of about 200 l of water a day during the winter dry season.	[10]

Table 2. *Selected fog collector designs [22].*

| The fog collector	Size/design	Type of application	Advantage	Maximum water collection (litres/day)	Country
Eiffel collector	4×8×0.3 m metal frame, two separated layers of Raschel 50% net with 10 additional stripes in between	Large scale experiment	A 3D collector that is advantageous for places with no unique wind direction associated with the occurrence of fog.	2650 l per day during the peak fog season.	Peru
Harp collector	2×4×0.3 m metal frame, 2256 m of 1.5 mm rubber string vertically installed	Large scale experiment		200 l/day during peak season	Peru
Diagonal Harp collector	2×4×0.3 m metal frame, 1520 m of 1.5 mm rubber string diagonally installed	Large scale experiment		94.2 l/day during peak season	Peru
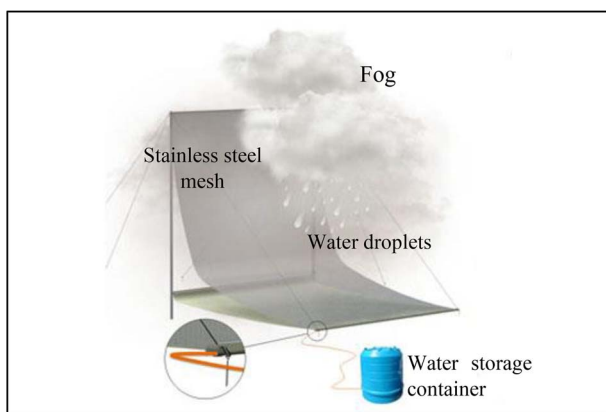
Figure 5. *The concept of the cloud harvester. The harvester is designed to catch and condense fog into water droplets that in turn run down on a stainless steel mesh into a gutter type extrusion leading to a water storage container [23].*

A unique design of fog collector called cloud harvester has been designed by Choiniere-Shields [23], see Figure 5. The concept of cloud harvester is based on a fog catcher that turn the condense fog into water droplet. In comparison to the current model available on the market, the unique part of in the design of cloud harvester is that it uses stainless steel mesh instead of the polypropylene nets with an extra sheet under the net for the water collection. The cloud harvester is expected to have a better condensing efficiency and much smaller than the similar products that are currently on the market. The cloud harvester has a potential water harvesting output of 1 l of fresh water per hour for each 10 square feet of mesh [23].

Aiming to harvest water from the atmosphere to supply fresh drinking water to the community in the developing world, a unique wooden atmospheric water harvesting project called Warka Water has been founded by Arturo Vittori [24]. The project won the World Design Impact Prize 2015–16 at World Design Capital(R) Taipei 2016 Gala [25]. Arturo and his team have developed 12 different prototypes since 2012. Figure 6 shows an example of the prototype and its working principle. The team's target is to develop a prototype that is lightweight (about 80 kg), easy and quick to build using local materials with-

out using scaffolding and power tools. They intend to use bamboo for the frame structure, while the water catchment system will be made from biodegradable mesh 100% recyclable materials. Fog and dew, and also rainwater, will be collected when they strike the mesh and then trickle down a funnel into a reservoir at the base. To prevent water evaporation, a fabric canopy will be used to cover the lower section of the water collector. There is no indication of the amount of water that can be produced by the prototype since the project is still in the exploratory phase. However, the aim of the project is to produce water from fog or highly humid places between 50 to 100 l per day [26].

2.1.3. *Fog collector efficiency and feasibility studies*

A fog water collector would act as the barrier to the wind-driven fog. However, a portion of the fog is unperturbed by the fog water collector. Although there is a collision with the fog collector, it cannot capture all the liquid water contained in the fog [9]. There are losses due to:

(i) Fog passing around the fog water collector.
(ii) Fog passing through the openings of the mesh.
(iii) Droplets bouncing back into the airflow.

For the fraction of the fog that is captured by the fog water collector, we call this fraction as fog interception efficiency [9].The captured water droplet merged, move to the lower part of fog collector, reached the water gutter and transported to the water tank. However, at water gutter, there is a potential of re-entrainment or water can return back to the air flow or some water from the mesh slack, wrinkles and folds, may be entering the gutter and collected at the water tank.

The basics calculation for the fog water collection has been discussed in Rivera [9]. To discuss the collector efficiency, there are four important factors that determine the efficiency of the fog collection and they are wind velocity, fog liquid water content, droplet size distribution and mesh characteristics. The water collector efficiency η_{coll} of a fog collector can be computed using the following equation (2).
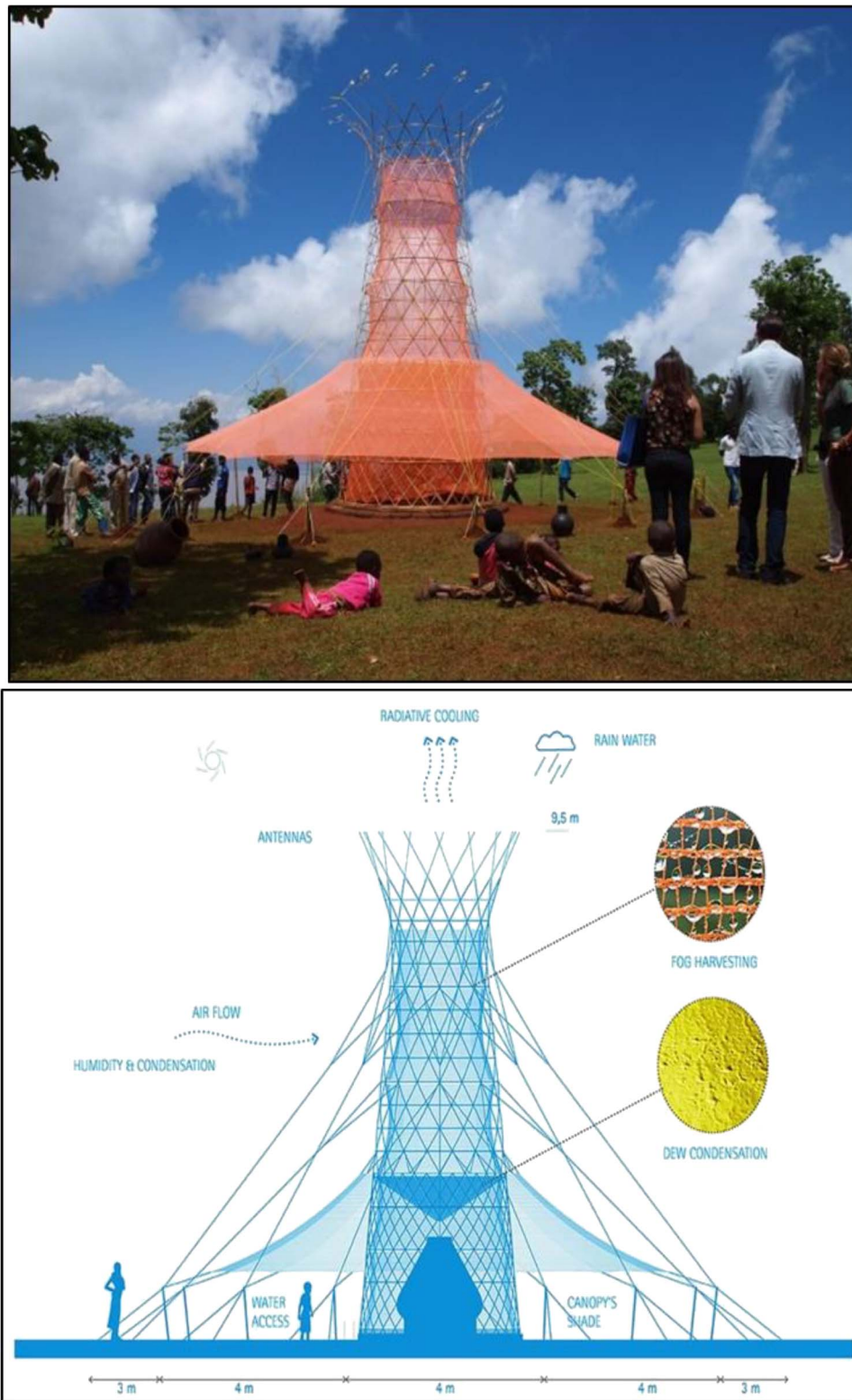
$$\eta_{coll} = \frac{\dot{W}_{coll}^{''}}{v_o . LWC} \tag{2}$$

Figure 6. *Water bamboo tower top: the working prototype and bottom: the concept [24].*

Where $\dot{W}''_{coll}\left(\frac{kg/s}{m^2}\right)$ is the water flow rate collected in the gutter per unit screen area, $v_o\left(\frac{m}{s}\right)$ is the unperturbed wind velocity of the incoming fog/air flow and $LWC\left(\frac{kg}{m^3}\right)$ is the liquid water content of the incoming fog/air flow.

Additionally, Rivera [9] reported that we can also express the collection efficiency by considering the following conditions:

i. The aerodynamic collection efficiency η_{AC}, calculated based on the amount of unperturbed fog droplets that would collide with the fog's mesh.
ii. The capture efficiency η_{capt}, to account for the fraction of the aforementioned intercepted droplets that are actually captured by the mesh wire.
iii. The draining efficiency η_{dr}, to account for the fraction of the water captured by the mesh that is collected by the gutter since some of the water can spill or re-enter the air flow.

Therefore, the fog water collector can also be expressed using the following equation [9]:

$$\eta_{coll} = \eta_{capt}\eta_{dr}\eta_{AC} \qquad (3)$$

Clearly, before installing a fog collector, its practicality must first be assessed. A group of Iranian researchers [27] have discussed the feasibility of implementing fog collectors as a mean to harvest water in their country. Their research has included analysis on the data collected from 10 representative stations located facing the Persian Gulf and Oman Sea. Among the important parameters recorded were 'hourly dry and wet temperature, relative humidity, wind direction and velocity and the dew point temperature'. The values were then used to calculate 'the atmosphere water vapour pressure, saturated vapour pressure and the absolute humidity of the atmosphere' and the feasibility of fog harvesting system predicted by using the equation (4):

For $RH \geq 69\%$, $WH_3 = (3 \times M_t \times U_z \times \eta_{coll} \times 3.6)$.

