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Sustainable Textile-Based Water Harvesting Systems: An Overview

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Abstract

Environmental concerns about water scarcity are among the world's most pressing issues, and with the rising population and effects of climate change, water demands have increased dramatically. Significant efforts are being made to find new sustainable and renewable sources of fresh water due to the lack of natural resources, such as rivers, lakes, and groundwater. Water harvesting techniques have emerged as promising solutions to address the water scarcity crisis in arid and semi-arid regions worldwide. Nature has inspired researchers to design water harvesters by mimicking the mechanisms that desert plants and animals use to collect water droplets. Technical textiles designed with specific materials, various structures, and surface functionalities have shown great success for water harvesting systems, due to their high surface area, versatile properties, and effectiveness in capturing water droplets. This paper provides an overview of the recent technologies used in water harvesting systems, highlighting the integration of textile materials and their efficiency in water harvesting. Several techniques are being implemented to find sustainable water resources such as seawater distillation, rainwater harvesting (RWH), and atmospheric water harvesting (AWH), which includes harvesting water from fog and dew. Advanced functionalization strategies used to enhance water harvesting performance such as fabric surface modification and nanostructured coatings are also addressed. By presenting the recent findings and technological advances in this field, the paper offers valuable insights into the development of sustainable and cost-effective textile-based water harvesting systems seeking to widen their applications in domestic and international sites.

Keywords*: Water Scarcity, Sustainability, Sustainable textiles, Bioinspired Water Harvesters, Rainwater Harvesting, Atmospheric Water Harvesting.*

1. Introduction

Water is a renewable resource; it is essential to support all forms of life. Over 70% of the earth's surface is made up of water, of which only 3% is fresh water and the remaining is found underground or in the form of glaciers, ice caps, and permafrost. About 0.5% is fresh groundwater and soil moisture, and less than 0.01% is surface water found in lakes, swamps, and rivers. Oceans, Seas, and groundwater make up 97% of the total water on earth [1,2,3]. With the rapid growth of population, urban development, industrialization, and climate changes, a lot of stress has been put on the natural water resources which caused water sacristy in many countries around the globe. The World Economic Forum Risk report has emphasized the water crisis as one of the top five risks for eight consecutive years, its detrimental effects are disastrous for billions of people worldwide in terms of their health, dignity, and prosperity [1,4]. About 2.3 billion people are living in water stressed areas, and due to severe water scarcity, 700 million people may have to be moved by 2030 [5]. It has been stated that by 2050, due to the increasing population, urban water demands could be increased by a further 80% [4]. Besides climate change, water scarcity has emerged as the largest global challenge [6,7]. Raising awareness about sustainability to preserve the world's resources for future generations and saving the environment has become a major concern in the last few decades.

The 2030 agenda for achieving sustainability adopted by the United Nations in 2015, included 17 interlinked sustainable development goals (SDGs), Figure 1 [8]. These goals aim to eradicate poverty, save the environment, and enhance the well-being and opportunities of individuals worldwide. These 17 goals are designed to be realized globally by the year 2030. The SDGS includes; No poverty, Zero hunger, Good health and well-being, Quality education, Gender equality, Clean water and sanitation, Affordable and clean energy, Decent work, and economic growth, Industry, innovation, and infrastructure, Reducing inequalities, Sustainable cities and communities, Responsible consumption and production, Climate Action, Life below water, Life on land, Peace, justice, and strong institutions, and Partnerships for the goals.

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Figure 1. Sustainable development goals [8].

Furthermore, SDG6 (clean water and sanitation) includes 8 targets: safe and affordable drinking water; sanitation and hygiene services; wastewater treatment and reuse for improved water quality; increased freshwater supplies and water use efficiency; implementation of integrated water resources management; preservation and restoration of water-related ecosystems; international support and capacity building; and encouragement and strengthening of community participation in water and sanitation management [1]. Water can provide food security, reduced mass migration, prosperity, quality education, and all-around growth of the young leading to harmony and national stability [9]. Accordingly, extensive research efforts have been made to find sustainable solutions for obtaining new water resources to avoid the global water crisis.

1.1. Conventional Water Resources

Freshwater serves as a critical resource for sustaining human life, irrigation, and urbanization across diverse industries. Conventional water resources are abundant in many countries, but they are not distributed equally, which causes shortages in various urban areas [10], Figure 2. So, the management of water resources is a vital issue [5]. Lakes and rivers are examples of natural freshwater resources that are depleting as a result of detrimental human activity and emissions [1]. The volume of water in rivers was estimated at 2,120 km^3. More than 145 lakes are found globally with an extra area of 1.3 Mkm^2, which holds about 167,860 Km^3 of fresh and saline water. The oceans hold the largest volume of water on the earth about 1338 Mkm^3. The annual global renewable water resources are 42,750 km^3, and water distribution differs among the continents in time and space. Asia has 13,500 km^3 and South America 12,000 km^3 which account for the largest share of the earth’s water, while Europe has 2,900 km^3 and Australia has 2400 km^3. The largest water scarcity is in Africa, followed by South America and Asia, while in Europe, the water scarcity due to population growth did not exceed 16% [11]. In 2020, the annual renewable water resource (ARWR) was about 5,400 m^3 per person, and it is expected that by 2050, 87 out of the 180 countries will have ARWR less than 1700 m^3 per person, and 45 out of the 87 countries will face absolute water scarcity, i.e., 500 m^3 per year [9]. Additionally, groundwater has a slower change rate compared to surface water, which make it a reliable and abundant source of water for extended use without concerns of exhaustion. It flows into the ground through surface water leakage and can be enhanced by redirecting and complementing it from surface water through the construction of reservoirs or containment tanks [12].

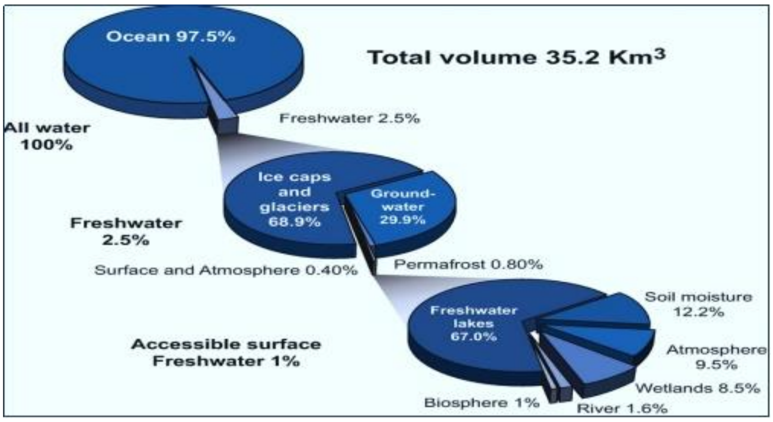


Figure 2. Distribution of the world's water resources [11].

Climate change and the severity of drought as a result of precipitation patterns and rising temperatures are effective factors in reducing freshwater resources [2]. Several regions have seen a considerable decrease in rainfall due to various reasons (e.g., global warming). Ineffective water distribution, treatment, and disposal systems that consume significant energy are another factor exacerbated by the issue, leading to additional expenses and environmental deterioration [10]. Generally, water scarcity is classified into two groups; physical and economic. Physical water scarcity happens when water resources are insufficient to fulfill necessities, and its symptoms include severe environmental degradation and increased incidence of conflicts. While economic water scarcity is due to deficiency of mechanisms and infrastructure to access water resources, its symptoms include inadequate infrastructure development, high exposure to seasonal fluctuations such as floods and drought, and unequal distribution of water [2,13]. Water scarcity is prompted by pollution as a significant environmental disaster. Also, the consequences of freshwater shortages have caused a reduction in economic growth affecting the overall quality of life [15]. According to the World Health Organization (WHO), about 785 million people did not have access to basic drinking water services in 2019, with 144 million depending on the surface water. Globally, about 2 billion people use contaminated drinking sources which results in around 485000 annual deaths from diarrheal diseases linked to polluted water. So, water scarcity will not only affect all living beings but will also influence vegetation types and biodiversity in affected regions [14]. To meet basic daily water needs, it is required to provide each person with a minimum of 20 liters. Isolated communities often lack connections to conventional water supply networks, while urban slum networks are insufficiently regulated by local governments [15].

This issue is further complicated by the fragmentation of water resources. There are 276 transboundary basins shared by 148 countries, representing 60% of the world's freshwater flow. Additionally,300 transboundary aquifer systems with 2.5 billion people reliant on groundwater. The challenges posed by fragmentation are replicated at the national level, necessitating cooperation is important to achieve optimal water resource development and management solutions. To address these intricate and interconnected water challenges, countries must enhance their approaches to managing water resources and associated services [16].

1.2. Potential Water Resources

Water scarcity as a crucial challenge has caused a persistent need to find new ways for efficient use of fresh water and on the other side find new resources of water, which can lead to reducing stress on drinking water supplies [17].There are endeavors to address water shortage problems and decrease water consumption in industries, processes, products, and services. For example, agriculture processes consume large amounts of water (70-90%) of the water resources on the earth, so new methods for efficient water management in agriculture are needed [9]. Numerous researchers have discovered and implemented various techniques for obtaining water such as seawater desalination, rainwater harvesting (RWH), wastewater reuse, and building more dams and wells, but these efforts may not be sufficient, particularly in dry and hot regions and areas far from water resources [2,4]. Desalination is mostly used for power plants in the oil and energy sector that are situated in remote places and deserts. There is a rising interest in desalination technologies including seawater, groundwater, surface water, and saline wastewater [2,18]. Groundwater aquifers are regions on the earth's crust which have pores or holes that are constantly saturated with water from rainfall and stop when they come into contact with an impermeable surface such as clay rocks. These aquifers are displayed in the form of springs on the ground [2].

In arid and semiarid regions, the growing demands for water have urged efforts to explore alternative nonconventional water source [19]. Atmospheric water harvesting (AWH) is a promising reliable freshwater resource. It is considered a new and sustainable solution to overcome the problem of water shortage, where researchers were inspired by nature, and mimicked the mechanisms of desert animals and plants in collecting water [19,20]. Sustainable technical textiles designed with specific materials and functionalities have shown significant potential for use in various water harvesting systems. Thus, the ideal water harvester should be designed with functional materials, have high water uptake, low energy required for water release, fast water capture/release, and low cost [21].

2. Technical Textiles Used in Water Harvesting Systems

Textiles play a significant role in shaping the future of sustainability, as textile production technologies evolve and the consumers' needs continuously change, looking for more functional, smart, affordable, and sustainable products. Technical textiles are one of the fast-growing segments in the textile market, they are manufactured mainly for their functional performance rather than their aesthetic or decorative features. These textiles exceed conventional textiles by integrating aspects such as sustainable materials, sensors, responsive materials, and coatings [22]. They have found extensive use in various industries such as automotive, construction, architecture, personal protection, medicine and hygiene, agriculture, sports goods, packaging, etc. Woven, knitted, and nonwoven textiles are commonly utilized in technical applications, in addition to fiber-reinforced composite materials. Natural fibers such cotton, jute, flax and wool are commonly used in the production of technical textiles, in addition to traditional synthetic fibers such as polyester, polyamide and polyethylene because of their balanced performance and cost-effectiveness. High-performance fibers such as glass, Kevlar, and carbon fibers are extensively used in various industrial applications. Textile finishing such as UV absorbers/blockers, antimicrobial, water repellency, flame retardancy, etc., can be imparted on textile materials using nanotechnologies to enhance the fabrics' functional performance [23-28].

Next-generation textiles (NGTs) show high priority to meet sustainability demands through using sustainable materials, renewable energy ideas, green technologies, and responsible manufacturing techniques to decrease the environmental impacts on the earth [22]. Recently, technical textiles have found increasing use in water harvesting systems, due to their functionalities, enhanced surface properties and water capture efficiency. They can be easily fabricated into the required configurations, making the devices scalable and adaptable to different environmental conditions. The basic requirements that textile-based water harvesters must fulfill from structural, economic and environmental aspects include high tensile strength, high air permeability, lightweight, large filter area in a small space, physical and chemical stability, high water harvesting efficiency, in addition to low manufacturing cost, low maintenance, and simple construction [29]. Textile-based water harvesters are widely used to collect water from rain, dew, and fog such as nets, screens, and canvases. The porous structure of the textile materials provides a large surface area with a specific feature that allows for a larger interface between the water molecules and the surrounding air [23]. The versatility of textile production techniques has a significant effect on the fabric's structural parameters, porosity, and surface characteristics to capture water droplets, which in turn affect their performance in harvesting water. Woven fabrics are produced by interlacing warp and weft yarns at right angles according to the weave structure, they are characterized by their smooth surface, high mechanical strength, and dimensional stability [30]. Knitted fabrics are characterized by their high porosity and flexibility, they are classified into warp-knitted or weft-knitted fabrics. Warp-knitted mesh fabrics are more stable and widely used as water harvesters. As well, nonwoven fabrics are produced by bonding the fibers together either mechanically or chemically or thermally. Nonwovens offer many distinct technical properties such as high air permeability, large specific surface area, manageable pore size distribution, high filtration properties, and low energy consumption [31]. These unique properties enhance their performance in water collection and filtration capabilities when used in RWH systems.

Moreover, three-dimensional (3D) fabrics have developed as major innovations in the technical textiles market owing to their distinctive characteristics in all three physical dimensions, they can be manufactured through the yarn or fabric architecture. 3D spacer fabrics can be woven, nonwoven, or knitted, they possess many properties such as low density and thermo-physiological properties. Also, they have a wide range of thicknesses from 2-65 mm, and tailor-made tensile, elastic, compression, and permeability properties without using foam, rubber, or other laminating techniques [32]. Innovative woven functional fabrics with different 3D structures such as square, honeycomb, and perforated fabrics have proved to exhibit high water-collecting efficiency [33].

Moreover, textiles can be integrated with other materials such as polymers and nanomaterials to obtain hydrophilic or hydrophobic capabilities which can significantly influence the performance of textile harvester in interacting with water droplets, and improve their water harvesting efficiency. For instance, a novel water-collecting system was developed by coating cotton fabric with Poly(*N*-isopropylacrylamide) PNIPAAm polymer, a thermoresponsive polymer. In lower temperature up to 34°C, the coated cotton has a sponge-like structure and is highly hydrophilic. It can absorb 340% of its weight in water from misty air, compared to just 18% without the PNIPAAm coating. Once the temperature rises above 34°C, the coated cotton becomes hydrophobic and the PNIPAAm coating causes the cotton to completely close, releasing all the absorbed pure water. This process can be repeated multiple times [34,35].