If $RH < 69\%$, $\rightarrow WH_3 = 0$ $\qquad (4)$

Where RH is relative humidity measured by weather station, WH is the potential water harvested (litres per square metre per day) and the subscript 3 represents for every 3 hours, an input value chosen because data at the representative stations was recorded 3 hourly, and they assumed stable conditions were achieved after this period is achieved. U_2 is the wind velocity at 2 m height above the ground, M_t is the absolute humidity that is defined as the humidity in grams per cubic meter of air in a specific temperature (g/cm³). The values of wind speed for eight different wind directions were then investigated. Their analysis have shown promising results for water collection at Abadan and Chahabar station with the amount of potential collected water is 6.7 l/m²/day and 156.3 l/m²/day, respectively [27].

2.1.4. *Studies on mesh topology*
To improve fog collector performance, understanding the effects of fog collector topology is a key as defined especially by the mesh radius and mesh diameter. Collectors can be categorized based on their fibre radius R and the half spacing of the fibres D [28], values that are important in the calculation of Stokes coefficient that is related to the collector efficiency. Stokes number typically determines the inertia of the moist air and its migration

across the streamline and thus indicates the effectiveness of the fog collector design, thus a large Stokes number implies a higher rate of water droplet collection [28]. However, this paper will not further elaborate the equation used for the calculation of Stoke coefficient. Interested readers may refer to [29] for further description. As previously discussed, Rivera [9] investigated aerodynamic collection efficiency (ACE). Rivera [9] considered that two important characteristics of the mesh were the shade coefficient and the characteristics of the fibres used to weave or knit the mesh. He also discussed a simple superposition model in analyzing the influence of these parameters to Regalado and Ritter [29] the ACE of the fog water collectors. Rivera [9] concluded that the ACE value can be increased by introducing concave shape to the fog water collector and improving the aerodynamics of the mesh fibres. Regalado and Ritter [29] have performed a theoretical analysis on wind catchers in the form of cylindrical structures equipped with several screens of staggered filaments to determine their efficiency. Like Rivera [9], these researchers also assessed the aerodynamic effects of the water/fog impacting on the mesh.

2.1.5. *Studies on surface wettability of a fog harvester*
While most researchers focussing on the mesh topology, Park et al. [6] have investigated the influence of surface wettability characteristics, length scale and weave density on the fog harvesting capability of woven meshes. In their research, Park et al. [6] have developed a model that combined the hydrodynamic and surface wettability characteristics of a fog water collector in predicting the overall fog collection efficiency. From their modelling, later validated against experimental results and depicted in Figure 7, there are two limiting factors that will effect fog harvesting and reducing the collection efficiency; first is the re-entrainment of collected droplets into the prevalent wind, and second one is the blockage of the mesh opening. However, they have concluded appropriate tuning of the wetting characteristics of the surfaces, reducing the radius of the wire and optimizing the wire spacing will lead to more efficient fog collection. Additionally, they have introduced family of coated meshes that have demonstrated enhancement in the fog collecting efficiency as high as five times of the conventional polyolefin mesh. To coat the mesh, quoted from the researchers' paper [6], 'a 1.7 wt.% 1H,1H,2H,2H-heptadecafluorodecyl polyhedral oligomeric silsesquioxane (fluorodecyl POSS) 98.3 wt.% poly(ethyl methacrylate) (PEMA, MW = 515 kDa, Sigma Aldrich) solution in a volatile hydrochlorofluorocarbon solvent (Asahiklin AK-225, Asahi Glass Company) at a concentration of 10 mg/m' was used by the researchers. They first dipped the mesh in the solution for 5 minutes and then air dried to evaporate the solution. To check the uniformity of the coating, they have used scanning electron microscopic method and also by contact angle measurements at several locations on the coated surface. The aim of the coating is to decrease the contact-angle hysteresis of the mesh wires that allows small droplets to easily slide down into the collecting gutter when they were captured by the mesh wires. Even in a mild fog with a droplet radius of 3 μm, wind speed of 2 m/s and liquid water content of 0.1 g/m³, the use
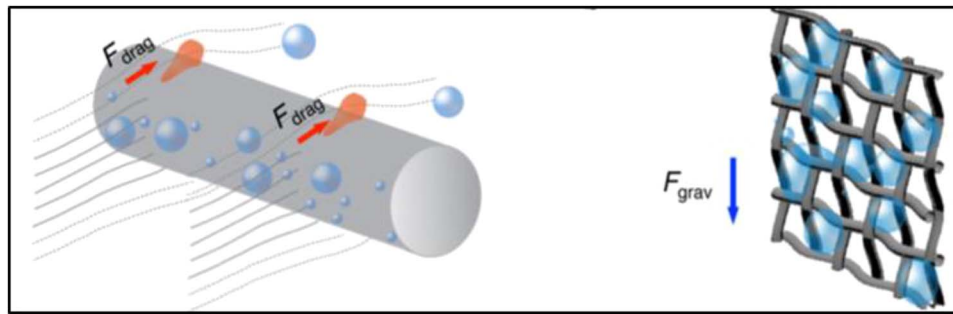
Figure 7. *Factors affecting fog harvesting and reducing the collection efficiency are (**a**) the re-entrainment of collected droplets in the wind and (**b**) blockage of the mesh. Adapted with permission from [6] Copyright (2013) American Chemical Society.*
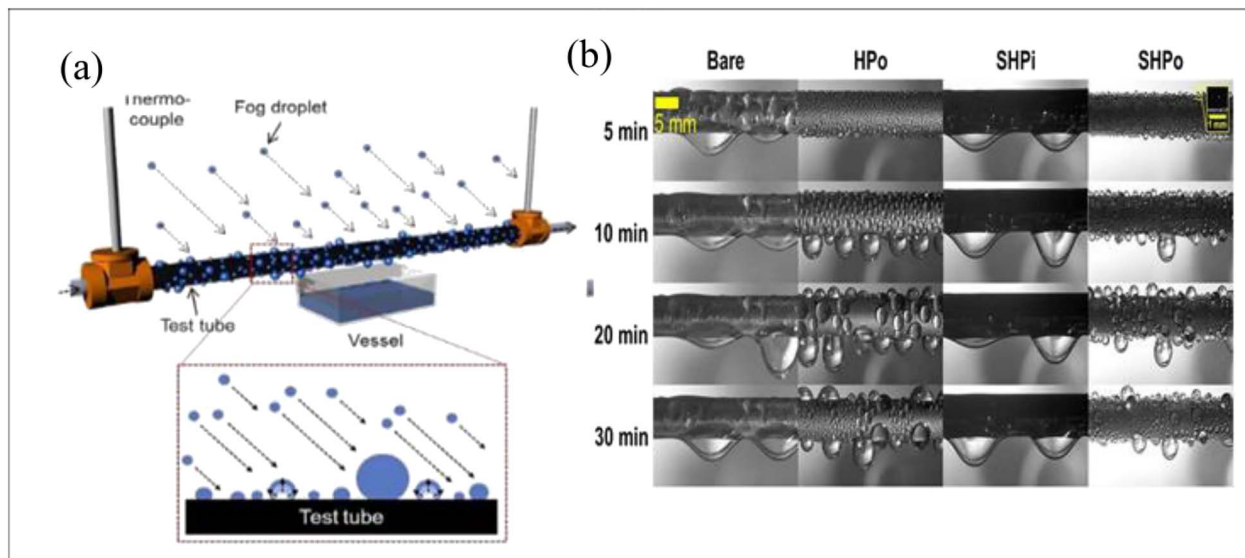

Figure 8. *(**a**) The schematics of the experimental arrangement and (**b**) the photos of different materials used to the test surface wettability in fog harvesting with the water droplets [30].*

of optimal dip-coated mesh surface can collect ∼2 l of water over an area of 1 m² in a day [6].

Seo et al. [30] have investigated the effects of surface wettability for both fog and dew harvesting. Their approach to fog harvesting involves different test surfaces. A commercially available copper was used in various wetting characteristics, see Figure 8b. The wettability of surface is determined by the contact angle of the liquid on the surface where the liquid-vapour meets the surface. When a droplet is flowing, the contact angle (Figure 9) can be classified as advancing or receding. The researchers showed that the moisture harvesting performance was determined by the combination of the moisture capture at the surface and the removal of the captured water from the surface. In their study, they found out that a large receding contact angle is a determining factor in performance. Among all the surfaces tested, the oil-infused surfaces with their large receding contact angle at a high supersaturation condition exhibit the best fog harvesting performance.

Azad et al. [32] compared the fog collection performance of three different categories of mesh sample for fog collection performance:
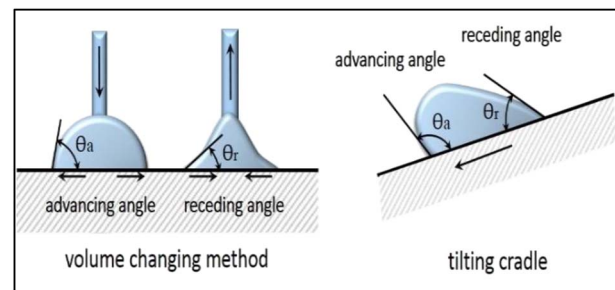

Figure 9. *Schematics represent advanced and receding angles from Weistron [31].*

i. Surfaces with fine microstructures and different coatings can have markedly different wetting behaviours than smooth surfaces. Therefore, in their research, they have investigated smooth and microgrooved copper wire with a diameter of 1.2 mm. They created the microgroove surface using a sandpaper. Then, microgrooves were implemented on the wire surface using Korn 80 sandpaper that contains
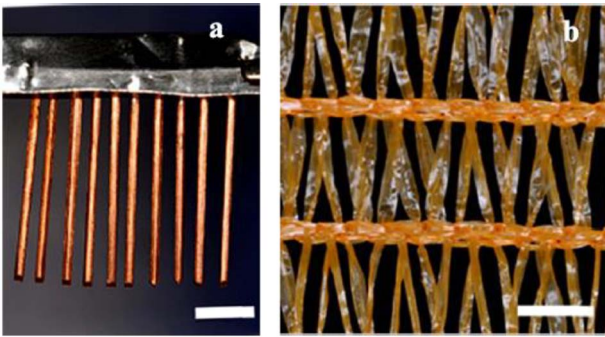
Figure 10. (*a*) *Copper comb sample and* (*b*) *polyolefin mesh (double layered) scale bar 1 cm [32].*

particles with the diameter of 190–265 μm. Illustrated in Figure 10a, the copper wires (10 of them, with smooth and microgrooved structure) were soldered electrically on a wire stick.

ii. Polyolefin mesh samples that comes in three types, hydrophilic mesh (attract water), superhydrophilic mesh that was dip coated with an aqueous TiO2 solution and dried at room temperature for 48 hours and 'hydrophobic mesh' (repel water) that were prepared by dip coating the polyolefin mesh with a hydrophobizing agent and dried at room temperature for 48 hours.

iii. Epoxy replication (replica) to replicate surface microstructures of Gunnera and Dendrocalamus under leaf surfaces and a smooth glass (microscope slide). The glass replica had a smooth surface, the Gunnera replica had a convex shape microstructure and random channels with hairs inside of the channel and the Dendrocalamus replica had microgroove surface.

It was found that the amount of collected water by superhydrophilic mesh was five times higher than the hydrophilic polyolefin mesh. Whereas water collection by hydrophobic mesh was 2.5 times higher than the hydrophilic mesh. In the microstructured replica, water dripped 2–3 times higher than unstructured replica and smooth surface. In addition, the water was collected more quickly for the micro-grooved copper wire than smooth wires [32].

Rajaram et al. [33] studied ways to improve the capacity of fog water collection by modifying the surface and geometrical shapes of Raschel mesh structure as shown in Figure 11. The surface modification includes coating the mesh using superhydrophobic coating such as Teflon, ZnO nanowires, NeverWet and hydrobead. In general, when compared with the uncoated Raschel mesh, the use of the coatings gives about 50% enhancement in the collection efficiency given by equation (3). Meanwhile, in terms of the modification to the geometrical shapes, they have increased the shade coefficient of the Raschel mesh by developing a new manufacturing method via a punching process. That has resulted in reduction in the pore size and also the increase in the distance between two inclined filaments. The change in the geometrical

shape leads to another 50% of enhancement. In general, both methods have collected water about two times that of a typical Raschel mesh.

2.2. Biomimicry-inspired fog water harvesting
2.2.1. *Animals and plants with special characteristics in harvesting water from the ambient*

In parts of the world, despite extreme water shortages resulting from the low annual rainfall, animals have evolved to survive in such conditions by acquiring special characteristics that allow them to collect water from the fog or the atmosphere. Namib desert beetles, such as *Stenocara gracilipes* (Figure 12), for instance, survive by collecting water although the annual rainfall is only 12 mm [34, 35].The surface of the beetle's back is covered with a random array of smooth hydrophilic bumps and microgrooves ∼0.5 mm in diameter and arranged at 0.5–1.5 mm intervals. These bumps on the forewings are micro size (in micron dimension) allowing water to condense and trickle directly to their mouth. Both fog and dew water harvesting efficiency are said to increase with the combination of hydrophilic (water attracting) and hydrophobic (water repelling) areas.

Other water harvesting animals are a lizard species known as *Moloch horridus* [36] (Figure 13).The lizard species is native to hot and arid regions, which drinks water droplets collected over its hydrophilic skin and that reach to its mouth by capillary action. In contrast, a spider, *Uloborus walckenaerius* uses its web (Figure 14) to collect water. A special structure formed a combination of its spindle-knot structure and the web joints. As seen in Figure 15, the spindle knots have rough surface and the joints have nanofibrils that make it less rough. The transportation of the water droplets towards the rough spindle-knots from the joints is promoted by the driving force resulting from the Laplace pressure gradient and surface structural anisotropy [37].

Plants are also able to survive in arid climates by harvesting water. An example is the endemic Namib desert grass called *Stipagrostis sabulicola.* The round shape of the plants' stem are covered with leaves whose surfaces are hydrophilic and have an irregular construction. The water droplets travel from the leaves onto the roots (Figure 16) via grooves along its cone-shaped structure. A combination of surface roughness, prickle hairs and wax prevent the scattering of water droplets [39].

Many of the cactaceae (cactus) family living in hot and arid regions also show great tolerance to water scarcity and capable of water harvesting [40]. One species, *Opuntia microdasys*, from the Chihuahuan Desert, has several characteristic with properties that provide effective fog collection [41]. It has hair-like needles (glochids) instead of spines on its large green leaves, thus reducing exposure to sunlight, which limits the evaporation of water, thus causing more storage of water. In this way, more water is stored for longer survival [42].

The water collection mechanism of *Lychnis sieboldii*, a plant species from dry grassland in Japan has surface hairs that show morphological changes when in contact with water, [43]. The microfibres in the hairs play a vital role in absorbing and releas-
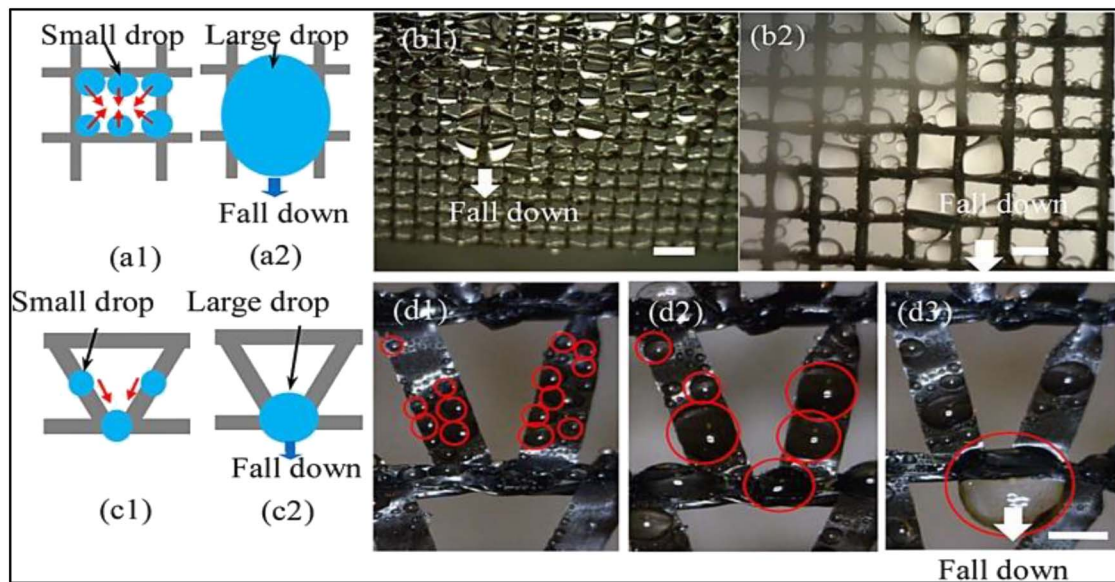
Figure 11. *Illustration and experimental results of mist flow (optical images) on two rectangular Rachel meshes with cylindrical fibres (real images) conducted by Rajaram et al. [33].*

Figure 12. *Fog-basking behavior of a Namib desert beetle. Courtesy of James Anderson/NSF/Creative Commons BY-NC-SA 2.0.*

ing water by becoming cone-shaped when exposed to water but changed to a perpendicularly twisted shape under dry conditions as shown in Figure 17.

A small desert moss, *Syntrichia caninervis* from the Great Basin in the western United States and the Gobi Desert in China, also survives arid conditions by condensing water using its hairs. The water condensation and the droplet formation are promoted by the grooves and barbs on the hair surfaces. The condensed water droplets will then travel from the tip to their base [44].

2.2.2. *Biomimicry approach in atmospheric water harvesting*
In recent decades, reports on bioinspired water harvesting have emerged rapidly [45]. Inspired by the Namib beetles, Garrod et al. [35] have investigated the influence in the degree of hydrophilicity/hydrophobicity of beetle backs in determining their overall micro-condensation efficiency. In this research, the micro-

condensation efficiency of fog water harvesting units has been explored in terms of the chemical nature of the hydrophilic 'pixels' and their dimensions. Imitating the pattern on the back of the beetle, they have applied plasma deposition method to make a hydrophilic polymer array on a superhydrophobic background. The performance of the surfaces as microcondensors were investigated by measuring the amount of water collected from a fine mist in 2 hours. The bumpy array patterns of the hydrophilic and hydrophobic surfaces are concluded to be more efficient at collecting suspended water droplets than a pure hydrophilic or hydrophobic surface. The amount of water collected by surfaces with bumpy array is more than 50% higher than the smooth surfaces.

To imitate the hairs of the cactus and its surface, Cao et al. [46] investigated a large-scale fog collector through integrating cactus spine-like, hydrophobic, conical micro-tip arrays. The tip arrays were arranged on a spherical hydrophobic cotton matrix, see Figure 18a–d. For the fog collector, about 30–40 micro tips were placed at each edge of the artificial cactus at 4∼5 mm distance, see Figure 18a and b. The experimental set up is shown in Figure 18d. The distance between the fogging jet and the collector was set at 3 cm. At fog velocity of 45∼50 cm/s, the biomimetic cactus-inspired fog collector was reported to harvest ∼3 ml of water in 10 minute. The results imply that at this wind speed, 100 cactus-like fog collectors will be able to collect the water in 1.5 hours, sufficient drinking water for human survival. Clearly, a promising device for collecting water in foggy regions.

More research on bio-inspired plants was conducted by Gürsoy et al. [47] who replicated the surface of the *Eremopyrum orientale* leaf, which displays an asymmetric-anisotropic directional mist collection behavior underpinned by macroscale grooves, microscale tilted cones (tilted in the direction of water flow)

Figure 13. *Moloch horridus lizard and the hydrophilic surface [36].*

Figure 14. *Water droplets on spider web [38].*

and nanoscale platelets to harvest water. The surface replication, achieved using soft lithography combined with either nanocoating deposition or functional nanoimprinting, was shown to be highly-efficient for directional mist collection, compared to mist water harvesting by flat surfaces. In a different study, Gürsoy et al. [48] have reported that non-woven and cotton fibrous materials are shown to mimic the fog harvesting behaviour of *Salsola crassa* hairs, see Figure 19. In order to enhance the overall mist collection efficiency, they incorporated multiple length scale (hierarchical) channel structures and tune the surface wettability by introducing hydrophobic functionalization of the fibres (in order to mimic the leaf waxes of the plant *Salsola crassa*) using initiated chemical vapor deposition surface coatings or plasma-enhanced chemical vapor deposition. The overall mist collection efficiency can be enhanced by over 300%.