3. Water Harvesting Systems

3.1. Seawater Distillation

About 97% of the water on earth is saline, which means it contains a high concentration of dissolved salts, so it is not suitable for drinking, irrigation, and industrial processes [23]. Seawater desalination technology has steadily emerged as a means of solving the problem of freshwater shortage [36], but it has several disadvantages, including expensive infrastructure, high energy costs, and detrimental effects on the environment [10]. There are many technologies used for the desalination of seawater like membrane distillation, reverse osmosis, multistage flash technology, electrodialysis, and solar-driven evaporation. Solar energy is an environmentally friendly source, it is widely used in seawater desalination owing to its cost-effectiveness, low energy consumption, safety, ease of manipulation, electricity-independent, almost zero carbon emission, etc.[23]. For instance, the Red Sea's coastal regions are presently undergoing seawater desalination to supply enough domestic water for towns and resorts, as the area's unit water value is high enough to offset the desalination cost. Desalination was first implemented in Egypt over a century ago when a sizable distillation tank was built in the Helwan region to provide fresh water for home consumption in isolated parts of public water supply networks. Egypt currently promotes increased building of desalination plants and the use of various technologies by the public and commercial sectors [18].

Interfacial solar steam generation (ISSG) composed of using photothermal materials to strongly absorb solar radiation and transform it into heat. These materials can be incorporated into various structures, including solar stills, solar evaporators, and solar collectors. When photothermal materials are exposed to sunlight, the surrounding water heats up to the boiling point because they absorb the solar radiation. The water evaporates leaving impurities and contaminates, then the vapor is condensed and collected as clean water [28]. To enhance the efficiency of interfacial evaporation, inorganic and organic absorbers are used like semiconductor nanomaterials, plasmonic nanoparticles, metallic nanoparticles, carbon fibers, carbon black, carbon nanotubes and graphene oxide. In textile materials, the spaces between fibers within the fabric are constructed through the arrangement and interlacing of fibers that twist and intertwine with neighboring fibers, making pathways for the movement of steam and water. Nevertheless, the dimensions of the fabric's thickness and porosity are significant factors in determining the water supply. Since, pores with higher dimensions can facilitate better water and steam transportation, while pores with smaller dimensions can augment the capillary forces [23]. Zhang et al. [38] presented an ISSG device composed of a woven fabric manufactured of cotton and carbon fibers blend, the device showed significant capabilities in generating solar systems due to carbon fiber's consistent and effective light-absorbing properties, in addition to the structure of the fabric. The design of the woven fabric's structure can control the levels of light absorption and the quantity of water within the fabric. Under 1 unit of sunlight, the fabric exhibited a notable efficiency rate of 1.87 kg $m^{-2}h^{-1}$ and evaporation efficiency of 83.7%.

Li et al. [39] made a 3D hierarchical tree-shaped biomimetic flax fabric (TBFF) with a basket weave layer and a plain weave layer. The fabric displayed vertical water transport properties along the continuous warp yarns. The obtained fabric was subjected to a one-step fabrication process to produce polydopamine-polypyrrole (PDA-PPy) hybrid nanofibers with a larger surface area and improved hydrophobicity. The fabricated design established an organized structure of micro-capillary porosity within the fibers and macro-interlaced pore spaces across the warp and weft yarns. This unique structure displayed a wide spectrum of light absorption, efficient water supply, large evaporation area, and easy steam leakage. The TBFF-PDA-PPy showed an evaporation rate of 1.37 kg $m^{-2}h^{-1}$ with a solar energy transformation performance of 87.4% when subjected to 1 sun irradiation. Gao et al. [40] presented a novel method that used ramie fabric coated with carbon black and cross-linked sodium alginate (CSRF) to separate the evaporation interface from the bulk water. The yarn fineness in the fabric area created an adjustable water supply system by optimizing the energy distribution. Also, the CSRF fabric showed an evaporation rate of 1.81 kg $m^{-2}h^{-1}$ and 96.6% efficiency when exposed to 1sunlight irradiation.

3.2. Rainwater Harvesting

Rainwater is regarded as the purest kind of water. In recent decades, rainwater harvesting (RWH) has attracted attention in many regions across the world as one of the most effective and affordable ways to conserve water due to the rise in water demands. Rainwater harvesting is a strategy that comprises gathering rainwater using an above tank or other methods [41]. It serves as a primary source of water supply for both potable and non-potable usage due to the lack of sophisticated water delivery systems [42]. RWH system aims to eliminate water waste caused by excessive runoff and transform it into a practical source of income. Also, it reduces the rate of soil erosion.

Precipitation can occur in many different forms, including rain, drizzle, snow, hail, and sleet. Rainfall is the most common type of precipitation and is regarded as the primary source of RWH. Rainwater collection is generally applicable to all types of precipitation. The course of action differs depending on the type of precipitation. In places where the blizzard effect is greater, large amounts of precipitation, such as dew and snow, are sometimes gathered using nets or thin sheets of fabric [41]. There are several approaches for rainwater harvesting and the choice of techniques is made by the amount of rainfall (average annual rainfall), the availability of nearby water bodies, and environmental and climatic factors. The water that is collected is then used for a variety of tasks including domestic chores, gardening, raising animals, raising the groundwater table, etc. Rainwater is typically gathered from an elevated platform with a sloping curvature, and the collected water is then directed into the appropriate storage basins or cisterns [41]. Figure 3 shows an example of the RWH system in house and the harvested water is used for different purposes.

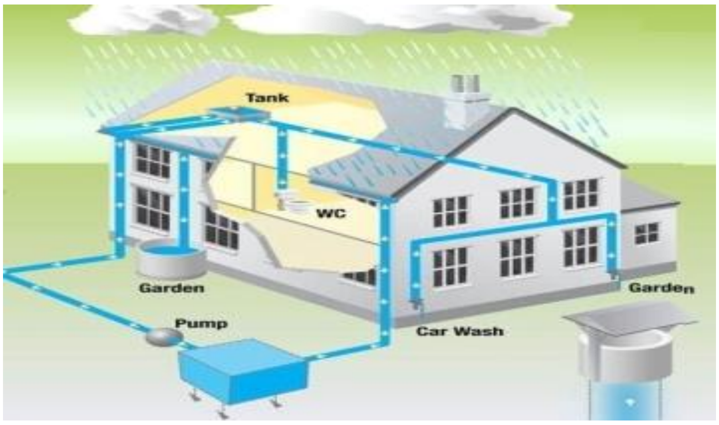


Figure 3. RWH system at the rooftop harvesting for sloped building [43].

Rainwater harvesting systems can be classified into two categories: medium and small, depending on the catchment size. The system of intermediate size gathers precipitation from catchment areas in various locations such as army camps, airports, and educational institutions [42]. Rainwater is collected by small systems from residential roofs. Additionally, water can be gathered from open spaces and kept in basins. Integrating rainwater harvesting technologies with the current traditional water supply infrastructure is the best course of action. This will support the sustainability of the water supply and help to fulfill the growing demands for it. Worldwide, there are still many nations that support the use of collected rainfall for both potable and non-potable purposes such as the United States, Germany, Australia, China, and Japan. There are variations in the amount of rainwater collected based on the locations. For instance, based on a trial operation in Zambia, Africa, 10 m^3 of rainwater were gathered each year [42].

Rainwater harvesting and storage systems (RWHSS) have gained attention and adoption in several countries as self-supply alternatives. Some nations, including China, Brazil, Australia, and India, even mandate the incorporation of RWHSS during the city planning stage for local authority approval. One significant advantage is economic savings, as rainwater is a freely available resource. Once collected, it can be utilized for various activities, either requiring purification or not. These systems typically have a straightforward structure and components, consisting of a catchment area, storage facility, and distribution system. According to the World Health Organization (WHO), certain conditions should be taken into account during the design of RWHSS including; site precipitation, surface catchment area, runoff coefficient, roof material, and water loss in the systems. RWHSS are categorized based on the type of collection surface utilized. There are two main types: in situ water conservation systems such as small water bodies, wells, and embankments) primarily used for agricultural purposes, and runoff-based systems designed for domestic use [44]. It is worth mentioning that rainwater collected from catchment areas (roof and gutter) is usually polluted with dirt, leaves, plant debris, etc. So, rainwater must be filtered before being stored. Filtration can decrease the contaminants and prevent larvae, eggs, and mosquitos from entering the storage. Several techniques are used to filter rainwater, the most appropriate is using geotextiles (woven and nonwoven). Woven geotextiles are used in separation and stability applications, while nonwoven geotextiles are used for areas needing increased filtration. Polypropylene or polyester fibers are typically used in RWH systems [45].

3.3. Atmospheric Water Harvesting

Atmospheric water harvesting (AWH) is a promising technology that can be used to address water scarcity issues and overcome the difficulties associated with long-distance transportation and provision of drinkable water to arid and semi-arid areas [21]. AWH can supply clean water. The atmosphere contains water at all times. Clouds are the most obvious example of atmospheric water, but water is present in even pure air as invisible water particles. The amount of water in the atmosphere at any given time is considered 12900 km^3 or 3100 mi^3. It represents only 0.001% of the Earth's total water content, around 332,500,000 mi^3 (1,385,000,000 km^3). A sudden downpour of all the water in the atmosphere would only cover the Earth to a depth of 2.5 cm or 1 inch. In places unconnected to the centralized water networks such as villages, relief sites, military installations, and other programs. Three primary factors determine the amount of water in the atmosphere namely; relative humidity, air temperature, and total atmospheric pressure (equal to 101.325 kPa). Heat and humidity are the ideal atmospheric conditions for removing water from the air [46]. Figure 4 shows atmospheric water harvesting techniques.

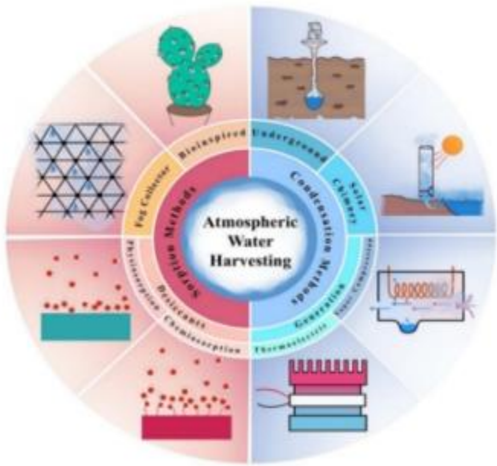


Figure 4. Atmospheric water harvesting methods [2] .

The three main types of AWH are sorption-based approaches, dew, and fog harvesting. In sorption-based technologies, water vapor is extracted from the air using absorbents. The vapor is then released into an enclosed room by heating it and finally, it condenses on a cold surface. Fog harvesting is a physical method that operates effectively under nearly 100% relative humidity (RH) and works with materials that resemble mesh to collect tiny water droplets [7]. Dew is definite as water drops condensed from vapor in the air onto a surface whose temperature is beneath the dew point [38]. The dew point is the temperature at which air must be chilled (while maintaining constant pressure) to reach 100% relative humidity (RH). The air is now at capacity to contain no more water in the gaseous state. Water vapor would escape into the atmosphere in liquid form, typically as fog or precipitation if the air were to cool still further [7,47]. The dew harvesting process involves cooling air beneath the dew point producing water vapor to condense onto surfaces and captured, it is dependent on the weather and the rate of radiative heat exchange [5,7] It is worth mentioning that dew harvesting has the benefit over fog harvesting in which dew needs fewer atmospheric formation conditions [48].

3.3.1. Bioinspired Water Harvesters from Nature

Living in nature may give answers to discovering new water resources. After 3.8 billion years of evolution, many plant and animal species in waterless regions of the world have developed effective methods for gathering water. Water harvesting lessons abound from living nature, it has evolved animals that can live in the world's driest areas by passively gathering water during the night from fog and water vapor condensation. Species have systems to move water for consumption or storage before it evaporates. These animals have special bodily structures and chemistry that allow them to collect and move water [49]. Examples of desert plants and animals that collect atmospheric water from the air will be illustrated as follows.

-Desert Plants

Desert plants might have to endure years at a time without fresh water. Certain plants, such as palm trees (Phoenix dactylifera L.) have developed extensive roots that reach far below the surface to draw water to survive in the arid climate. Examples of other desert plants that have unique techniques for gathering and preserving water are wildflowers like desert lily, blue phacelia/wild heliotrope, California poppy, and Sand verbena, Cacti, other succulents like prickly pear cactus, cholla cactus, and saguaro cactus. Trees and shrubs like the Joshua tree, the Mesquite tree, the ocotillo, and the California fan palm. Also, Grasses, mosses, lichens like Bushman grass, mitten steppe screw moss and lichens (Santessonia hereroensis) [49]. Examples of desert Plants are illustrated in Figure 5.

Prickly Pear Cactus Cholla Cactus Saguaro Cactus

Figure 5. Desert Plants Examples [44].

- Desert Animals

To survive in a desert environment, animals employ a variety of behavioral, physiological, and anatomical adaptations. The Namib desert in southern Africa is among the driest places on earth with an average annual rainfall of just 18 mm. Hamilton and Seely made the first reflection of fog harvesting in the Namib Desert Beetle, Figure 6 (a,b). It was discovered that water seeped into the beetle's mouth from its body. When the beetle collects drinking water from winds containing fog, it angles its body forward, spreads its wings, and exposes the dorsal shell with many bumps to the wind. A haphazard collection of 0.5 mm diameter bumps spaces 0.5-1.5 mm apart makes up the beetle's back. Micro-structured wax covers the surrounding area, while the bumps themselves are smooth. The droplet keeps growing (up to 5 mm) on the bumps until its weight is greater than the force of the capillaries, at which point it separates and rolls down the back of the titled beetle. It is discovered that the background wax is hydrophobic and the bumps are hydrophilic [49,50]. The dimensions of the small water droplets in the air are about 1-40 mm, which is gathered by the hydrophilic bumps on the back of the desert beetle beneath the action of wind. Then, lots of water droplets collect and grow until they cover the whole bump [50]. The flower beetle is another beetle that resembles the Namib beetle and uses a similar method of gathering water. This enormous insect, which reaches a length of 11 cm, is well recognized for its characteristic white and black shield, which is hydrophobic and hydrophilic, respectively [49,51]

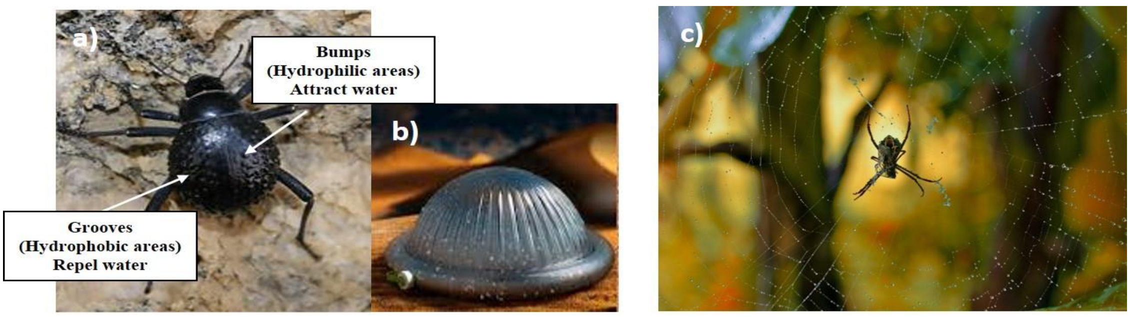


Figure 6. a) The Namib Desert beetle's body structure of bumps and grooves, b) self-filling water container bioinspired by the Namib Desert beetle, and c) spider silk web with water droplets.