An interesting fog water harvesting concept has been demonstrated by Park et al. [49] on the design of the fog water harvesting surface bioinspired by combining three different elements from different species: Namib desert beetles, cacti and pitcher plants. Inspired by the bumpy surface of Namib desert beetles, they have performed modelling to optimize the radius of curvature and cross-sectional shape of the water harvester surface to promote condensation. Then, inspired by cactus spine, they integrated the geometry with a widening slope in facilitating water droplet to

the collector in a faster rate to avoid a decrease in the droplet size. Finally, they integrated the optimized bump radius and the wide slope structures with a slippery nano-coated surface that is inspired by pitcher plants. The role of the slippery surface is to promote coalescence droplet growth.

Shang et al. [50] mimic the special characteristics of the spider web silk in order to harvest water. In their research, they have developed a novel microfluidic technology that can control the size and spacing of the spindle knots in order to adjust the flow rates. In this way, the size and spacing of the spindle knots can be controlled and thus, the function of humidity-responsive water capture can be obtained. As a result, some features are gained such as thermally triggered water convergence, humidity-responsive water capture that can be used for many applications.

3. DEW WATER HARVESTING

In fog water harvesting, the collection of water will occur when the fog droplets impact and intercept with the collection surfaces. However, the main limiting factor of harvesting water from the fog droplets is the global fog occurrence that is highly dependent on the geographical and metrological factors or conditions. Only limited number of places experience environmental conditions whereby the temperature of moist air could naturally drop below its saturation temperature thus form fog. Not surprisingly therefore, on a global scale, fog is reported to be even less accessible than seawater as an alternative source of freshwater [51]. Water vapour is ubiquitous in the atmosphere, so, if condensed by cooling, freshwater can be harvested at many locations. Nevertheless, the condensation process is more thermodynamically complicated than fog harvesting and as reported in Gido et al. [51], the process involves a significant release of heat.

Water droplets that are formed due to the condensation of water vapour on a surface at temperature below its dew point temperature are called dew water [3, 52]. In this paper, dew water harvesting processes are divided into three categories: i) passive (radiative) cooling condenser, ii) solar-regenerated desiccant and iii) water harvesting from air using active cooling condensation technology. This review includes dew water collection under both high and low humid air conditions.
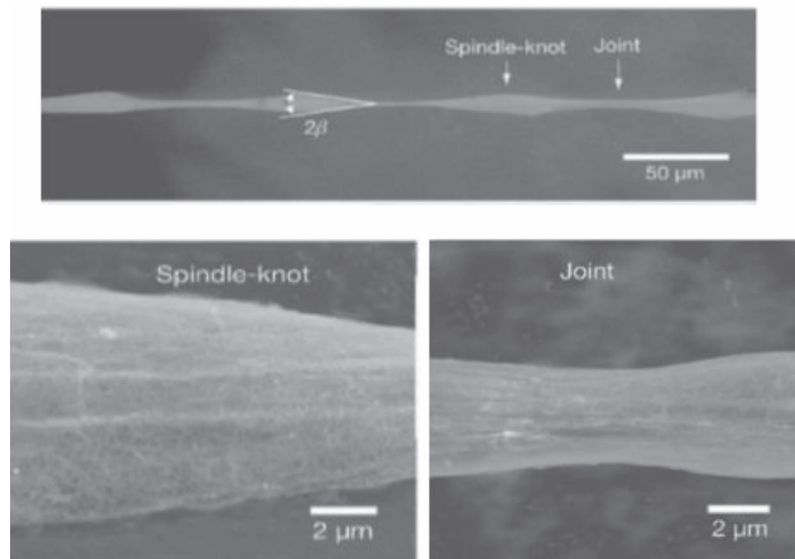
Figure 15. *Structure of the spindle-knot and joint [37].*

Figure 16. *Stipagrostis sabulicola in their natural habitat [39].*

3.1. Water harvesting using radiative cooling condenser (passive systems)

The principle of radiative cooling condenser is very simple. Inspired from dew formation on plants in the morning, the formation of dew is driven by radiation phenomena of the surface of the materials. The formation of the dew is physical and determined by the surface cooling without additional energy, and the most important element being the power gradient between the condenser outgoing radiative power and the sky radiative power P [53] which is presented by the Stefan–Boltzmann law presented in equation (5):

$$P = \varepsilon \sigma (T)^4. \tag{5}$$

The radiative power per unit area P (W/m²) also depends on the local surface temperature T (K). In equation (5), σ is the Stefan–Boltzmann constant (W/m²K⁴), and ε is the emissivity of the surface. Thus, to optimize the dew formation, as reported in [52] cited in [3], one could:

(i) maximize the infrared wavelength emitting properties of the surface to allow surface cooling at night;

(ii) increase the reflectivity of the condensing surface to ensure that the surface will not trap heat that will warm the condenser and resulting in evaporation during the day;

(iii) reduce the wind effect to the condenser by tilting the condenser surface;

(iv) increase the hydrophilic property of the surface, and this can be achieved by applying hydrophilic coating to the surface and lastly;

(v) reduce the heat inertia of the condensing surface to promote change in temperature difference and also as a means to avoid heat transfer from the ground.

Studies on passive cooling system include investigation on materials with low emissivity surfaces. Early study on the influence of condensing surface materials to the dew formation has been investigated for Bahrain climatic condition [54]. Three materials: aluminium, glass and polyethylene foils were investigated as the condensation surfaces. From their study, aluminium surfaces were reported to have the highest amount of average dew collected at 3 kg/m² per hour, followed by glass and polyethylene foils at 0.8 and 0.3 kg/m² per hour, respectively. Three different types of condensing surface namely: i) galvanized iron (GI) sheet with emissivity 0.23 and thickness 1.5 mm, ii) commercial aluminium sheet with emissivity of 0.09 and thickness 1.5 mm and iii) PETB film (polyethylene mixed with 5% TiO2 and 2% BaSO4) UV stabilized with emissivity 0.83 and thickness 0.3 mm have been investigated, see Figure 20 [55]. The condensing surfaces were tested as a radiative condenser at 1 m × 1 m in size installed at the village of Kothara (23° 14 N, 68° 45 E, 21 m a.s.l.) that is a part of the semi-arid coastal region of northwest India. The aim of the project was to use the water harvesting system as a solution to drinking water problem in that region that is well known with
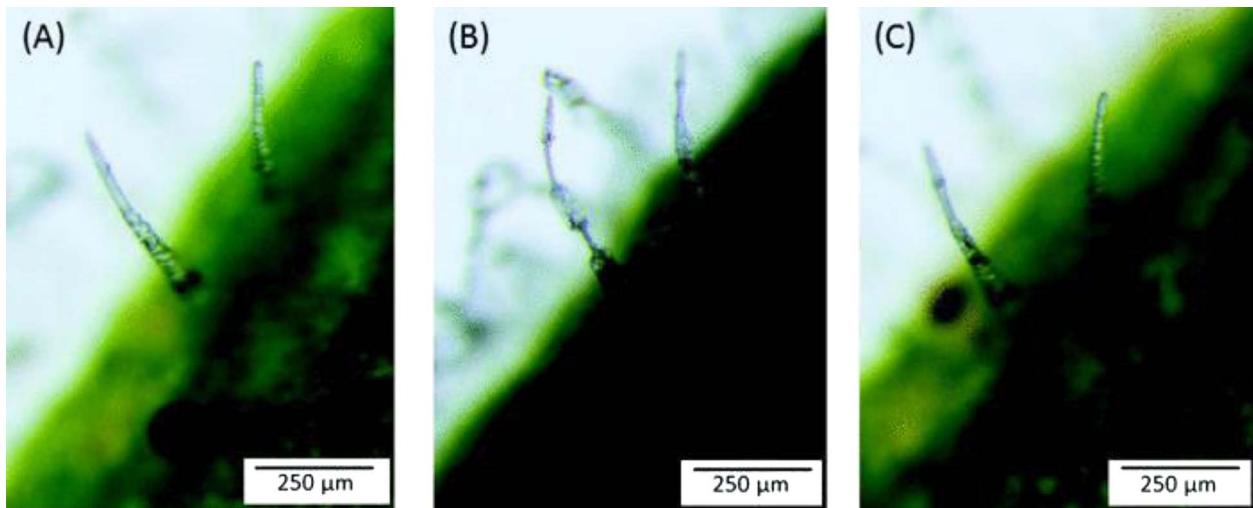
Figure 17. *The morphology changes of hairs on the leave of Lychnis sieboldii [43].*
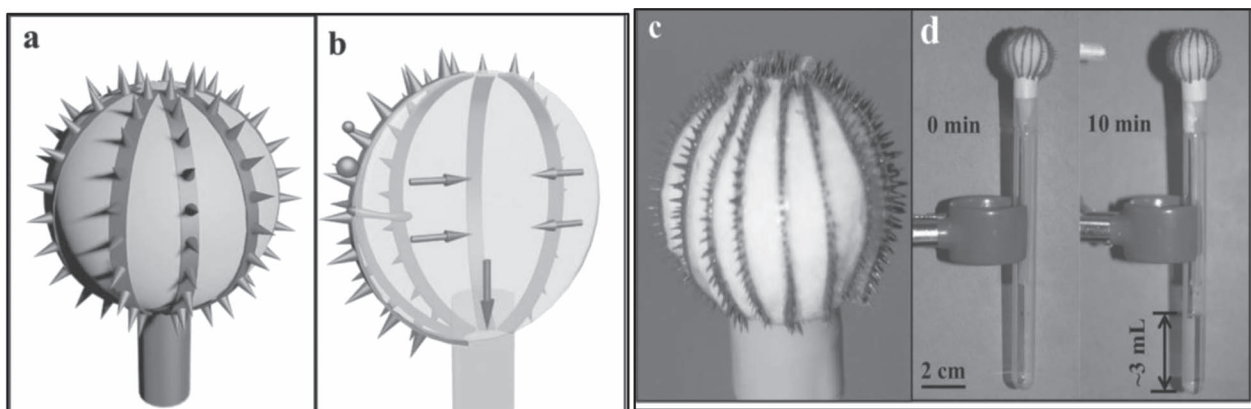