Also, spider silk has outstanding mechanical and chemical properties which has inspired people to develop new water collection materials. Every day, water droplets are evenly distributed and stained on the surface of spider silk, as shown in Figure 6(c). Two main axes are made of spider silk nanofibrils, which have a high degree of hydrophilicity and help to collect tiny water droplets in the air, dividing the puff with a particular periodicity. As the mass of water droplets increases, the hydrophilic puff gradually bulges, forming a periodic spindle knot. At this point, the hydrophilic puff's primary function is to collect water rather than condense it, and the joints serve as the primary condensation point [50]. Shang et al. [52] mimicked the unique properties of spider web silk, they created novel heterostructured microfibers with spindle knots and joints using microfluidic technology. The emulsification process of the knots can be precisely adjusted through the flow rate, which allows for controlling the size and spacing of the spindle knots of the microfibers. Certain distinctive features are gained in the resultant microfibers, including humidity-responsive water capture, thermally triggered water convergence, and cell microcarrier arrays, making them suitable for use in various applications.

3.3.2. Fog Harvesting

Fog harvesting is the practice of collecting fog to produce clean water, it has garnered significant interest. The scarcity of fresh water has led to the widespread usage of this technique since it is considered as economical and reliable [14]. In the Middle Eastern desert region, fog harvesting has been a long-standing traditional practice dating back approximately 2,000 years [53].The principle of fog harvesting is when humid air meets a cold solid surface, water particles within the air adhere to that surface, thereby facilitating water collection. Fog collection techniques are primarily employed in regions without access to freshwater, where they are employed for farming and occasionally the provision of potable water. Farmers originally devised the basic concept of harvesting fog when they placed various adjacent cavities and containers around plants to gather water from humid air. Eventually, these approaches evolved into structures that harvested fog [14]. A passive mesh system can be put up to collect fog water in areas where fresh water is scarce and fog frequently occurs [54]. Alongside the introduction of fog harvesting techniques came new materials and structures that offer various options for both the meshes and the harvesting processes [15].

An enhanced fog collector, for instance, was built by first depositing copper particles in situ and then utilizing woven super hydrophobic-super hydrophilic patterned fabric. Combining pristine hydrophilic copper sheet with femtosecond laser-fabricated polytetrafluoroethylene nanoparticles deposited on the superhydrophobic copper mesh, the surface containing micro/nano patterns is generated [20]. Because sorption materials and related devices can function at low relative humidity which is typical for arid environments, they are the focus of attention. Recent advancements in porous adsorbents, like aerogel, metal-organic frameworks (MOFs), manganese oxides, silica, and zeolites have been investigated [7]. The fog harvesting system is based on exposing the mesh directly to the atmosphere, allowing foggy air to pass through it driven by the wind. Larger droplets of fog are formed by combining with smaller droplets that land on the mesh and flow down into a storage tank. Although fog water collection rates vary greatly between sites, active projects typically yield yearly averages ranging from 3-10 liters per square meter of mesh per day [55]. Harvest efficiency is directly impacted by the fiber thickness and the percentage of covered surface. A thinner fiber has a higher efficiency than one that is 10 mm in diameter, but the surface covering cannot fully block the wind to ensure that the wind-carrying fog gets through. The ratio of the total quantity of droplets that pass through the mesh over a predetermined period and the amount of water that reaches the gutter is typically used to determine the mesh's efficiency [15].

Numerous mesh materials have been studied, for example, resilient material that is co-knitted with poly material and a stronger stainless mesh has been tested for extremely windy locations. Alternative collector designs beyond the SFC (Standard Fog Collector) and LFC (Large Fog Collector) have been explored and could offer advantages in specific scenarios. In the rarest of circumstances, when fog is not specifically correlated with any one wind direction, a 3D mesh structure in the landscape might be useful. Examples of 3D collectors are the "Eiffel" collector, which is utilized at some sites in Peru, and a system used in South Africa consisting of 9 panels placed in the shape of four equal triangles. However, a comprehensive comparison of different materials or designs in terms of collection efficiency, aerosol deposition, and economic considerations has not yet been conducted [54]. Raschel mesh is the main material used in fog harvesting applications globally. The mesh is composed of polyethylene with a wire radius and woven spacing ratio that optimizes water collection, Figure 7. On the other side, the shortage of materials in some places prevents the raschel mesh from being used in fog-harvesting structures [54].

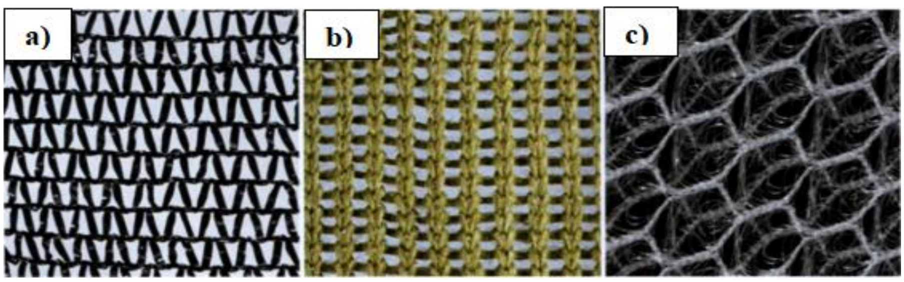


Figure 7. Three mesh types for fog collection: a) Raschel mesh made of double-layered in SFC and LFC applied in 35 countries in five continents, b) a robust material with a stainless mesh, co-knitted with poly material which has been employed in South Africa, and c) a newly proposed design of a 3D net structure (1cm thickness) of poly material [54].

Hadba et al. [14] had made a practical and theoretical evaluation of different types of fog harvesting meshes to characterize their economic, chemical, and physical features and their performance in different conditions. In this study, most of the meshes are made of polyester with Polyvinyl Chloride (PVC) coating, other types are made of polyethylene or polyamide. Jute meshes are more efficient when it comes to coating alternatives, and they have far lower levels of embodied carbon and energy than the majority of the other meshes, even if they appear to have lower fog collection, see Figure 8. The results revealed that jute meshes have lower fog collection efficiencies but also have low environmental impact followed by polyethylene meshes, which are useful in some situations. However, the other meshes with different physical properties have a higher possibility of using as a fog harvesting mesh, can absorb water, and have some good environmental effects, even if they might have bigger economic and damaging environmental impacts if not treated appropriately.

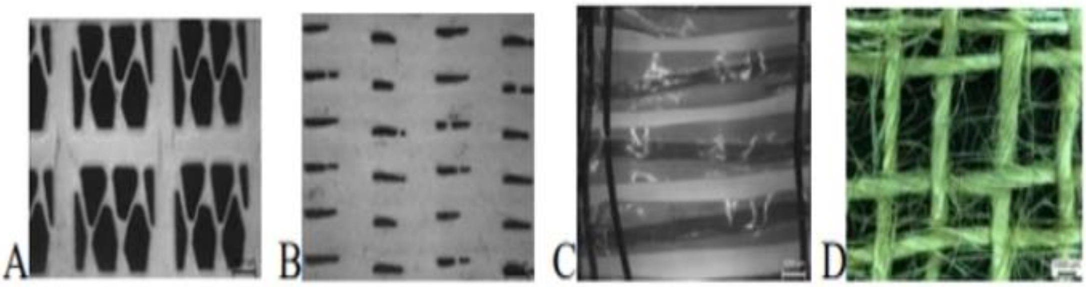


Figure 8. Meshes with different opening areas [14].

High-altitude areas with 100% relative humidity (RH) or areas close to the ocean with adequate wind speed may be suitable for fog collection. The sorption/desorption method using desiccant materials to capture water from the air is highly recommended in tropical buildings. Radiative dew condensation produces a limited quantity of water, but can still be integrated into tropical building structures, such as roofs and car parks to enhance water supplies in the future [10]. The most widely used interception mesh for this purpose is the raschel mesh, a food-safe mesh made in Chile. Triangularly woven polyethylene or polypropylene fibers have a total covered area (shading coefficient) of approximately 35%. Each flat fiber is 1 mm broad and 0.1 mm thick. Droplets can be transported effectively owing to the triangle design. A double layer with the ability to move against one another is utilized to reduce runoff and achieve a shading coefficient of roughly 70%.

Nguyen et al. [20] developed new kinds of vertical filament mesh (VFM) fog harvesters inspired by the water-harvesting abilities of desert beetles and spider silks. Among them are 3D VFM fog harvesters and multilayer 3D VFM fog harvesters. Four different kinds of polymer filaments with different hydrophilic-hydrophobic characteristics were studied. After applying a polyurethane-sodium alginate (PU-SA) mixture solution to the polymer filaments, a simple spraying method was used to produce alternating 3D PU-SA micro bumps on the filaments. The polymer VFMs demonstrated superior fog-harvesting efficiency compared to traditional vertical metal meshes. Additionally, hydrophobic VFM showed to be more effective in fog harvesting than hydrophilic VFM. This innovative approach highlights the potential of biomimetic design and polymer modification techniques to enhance fog harvesting technologies. A significant enhancement in fog-harvesting performance (increased by 30–80%) was achieved by applying a mixed PU-SA solution through spraying to create a 3D geometric surface structure (resembling the rear surface of desert beetles) known as 3D PU–SA micro bumps on all VFMs, Figure 8. This increase in the efficiency was due to the 3D micro bump structure's improved synergistic effects on fog collection, droplet growth, and droplet shedding. With a maximum efficiency of 287.6 mL/m^2/h, the four-layer PTFE 3D VFM with the type B PU−SA bump surface (bump/PU−SA) was found to be the most efficient configuration. The proposed polymer VFMs have high fog harvesting efficiency and are also very stable, cost-effective, rust-free, and simple to install in real-world applications. These benefits are attributed to the elasticity of polymer filaments [20].

Wasti et al. [56] examined new developments in a range of adsorbent materials, such as solid (MOFs, silica-gels, and zeolites), liquid ($CaCl_2$ and LiCl), and composite adsorbents, by investigating their ability to produce water under various air temperatures and relative humidity (RH) conditions. At RH ranging from 10–40%, the MOF of type MIL-101(Cr) has a water production capacity of 3.10 L/m^2/day. Similarly, Zr-MOF-808 can produce 8.60 L/m^2 of water per day with RH of over 50%. Mesoporous silica gel has the greatest capacity for producing water, 1.30 L/m^2/day under RH ranging from 10 – 40%. The zeolite produced 0.94 L/m^2/day of water between 10% and 40% RH levels. However, at an approximate RH of 70%, liquid adsorbents such as K-LiCl and $CaCl_2$ demonstrated a water production capacity of 2.9 g/g/day and 3.02 L/m^2/day, respectively. At roughly 35% RH, a composite adsorbent treated with binary salts and functionalized carbon nanotubes produced 5.60 g/g of water. So, finding an energy-efficient adsorbent will help to develop a sustainable AWH device.

Abualhamayel and Gandhidasan [57] investigated the efficiency of two sizable fog collectors, each measuring 20 m wide by 2 m high with a surface area of 40 m^2, with bases 2 m above the ground to increase the exposure to wind, see Figure 9. As illustrated, the large fog collectors (LFCs) are flat rectangular meshes, woven in a triangular pattern and their surface is made of black polypropylene mesh with a single layer of the mesh fibers covering 35% of the whole area. These meshes are tightly secured to the LFC frame in a double layer. The LFCs are positioned perpendicular to the direction of the wind and supported by posts at both ends. The structural stresses caused by the wind, humidity, and friction between components are all intended to be tolerated by the LFC panels. The results showed that the maximum daily collection of fog water from the LFCs are 598 L and 473.8 L, respectively. The chemical analysis revealed that the water's quality met WHO drinking water requirements, making it suitable for human consumption.

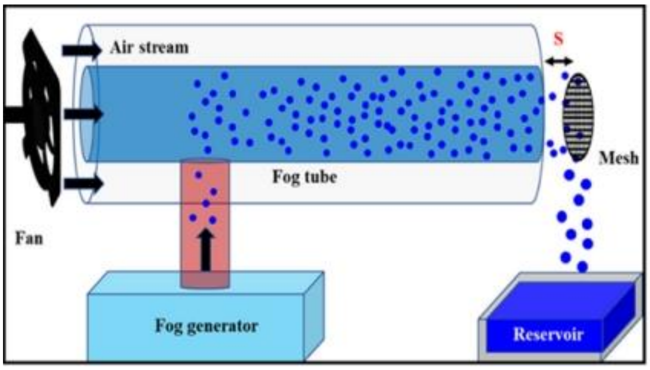
Figure 9. The LFC at the Glider Club site [57].

Liu et al. [58] pointed out that in the context of future practical applications, the use of a proposed meta surface, combined either with grooves or with surfaces featuring a cascading effect, could optimize water collection performance and approach the limit of 'zero pinned water. Leveraging the remarkable optical emissivity of Black Silicon, especially in the infrared range within the atmospheric window frequency band, a 1m^2 meta surface panel could passively provide over 1 liter of water per night without any energy consumption. This quantity is significant for drinking water or irrigation purposes, particularly in regions facing freshwater scarcity or water pollution issues. Despite being covered by condensation; the radiative cooling performance of the proposed panel can still be maintained due to water's high emissivity in the atmospheric window. Typically, an open radiative cooling system with good thermal insulation can anticipate a cooling effect of 5-10°C. Thus, achieving subcooling similar to that of black silicon panels cooled by Peltier coolers through radiative cooling seems feasible in practice. Moreover, the proposed meta surface requires only 10 minutes of processing time per equipment, making it highly suitable for mass production. With its advantageous processing, optical properties, and wetting, the silicon-based meta surface holds great potential for designing great-area panel-like platforms, for example, highly efficient water harvesting panels based on radiative cooling, self-cleaning solar panels, or even dual-function panels for water and energy harvesting in nighttime and daytime, respectively.