Figure 18. *The illustration of the (**a**) cactus-inspired device and (**b**) the water transportation pathway in the device. (**c**) The photographs of the cactus-inspired continuous fog collector and (**d**) the photographs of collection process of the device [46].*
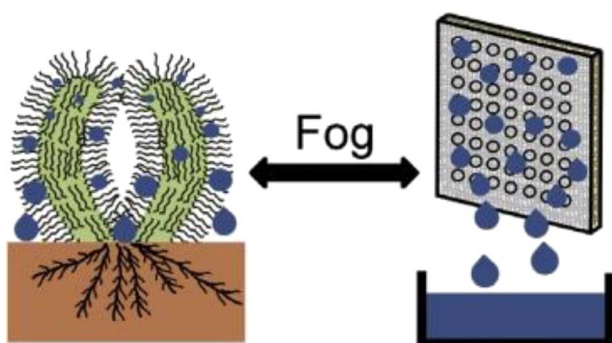

Figure 19. *'Fog collection mechanism of salsola crassa plant species and bioinspired fibrous water harvesting' [48].*

poor groundwater quality. From the daily data collected over 2-year period in 2004 and 2005, the quantity of water collected on most (60%) nights varied more or less uniformly between 0.05 and 0.25 mm and there were two peaks. The peaks that one of them centred over March–April (summer) and the other over October (fall) shows water collection of 0.55 mm. From all the three surfaces being tested, the highest collection was in the PETB units (19.4 mm) followed by GI (15.6 mm) and aluminium (9 mm).

Kothara village in the Kutch region now has India's first potable large-scale water production plant designed to harvest atmospheric moisture and process it into drinking water. The condensers were made of planar panels using high emissivity plastic film insulated underneath that promotes cooling. In addition to dew water harvesting, the condenser are also capable to collect rainwater. It was reported that the expected cost of 1 l of bottled water is 0.5 rupee with the expected yield of filtered, treated potable water from the plant is 150 000 litres a year [56].

Another important surface parameter that influences the performance of the passive system is the shape of the radiative condenser. As reported in Khalil et al. [3], among the early researchers who investigated various shapes of these passive condenser

Figure 20. *Different types of condenser surfaces investigated by [55].*

surfaces were Jacobs et al. [57] who investigated an inverted pyramid shape. Investigated at the grassland of the Netherlands, the authors concluded that their collector collected water 20% more that the planar shape at angle 30°. Researchers [58] have performed a CFD simulation Computational Fluid Dynamics using PHOENIXS to simulate the innovative designs proposed in their study.

Reported in 2011, the world's largest dew and rain water collecting system was constructed in 2006 at Panandhro in the semi-arid area of Kutch (NW India). Ridge-and-trough shape modules have been chosen as the shape of the dew water collector [59]. The performance of the large dew condenser at 850 m² net total surface with 10 ridge-and-trough modules had a total output for 2007 of 6545 l, corresponding to 7.7 mm/day on average. The maximum collection rate reported was 251.4 l/night (0.3 mm). In addition to dew, the designed condenser could also collect rain (and, to a lesser extent, fog).

In a passive system, natural convection between the condenser surface and the air flow is not favoured since it will reduce the condensing efficiency of the condenser system. Thus, a condenser in a hollow form such as a funnel will reduce the free convection along the surface since the heavier cold air will remain at the bottom of the funnel due to gravity regardless of the wind direction [53]. The researchers have performed both simulation and field studies. From their simulations, cone angle ≈ 60° give the best condenser cooling efficiency. Based on experimental work and field testing, a repetitive pattern of hollow shapes to pave a planar or weakly curved roof surface, have been considered, providing pleasing aesthetics and construction cost advantages. The egg-box and origami types were specifically investigated. The prototypes were fabricated and installed at Les Grands Ateliers (Villefontaine - France) during the 'Chaleurs urbaines' project (ENSA de Grenoble - Métro).

3.2. Solar regenerated desiccant in water harvesting (passive system)

Low yield is a key issue for the passive, radiative condenser system because of its dependency on certain parameters, notably the sky emissivity, the amount of water vapour in the air (relative humid-ity), wind speed and topographic cover [3]. Desiccant materials such as silica gel, zeolites and $CaCl_2$ are hygroscopic and can absorb moisture through adsorption and absorption process thus increasing the amount of the dew water collected. As a result, desiccant beds are now commonly being used in atmospheric water harvesting applications. Figure 21 presents the generic process of atmospheric water harvesting using desiccant. The process may be explained as follows: the first stage is water absorption stage at night where the desiccant bed will absorb moisture from humid air. The second stage is water desorption during the day by heating the bed with solar radiation, which will regenerates the desiccant by driving out water vapour. In the third and final stage, the evaporated water will then condensed into water droplets and collected in a tank.

The advantages of a desiccant system over radiative condensers include the hygroscopic capacity of the desiccant that enables more efficient water collection, achieving low dew points without the risk of freezing thus reducing operational cost [51]. Early studies on solar regenerated systems involve desiccants such as saw dust [61], silica gel [62] and recycled newspaper [63]. In a patent, Ackerman [64] claimed a spiral water harvester containing hydrophilic particles such as silica gel and tilted at an angle that optimized water collection. To improve the atmospheric water harvester performance, various collector designs have been investigated by researchers and several are described below.

3.2.1. *Glass pyramid collector*
Kabeel [65] described a glass pyramid collector (Figure 22) comprising: i) desiccant beds on shelves, ii) a slanting wall cover, iii) a collection cone and iv) a condenser section mounted on top of the pyramid, shading it from solar radiation. Sawdust and cloth, saturated with $CaCl_2$, were investigated as the desiccants. The covers over the beds are open overnight so the desiccant can absorb water vapour from the air. During the day, the covers are closed so the beds are heated by solar radiation driving off the absorbed water, which condenses on the sides and especially at the pyramid apex water, where it is collected by a central cone and flows through a tube to an external container. The reported water yield is 2.5 l/day/m³; the cloth bed showed better performance than the sawdust bed system.

3.2.2. *Corrugated surface*
Based on the principle of desiccant moisture absorption at night and simultaneous desorption (regeneration using solar energy) and water vapour condensation during the day, Gad et al. [66] introduced the use of an integrated desiccant/solar collector to harvest water from humid air. In their study, a small air circulation fan was used to force the ambient air to enter the glass-enclosed solar collector during the evening (Figure 23). In the collector, a thick layer of corrugated cloth was used as the desiccant bed. The use of corrugated surface was meant to increase the heat and mass transfer area during the absorption/desorption mechanism. During the day, water vapour condensation will occur on the
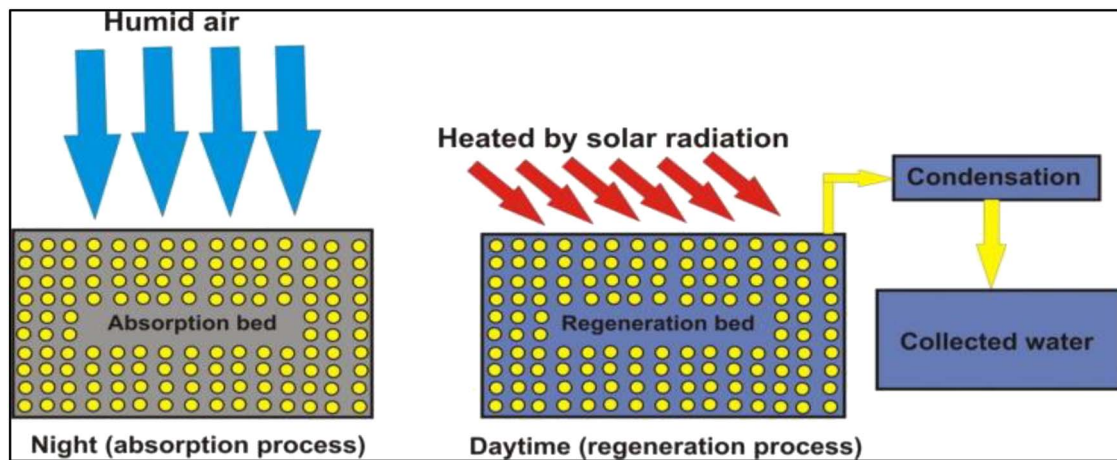
Figure 21. *Wet desiccant technique for water production from atmospheric air [60].*
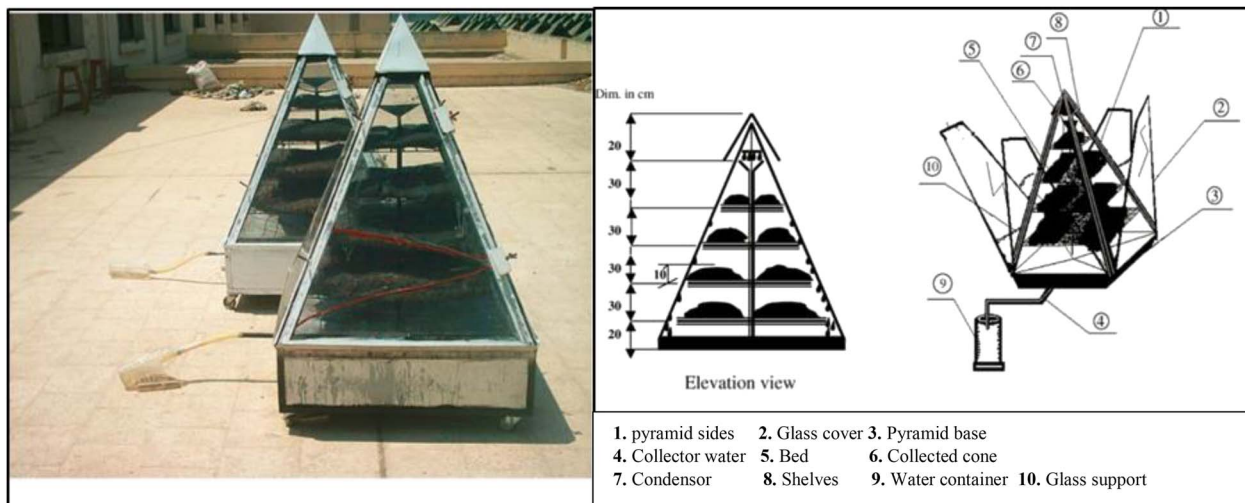

Figure 22. *(a) Photograph of the system used. (b) Pyramid with glass covers open at night (right) [65].*

inner surface of the glass enclosing the solar collector. According to the researchers, the solar driven system could produce 1.5 l of fresh water per square meter per day.

3.2.3. *Trapezoidal prism*

William et al. [67] designed a trapezoidal prism with $CaCl_2$ as the desiccant (Figure 24) supported on sand and on dark cloth. For the prism wall, transparent fibre glass bolted to aluminium frames was used while the top of the prism was an opaque material that acted as a condenser and to facilitate collecting the condensate water, the walls were slanting. The trapezoidal prism worked in essentially the same way as the pyramidal system described above in that moisture absorption occurred at night time and the solar radiation driven desorption occurred during the day with the evaporated water forming water droplets that collected in the water tank. The system efficiency was computed by considering the total heat of evaporation to the total incident solar radiation

during the day time. The recorded daily total evaporated water for cloth and sand bed achieved a maximum of 2.32 and 1.23 l per m² at system efficiency of 29.3% and 17.76%, respectively.

3.2.4. *Solar glass desiccant box type system*

In India, an atmospheric water harvesting system that named 'solar glass desiccant box type system' (SGDBS) with a capture area of 0.36 m² was developed and investigated. The box was made of a 3 mm single glaze glass; the desiccant bed was fixed at 0.22 m at inclination of 30°. The desiccant bed was a composite material using sawdust impregnated with $CaCl_2$ (Figure 25a, absorption and Figure 25b, desorption). Three boxes were tested under the Indian climatic conditions at NIT Kurukshetra, India [29° 58′ (latitude) north and 76° 53′ (longitude) east] in October. The researchers observed that the performance depend mainly on the concentration of $CaCl_2$, which generated 180 ml/kg/day at a loading of 60% on the sawdust.

1- Flat plate collector.
2- Glass cover.
3- Fans openings.
4- Collected water channel.
5- Foam (Insulation).
6- Aluminum sheets.
7- Steel sheets.
8- Metallic frame.
9- Collected water tube of condenser.
10- Collected water tube of collector.
11- Graduated Flask.
12- Flat plate condenser.
13- Connected channel.
14- Condenser support.
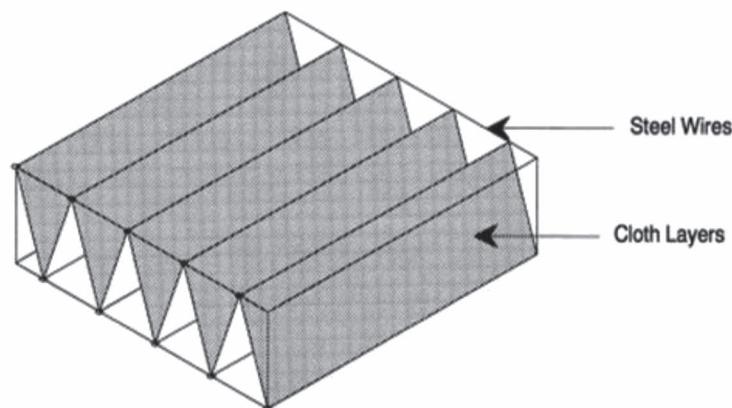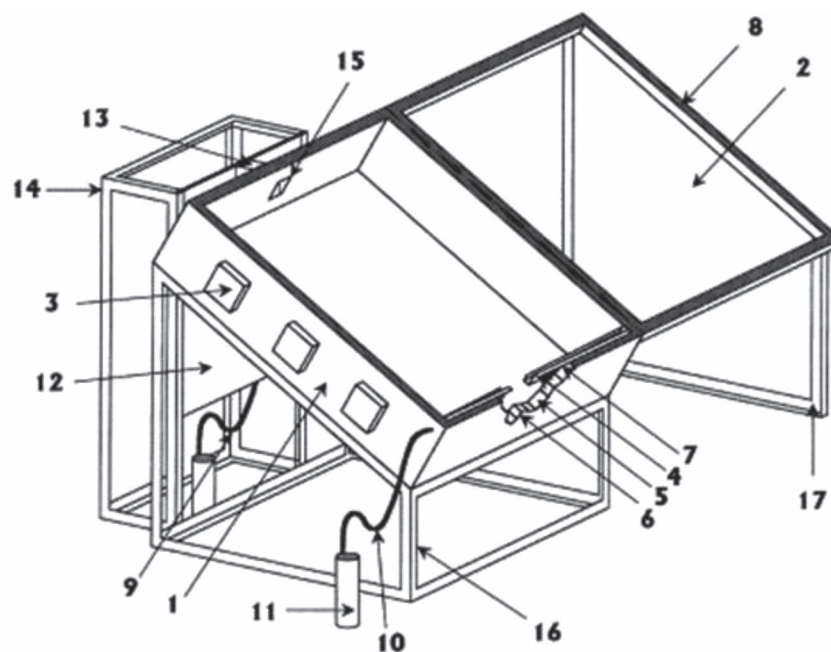15- Condenser opening.
16- Collector support.
17- Glass cover support.

Figure 23. *Schematic diagram of the experimental apparatus and the corrugated desiccant bed [66].*

3.2.5. *MOF porous metal-organic framework-801*

Recently, the potential of harvesting water from humid air as low as 20% have been investigated by researchers from Berkeley and MIT [69]. Based on the same principal of introducing hygroscopic element to improve moisture uptake, the researchers have developed an hygroscopic sheet using a kilogram of dust-sized MOF porous metal-organic framework-801 [Zr6O4(OH)4(fumarate)6] crystals pressed into a thin sheet of porous copper metal positioned between a solar absorber plate (at the top) and a condenser plate (see Figure 26), both placed in a chamber [70].

The device is shown in Figure 26. At night flaps are open, allowing ambient air to enter the chamber. Water vapour diffuses into the porous MOF and is absorbed on its internal surface in clusters of eight molecules, essentially tiny 'cubic droplets'. In the morning, with the chamber closed, natural sunlight ($\sim 1\,kW/m^2$) heats MOF causing the water to desorb as vapour, which then condenses on the bottom of the chamber [70] and the resulting liquid drains

to a collecting tank. Published results suggest that MOF-801 is superior to other absorbents, being capable of generating 2.8 l of water per kg and with the ability to operate a relative humidity level as low as 20% [70].

3.3. Water harvesting from air using active cooling condensation technology

The water harvesting systems described previously can be described as 'passive', i.e. they are driven simply by solar heating and do not require the input of electric or other high-grade power. In contrast, 'active' systems typically require electrically powered compressors or vacuum pumps and the quantity of water harvested in directly related to the input energy [3]. Active harvesters range in scale from those suitable for domestic drinking water (15–50 l per day) to industrial scale units for irrigation (2000 l per day), outputs typically significantly larger than passive systems. The power consumption per kilogramme

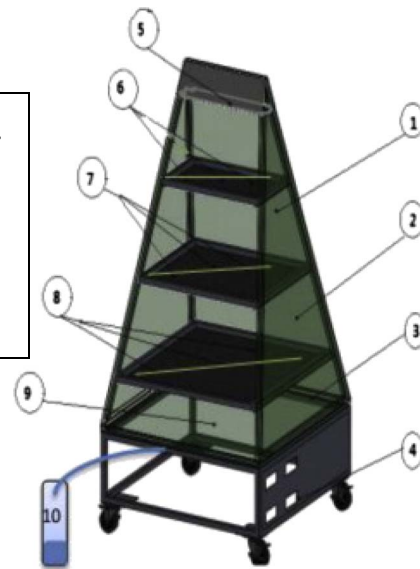| No	Description
1,2,3	Temperature measuring points in each fibreglass side
4	Thermocouple selector switch position
5	Roof surface remperature measuring point
6	Top bed temperature measuring points
7	Middle bed temperature measuring points
8	Bottom bed temperature measuring points
9	Collecting surface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

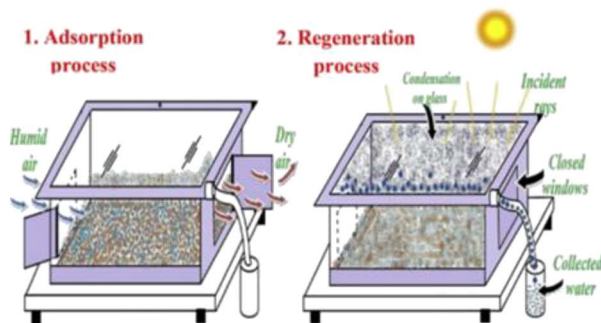**Figure 24.** *Schematic diagram of experimental test rig [67].*

Figure 25. *(a) and (b) the design of the SGDBS and (c) the experimental setup [68].*

of water collected is a major concern for active systems and will be affected by the ambient temperature, humidity and efficiency of 'coolth' recovery in the equipment. Leading active technologies are described below.

3.3.1. *Dehumidifier using selective membrane*
Water vapour is only a minor component of air in the atmosphere, even at 30°C/100% RH only 30.4 g is present, while at 10°C/RH 100% the moisture content is 9.4 g/m³, so the maximum quantity of water that can be recovered by cooling between these temperatures is 21 g/m³. However, this requires cooling 1 m³ of air by 20 K that requires the removal of 24 kJ of heat plus 52.5 kJ of latent heat to condense the water. If the coolth of the outgoing air after condensation is not recovered, it represents a significant inefficiency. To minimize the power requirement of the dehumidification process, as shown in Figure 27, researchers [71, 72] have used water vapour selective membranes to separate the water vapour component prior to cooling and condensation, thus avoiding cooling the other atmospheric gases. The key element

of the system is the water-selective membrane that allows only water vapour to pass through driven by a concentration gradient imposed by the vacuum pump. The concept underlying the membrane system is shown in Figure 28 in a different study by Woods [73]. The researchers [74] found that with a 62 kW power input, the harvester produce water at the rate of 9.19 m³/day, a 50% better efficiency than the equivalent system without the membrane. In addition to improved energy efficiency, the selective membrane generated fresh water that cleaner than water condensed directly out of the air. Other than selective membranes, some researchers also use desiccants systems (liquid and/or solids) to absorb the water vapour from an incoming air stream. However, these methods require regeneration steps and cyclic operation conditions reduce the rate of water production. Furthermore, the use of spatially separated liquid desiccant dehumidification methods results in energy-intensive regeneration and condensation processes [75].