Metal-organic frameworks (MOFs) are crystalline porous materials with well-defined intramolecular pores that are created into 3D interconnected networks through the coordination bonds between organic ligands and metal ions or clusters. Due to the intriguing properties of their porous structure and chemistry, they have been widely used in AWH, because a large number of possible sorption sites for water molecules can be provided by their extremely porous structure. Three different mechanisms cause water sorption in MOFs: capillary condensation when the pore size is bigger than the critical diameter of water, physisorption in the form of layers or clusters, and chemisorption on open metal sites. It is possible to modify the sorption/desorption behaviors of MOFs by adjusting their geometry, pore size, and hydrophilicity. By altering the metal nodes and organic ligands with various functional groups, MOFs' hydrophilicity can be adjusted. The adsorption isotherms moved to a lower relative pressure value as the hydrophilicity of MOF increased, suggesting that the adsorption process can take place at a lower RH [59]. Yilmaz et al. [59] introduced a polymer-MOF to harvest atmospheric water using MIL-101(Cr). At 90% RH, they generated 6 grams of fresh water per gram of adsorbent per day. Rieth et al. [60] studied MOF-Co_2Cl_2BTDD, at 30% RH, this MOF can absorb 82 wt.% of water. After analyzing how various MOFs absorbed moisture, Trapani et al. [61] presented UiO-66 as the top option for air-to-water conversion. A total of 0.054 g of water was collected for every gram of MOFs after the water absorption tests were conducted at 25 °C and 40% relative humidity, and the desorption process at 45 °C and 10% RH.

Cao et al. [62], developed a cactus-inspired fog collector with a 2 cm diameter through combining hydrophobic conical micro-tip arrays, which mimic the spines of cactus with a hydrophilic cotton matrix. This cactus-inspired fog collector was able to collect roughly 3 mL of water every 10 minutes at a typical fog velocity of 45–50 cm/s. Kang et al. [55] have attempted to enhance fog harvesting efficiency by adjusting mesh wettability. However, the impact of wettability on water collection from white plumes, particularly in industrial settings like cooling towers where significant fog plumes are generated, remains largely unexplored. The study experimentally investigated the effect of modifying mesh wettability on atmospheric and industrial fog harvesting. Results showed that in atmospheric fog harvesting, both super-hydrophilic meshes (SHPMs) and superhydrophobic meshes (SHBMs) enhance harvesting performance with SHBMs demonstrating the highest collection efficiency. Conversely, in industrial fog harvesting, using flat mesh screens, only super hydrophilicity improves performance. Successful modification methods included creating hierarchical micro/nanostructures after treatments with

NaOH solution and hot water, and applying (heptadecafluoro-1,1,2,2-tetrahydrodecyl trichlorosilane $C_{10}H_4Cl_3F_{17}Si$) HDFS self-assembled monolayer (SAM) coating. Super-hydrophilic (SHPM) and superhydrophobic (SHBM) meshes both performed better than the original mesh in atmospheric fog harvesting in terms of collection efficiency. SHBMs were particularly effective due to their ability to maintain aerodynamic characteristics and prevent clogging. Conversely, in simulating cooling towers for industrial fog harvesting, super hydrophilicity proved more effective as it minimized gravity-induced draining loss. These results guide the design of fog-harvesting mesh screens, taking into account how changes in mesh wettability affect the efficiency of water harvesting in a wide range of atmospheric and industrial applications [63], see Figure 10.



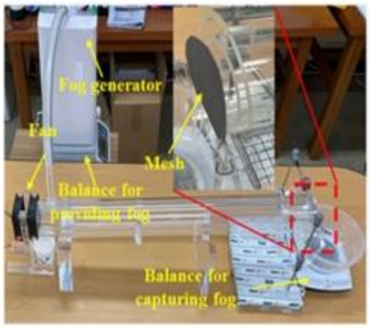


Figure 10. Schematic (left) and image (right) of an experimental setup for simulated natural fog harvesting [63].

The collection of fog in industrial cooling towers has not gotten much attention. The collector screen structure is highly affecting its harvesting performance, and only flat meshes have been taken into consideration in previous studies. In this regard, Kim et al. [6] designed an economical and simple method for collecting freshwater to address water shortage problems. They proposed that the modified collector structures improve harvesting performance in industrial cooling towers. To enhance the performance of fog collection, the structure of the fog collector and mesh surface properties were modified. The screen shape was modified in three steps; a concave shape was used for the mesh to increase the aerodynamic characteristics of the collection structure. Then, a sidewall was constructed to gather extra fog produced from defected flows caused by the concave structure. Finally, the discharge direction of the fog flow was changed to resemble naturally occurring flows that are dense with fog to minimize loss during the draining of collected water droplets. The harvesting performance of commercial Aluminum (Al) meshes with wettability modification was experimentally evaluated. In this study, the modification process involves immersing the Al mesh in sodium hydroxide solution, followed by etching in a hydrochloric acid solution which creates hydrophilic surface. This super hydrophilic mesh was coated with a self-assembled monolayer single (SAM) using n-hexane and heptadecafluoro-1,1,2,2-tetraphydrodecyl trichlorosilane ($C_{10}H_4Cl_3F_{17}Si$, HDFS, Gelest) to obtain a superhydrophobic mesh. The results showed that the concave shape increased the drag coefficient, enhancing fog harvesting performance compared to a flat mesh.

Moreover, a novel fog harvester known as the cloud harvester developed by Choiniere-shields, see Figure 11. It is designed to convert condensed fog into water droplets. It suits for use in poor, rural, mountainous or coastal areas that have limited freshwater resources. Unlike traditional fog collectors that use polypropylene nets, the cloud harvester employs stainless steel mesh and includes an additional sheet beneath the mesh for collecting water. This design aims to enhance the condensing efficiency and offers more compact solution compared to similar products. The cloud harvester can collect fresh water up to 1 liter/hour for each 10 square feet of mesh [64].

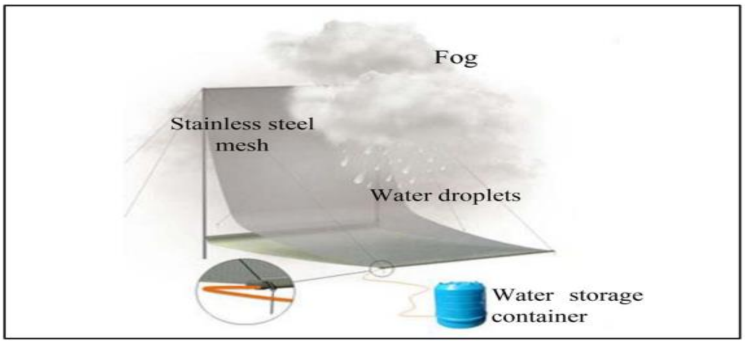


Figure 11. The cloud harvester is designed to catch fog and condense it into water droplets which in turn run down on a stainless steel mesh in a gutter-type extrusion leading to a water storage container [64].

Park et al. [65] studied the effect of surface wettability features, length scale and weave density on the efficiency of woven meshes for fog harvesting. They developed a combined hydrodynamic and surface wettability model to investigate the overall fog collection effectiveness. Two specific constraints on surface wettability affect the re-entrainment of collected droplets and blockage of the mesh openings, Figure 12. They determined that more effective fog collection will result from properly adjusting the surface wetting characteristics, reducing the wire's radius, and improving the wire spacing. They used a family of coated meshes that showed improvement in fog collection efficiency up to 5 times higher than that of conventional polyolefin meshes.

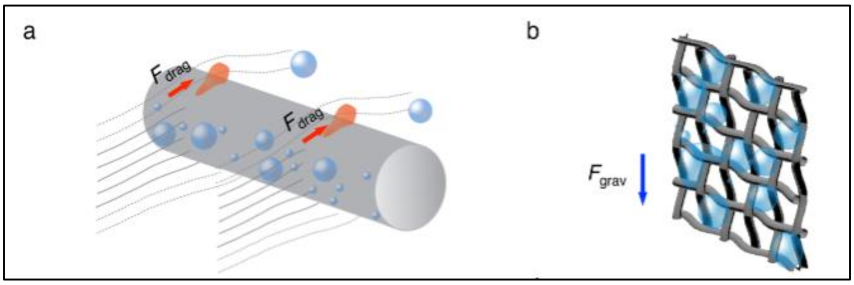


Figure 12. Factors affecting fog harvesting and reducing the collection efficiency ; (a) the re-entrainment of collected droplets in the wind and (b) blockage of the mesh [65].