Various selective membranes have been investigated. A Singapore group investigated water vapour permeation through
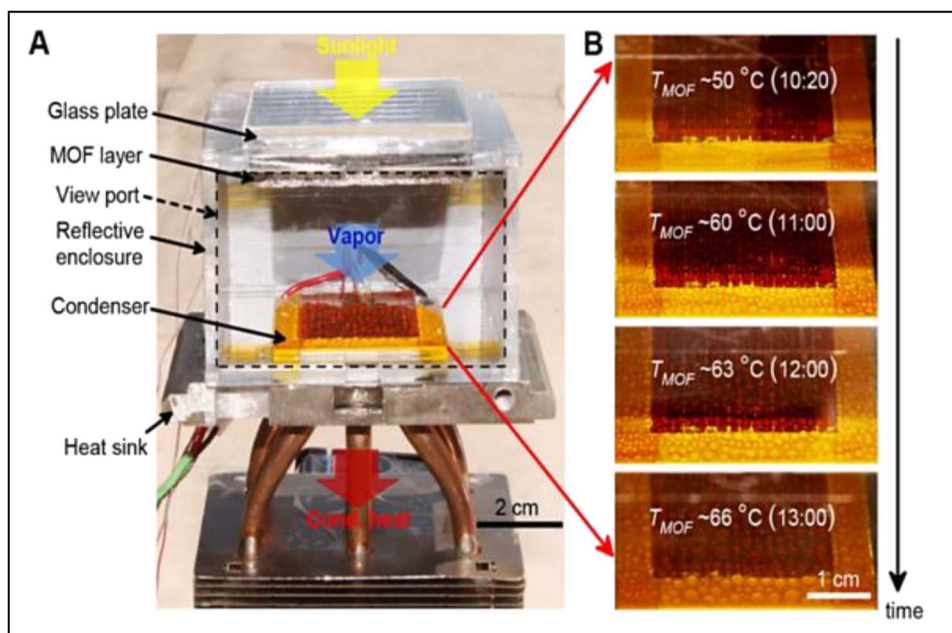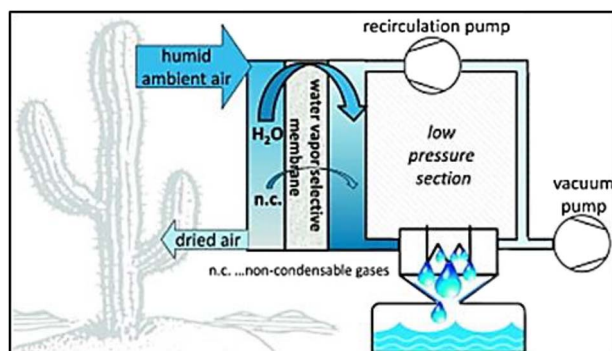
Figure 26. *The experimental setup [70].*

Figure 27. *The representation of the water vapour selective membrane in an atmospheric water harvesting system [74].*
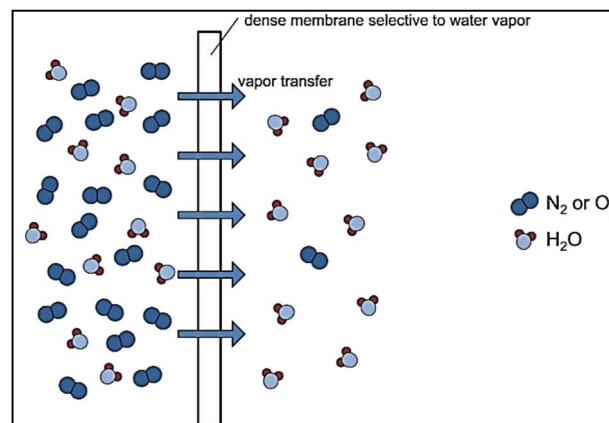

Figure 28. *The concept of water vapor selective membrane [73].*

membranes fabricated by impregnating poly(vinyl alcohol) (PVA) with LiCl [76]. They concluded that higher LiCl contents and lower temperature optimizes the water vapour permeance of the membrane. With respect to humid condition, the tests showed that the membrane was suitable for dehumidifying air at high humidity conditions.

In a separate publication, the group compared two different membranes, one containing LiCl and the other triethylene glycol (TEG) supported on PVA. The researchers concluded that the water vapour permeability of the membranes increased with increasing amounts of the hygroscopic component (LiCl or TEG), because it lowered the diffusion energy and thus the barrier to permeation. The researchers further claimed that a membrane with PVA/TEG is highly durable, has less corrosive problems and more environmentally friendly in comparison to the membrane with LiCl as the hygroscopic component [77].

3.3.2. *Atmospheric water harvesting integrated with air conditioning system and condensing coil*

Active condensing systems, using the conventional reverse Rankine cycle, operate in the same way as a dehumidifier where passage of moist air passed over a coil cooled by a refrigerant, causes the water vapour to condense. The rate of the water production depends mainly on the relative humidity and the air temperature. Versions of the technology have been described in various academic papers and patents. For example, Lukitobudi [78] claimed a mobile dehumidifier unit that simultaneously produced drinking water. Sawyer and Larson [79] who presented a disclosure unified system that provides both air conditioning and atmospheric water harvesting. Magrini et al. [80] have discussed in their paper the advantage of water harvesting from the integration with an HVAC

Figure 29. *Ecolo Blue EB30 [82].*

Figure 30. *Atlantis H2O Elite Atmospheric Water Generator [83].*

system that also serves as the air conditioning system for a hotel in a sub-tropical arid climate. Rather than having the condensate water from an HVAC system wasted, the water is collected and utilized. The researchers found that the integrated system water produce ∼56% of the hotel water daily demand.

Another study into water harvesting from an air conditioning system has been recently conducted by Dalai et al. [81] to maximize the amount of water vapour captured by a window air conditioner, a process termed 'atmospheric water vapour processing' (AWVP). The water was claimed to be sufficiently good quality for human consumption. With a power input of 160 watt and air flow rate of 0.00623 m³/s, the amount of water collected was reported to be as high as 1025 ml.

Ecolo Blue, a United States company, produces the EB30 commercial unit based on dehumidifier circuit to harvest atmospheric water (Figure 29). To minimize contamination of the water by the metals of the cooling coils, they are treated with a food grade coating. The EB30 can generate up to 30 l of water from air over a 24 hour cycle with a unit cost of 1300 US dollars.

Another company, Atlantis Solar, offer the Atlantis H2O Elite range of units providing atmospheric water harvesting from 100 l up to 10 000 l per day (Figure 30) (Atlantis [83]).

3.3.3. *Thermoelectric cooling in atmospheric water harvesting*
The application of thermoelectric cooling (TEC) is being actively investigated as an alternative approach to conventional Rankine cycle for water harvesting for example by Joshi et al. [84] who constructed a prototype containing 10 Peltier components (Figure 31).

To enhance the cooling performance, the researchers have introduced an internal heat sink on the cold side to increase the cooling rate and thus the condensation rate. Over a 10 hour run, the TFWG with internal heat sinks showed 81% improvement over in amount of water collected compared to the TFWG without the heat sinks. Other parameters being investigated are electric current, air mass flow rate and air humidity.
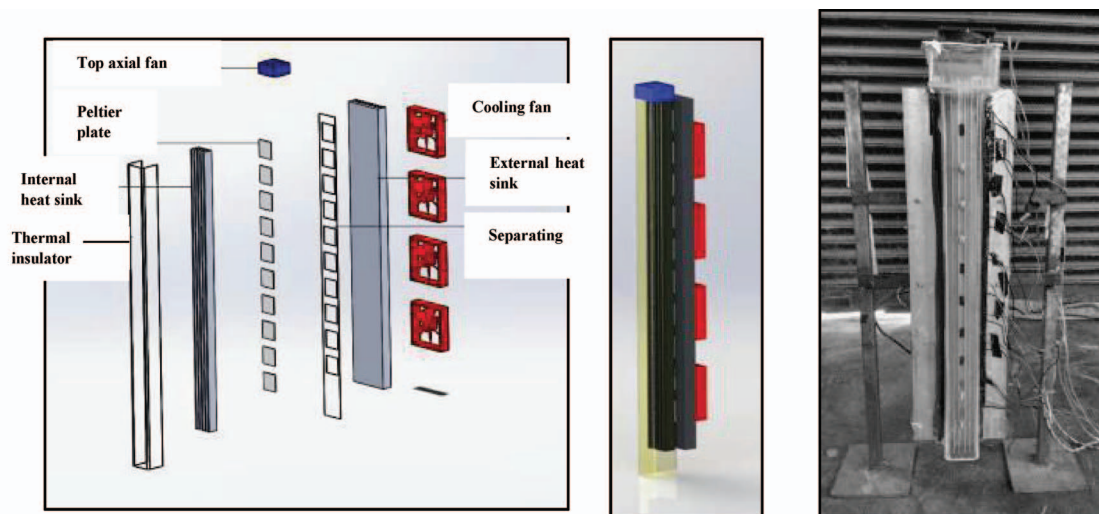
Figure 31. *Left and middle: diagram of prototype and right: actual water harvester prototype [84].*

Liu et al. [85] have investigated a portable water generator, with two TECs. In their system, air is forced into the mixing chamber and then humidified. The humidified air is then flow through the TECs via the inlet air channel. At TECs, the temperature of the inlet air was reduced by the cool surface of the TECs to the dew point temperature and water condensation occurs. The researchers investigated the relationships between inlet relative humidity and air flow rates with the amount of the water generated/condensed. They concluded, not surprisingly, that the higher the air relative humidity the higher the amount of water generated, while increasing the air flow rate lowered the condensation rate, possibly because the reduced contact time between the air flow and the TEC degraded the heat transfer rate. Lui et al. [85] showed that the maximum amount of generated water was ∼25.1 g/h with 0.216 m² of condensation surface and 58.2 W power input.

3.3.4. *Innovative cooling condensation technology: concept and prototype development*

Exciting developments integrate cooling condensation technology with wind energy source element. The water harvesting billboard (2013) designed by University of Engineering and Technology of Peru (Figure 32) contains five generators that extract moisture from air using an inverse osmosis filtration system [86]. The water flows through the small ducts to a central holding tank at the billboard's base. Although the billboard requires power supply, it could provide as much as 100 l of drinking water per day.

EOLE WATER have introduced the WMS1000 wind turbine (Figure 33) that harnesses wind energy to simultaneously drive the compressor of a Rankine cycle dehumidifier-type system and create an airflow over the cold coil. With an electrical output of 30 kW, the WMS 1000 can produce up to 1000 l of drinking water per day and requires no additional external electrical input [87].

Figure 32. *Water harvesting billboard [86].*

Over the past decade, Australia has suffered severe droughts causing considerable economic hardship to its famers. To alleviate their plight, Edward Linacre has therefore invented the airdrop water harvester [88]. Airdrop comprises a mast-like tube above ground through which air is sucked and driven into an underground metal coil by a wind-powered turbine. Since the earth is at a lower temperature, it cools the air below its dew point resulting in water vapour condensation. Liquid water collects in a reservoir from where it is pumped to a network of irrigation tubes to the plant roots, a very efficient method of distribution since it minimizes water loss. The airdrop can harvest 11.5 ml of water for every cubic meter of air in the driest deserts such as the Negev in Israel, which typically has a relative humidity of 64%, and can produce 1 l of water per day [88]. The airdrop is a low-tech solution that could be installed and maintained easily and it is self-contained, using a combination of wind and solar power. The turbine is generally wind powered, but when wind speeds are low it is powered by solar PV buffered by a battery.
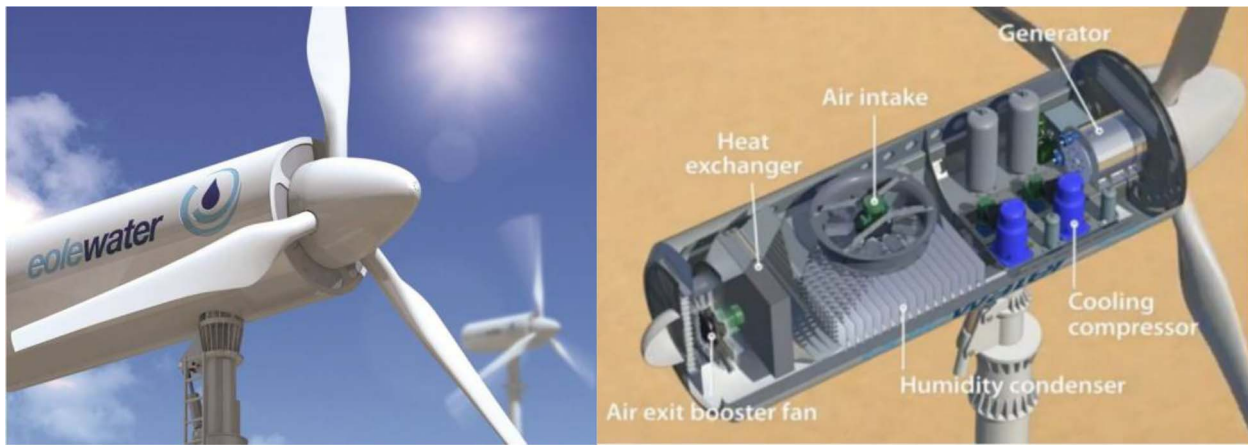
Figure 33. *The WMS1000 wind turbine from EOLE WATER [87].*

4. DISCUSSIONS AND CONCLUSIONS

At least 2.7 billion people worldwide experience water scarcity, a problem that is increasing and has the potential to cause conflicts between countries as they compete for an increasingly short resource. Clearly, this crisis needs tackling urgently and will be compounded as climate change causes profound shifts in rainfall patterns. Although traditionally arid regions, such as the Middle East will suffer, developed countries are certainly not immune as prolonged droughts in parts of Australia and California have demonstrated. Not surprisingly therefore, harvesting atmospheric water has received considerable attention from researchers worldwide since starting with the traditional method of capturing water from fog 50 years ago.

This review has described various technologies in rapidly developing field we expect more to appear in the near future. All have their merits and disadvantages with some being more suited than others to specific situations. Fog harvesting systems are simple, relying upon simple, relatively cheap materials that may be obtained from indigenous natural resources. However, fog only occurs in a limited number locations where rainfall is low, so can only make a modest contribution to alleviating water shortages.

Atmospheric water vapour is a world-wide resource and is available even in the driest climates. Passive harvesting devices relying upon radiative heat loss, and, like fog collectors, also have advantage of being simple and not requiring an external power source. The surface energies and topographies can be modified to facilitate the collection of water and facilitating drainage. However, long term testing is required to check whether fouling, either natural or man-made, might compromise performance over a time scale of several years. Will regular cleaning be required? The quantities of water that can be harvested by passive systems are limited and are perhaps limited to providing drinking water to small communities rather than large-scale applications such as agricultural irrigation.

Desiccant-based water collection systems are more sophisticated than radiation-based systems, but can collect more water for a given size of unit. Although cheap absorbents can be fabricated from sawdust and calcium chloride, recently developed modern metal organic framework (MOF) materials are able to operate with relative humidities as low as 20%, but will be more expensive. The choice of absorbent will be determined by economics versus technical efficiency. The desiccant systems described in this review rely upon thermal solar energy to drive the desorption process, which is not a problem since most arid areas have plentiful sunshine. Desiccant systems would benefit from fans to drive moist air over the beds on windless nights, which require solar PV cells and batteries. All the systems reviewed rely upon flaps to opened and closed manually. Obviously, this is not a problem for an experimental system, but for a production unit an automatic vent opener typically used for greenhouses would allow water harvesting with minimum of attention. Of course, it would need to be installed to close the vent during the day and open at night, the reverse of its normal operation.

'Active' water harvesting units that require the cooling of air by the input of electric or mechanical energy are capable of operating from scales of few litres to 1000s litres per day and can be used for domestic water to agricultural irrigation. Whether fossil fuel or nuclear, provide the power for condensation, it is questionable whether this makes technical or economic sense since such stations require large quantities of cooling water. If such water is available why not use it directly. However, solar or wind power is readily available in an arid area, using it harvest water is potentially attractive. Furthermore, water can be readily stored; a renewable energy installation might be scaled to supply both the power and the water for an arid locality, with water harvesting continuing when power demand was low. Water can also be used for evaporative air conditioning systems so conceivably integrated power and a/c systems might be designed. Maybe in arid climates, we shall see the construction of fully self-contained dwellings that do not rely upon any connections to public utilities? Of course,

there may more than one system installed, so that the house derives its power and water from PV cells, while the garden is watered by several 'airdrop' units scattered around the grounds. For public buildings and facilities such as golf courses and where adequate land is available, the EOLE WATER WMS1000 water unit might be attractive because of its large scale.

Water harvesters based on the reverse Rankin cycle, operating on the same principle as present-day dehumidifiers, require a conventional refrigerant. Over the past 25 years, the major refrigerants have been the Hydrofluorocarbon (HFCs), but these are now being phased-down and ultimately phased out because of the high global warming potentials (GWP). The low GWP replacements are the so-called 'natural' refrigerants, carbon dioxide, ammonia and hydrocarbons and the so-called 'synthetic' refrigerants the HFOs (hydrofluoroolefins), notably R1234yf and R1234ze(E). Ammonia and hydrocarbons have well-known hazards so increasing their applications in close proximity with the public means they must be treated with caution. Carbon dioxide is non-flammable and has low toxicity, but of necessity has to operate at high pressure supercritical conditions for part of the cycle, which presents significant thermodynamic efficiency problems. The two HFOs have low toxicity, are only marginally flammable and can operate on a conventional reverse Rankine cycle. However, they attract considerable opposition from campaigning environmentalists who strongly advocate the 'natural' refrigerants, although, as presently sourced, these are just synthetic as the HFOs being manufactured in large chemical plants. Any future work on active reverse Rankine cycle harvesters should consider what refrigerants will be available in the future. The 'airdrop' system does not rely upon refrigerants or external power, so is possible to develop a large-scale version? Maybe this is the way forward? The TEC cooling systems also avoid the need to choose a refrigerant, but are they as efficient and can they be operated at large scales?

Several of the technologies we described above are essentially laboratory studies; water harvesting technology is only now being to be commercialized. If water is being collected for drinking water then attention must be paid to potential contamination. Fog nets, passive radiation and even desiccant collectors may be fouled with algal and bacterial growth and bird droppings, so the water obtained may need to be treated before being drunk. The problem of legionnaire's disease in a/c water tanks is well known. Atmospheric pollution, such as soot particles, might also be a hazard. Comparable problems might occur with active collection devices.

Dalai et al. [81] recognized the need to treat the water collecting plates of their AWVP windowbox device with a coating that prevented potential contamination of the water with metals to ensure it was drinkable. This is an important point; chemical as well as natural contaminants must be considered. Standard horticultural Raschel fabric may contain additives, such as plasticisers and UV stabilisers, that would contaminate collected fog water. A food grade material might be specified, but would this survive sufficiently long in the open air? In any case, natural contamination accumulating during use might nullify the value of food grade material. Fluorochemical coatings provide the highest water repellency so they would seem to potentially useful for water harvesting devices. However, it has been known for over 20 years that they slowly release non-biodegradable perfluoroalkylsulfonic salts that can accumulate in the fats within organisms. The use of fluorochemical coatings is therefore best avoided. For crop irrigation, potable quality water is not required so these problems are not issues, apart perhaps from the fluorinated coatings.

Water harvesting is a technology whose time has come. Clearly, considerable challenges remain to optimize efficiency and ensure the delivery of water with a quality appropriate to its end use at cost the customers can afford. These problems can be solved.

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