Azad et al. [66] investigated the influence of microstructures and/or surface wettability on the efficiency of fog collection for three distinct mesh samples. Compared to smooth surfaces, surfaces with fine microstructures and various coatings may exhibit noticeably different wetting behaviors. Thus, the three mesh samples were produced with different materials and surface properties namely; replica (with and without microstructures), copper wire mesh (smooth and micro-grooved), and polyolefin mesh (hydrophilic, superhydrophobic and hydrophobic), see Figure 13. It was found that the super hydrophilic mesh exhibited more efficiency in water collection compared to the other mesh samples, it collected five times more water than the hydrophilic polyolefin mesh, and 2 times higher than the hydrophobic mesh. Water collected 2-3 times higher in the microstructured plant replica than in the smooth surface of the unstructured replica samples. Furthermore, compared to smooth wires, the micro-grooved copper wire mesh collected water more quickly.

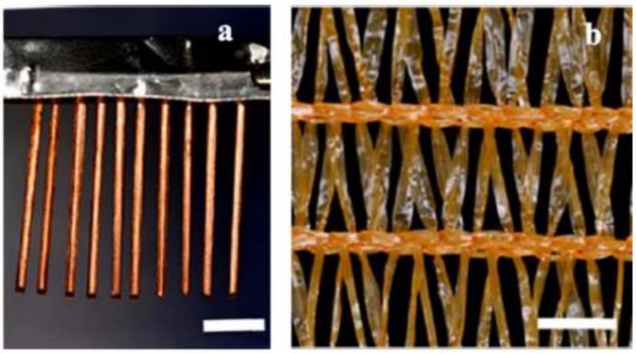


Figure 13. (a) Copper comb sample and (b) polyolefin mesh (double layered) scale bar 1 cm [66].

3.3.3. Dew Harvesting

In certain arid/semi-arid regions, dew water collection, a non-conventional source help to compensate for water shortages. [67]. Under humid weather conditions on clear nights, radiative cooling can decrease the temperature of leaves below the dew point causing dew point formation on the surface of leaves [68], see Figure 14(a). Dew harvesting technologies have raised great interest in the past few years, as they present a promising cost-effective candidate for a supplementary resource of water. Dew formation includes two stages; nucleation and growth. In contrast to homogeneous nucleation, heterogeneous nucleation involves the condensation of water vapor on a substrate, which can lower or even suppress the energy barriers. Regarding the formation conditions necessary for dew, the first crucial step toward achieving effective dew harvesting is rapid nucleation at a surface. The temperature difference between the substrate and the surrounding atmosphere is the first important factor influencing the nucleation rate. Owing to this feature of dew formation, the design concept of effectively cooling the surface below the dew point is proposed for dew harvesting. Passive radiative cooling is the most suitable methodology that doesn't require advanced technology or outside energy sources. The idea behind this technique is based on emitting infrared radiation from a surface at night tends to exceed the radiation absorption from the ambient environment, resulting in lower surface temperature that is lower than the surrounding air. When daytime comes and more water moisture enters the atmosphere, dew forms at the surface, with this idea motivating research on low-emissivity material [38].

Arturo Vittor and his group have created water towers to harvest clean drinking water from the air, Figure 14(b). The tower is constructed from locally available materials without the need for scaffolding or power tools. Bamboo was chosen for the frame structure and 100% recyclable biodegradable mesh was used to create the water catchment system. Rainwater, dew, and fog will gather when they hit the mesh and trickle down a funnel into a reservoir at the bottom. The lower portion of the water collector will be covered with a cloth canopy to stop water from evaporating. Nonetheless, the project's goal was to generate between 50 and 100 L of water per day from fog or extremely humid environments [69] [70].

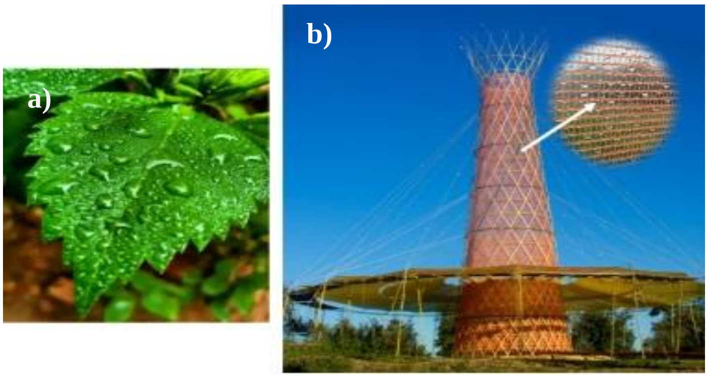


Figure 14. a) Dew drops on leaves, and b)Warka water tower made of bamboo and a biodegradable plastic grid to harvest dew.

Carvajal and Minonzio [71] evaluated dew water harvesting in Combarbalá, Chile, over a year using a painted galvanized steel roof as the collecting surface. Aluminosilicate mineral-containing paint with a high infrared emissivity was applied to the 36 m² roof. The dew yield and its relationship with meteorological variables were analyzed. The findings showed that dew collection happened on 56.1% of the days that were recorded, despite the low overnight relative humidity that was experienced throughout the year (average: 48%). With a maximum of 15 liters collected per day, the average daily collection rate was 1.9 liters. The maximum daily dew yield has a weak correlation with wind speed and air temperature and a strong correlation with relative humidity. Considering that the same rooftop can collect both dew and rain, it was estimated that over one year, dew water could contribute to roughly 8.2% of the total water collected from both sources.

Alnaser and Barakat [72] examined the efficiency of polyethylene, glass, and aluminum foils in collecting dew. Out of all the materials, the aluminum sample recorded the highest collection rate, measuring 1.3 $Lm^{-2}h^{-1}$. Different designs, such as film-based, nanoparticle-based, or photonic radiators were swiftly developed as interest in passive radiative cooling increased, leading to a more effective cooling process [73]. Moreover, active condensation has attracted attention, although external energy is normally input into the systems. Active condensation based on keeping the surface cool for a longer time than passive ways by integrating the surface with a cooling system. To achieve a greater water harvesting efficiency, designs combining dew condensation with water extraction from the air were integrated in addition to passive radiative cooling and active condensation [38]. Surface properties are other parameters that influence the dew harvesting efficiency. Varanasi et al. [74] examined dew condensation capability on surfaces that have alternating hydrophobic and hydrophilic regions, it was found that the water droplets condense on the hydrophilic regions due to the lower energy barriers.

Lee et al. [75] found that, in comparison to moderately hydrophobic surfaces, whose areas were both 9 cm^2, the hydrophilic surfaces could condense roughly 30 mg/hour more water. Chen et al. [76] designed a two-tier surface inspired by lotus leaves, Super-hydrophobicity may remain on the surface both prior to and following dew condensation. The structure gave water droplets greater mobility and the ability to remain in Cassie's state for extended periods. As well, nanotechnology has been used for dew harvesting purposes by modifying the surfaces to obtain more micro/nanostructures to achieve the superhydrophobic property. Hou et al. [77] examined the dew harvesting effectiveness of biophilic structured surfaces made up of superhydrophobic substrates and nanoscale hydrophilic bumps that were inspired by the lotus effect and desert beetles. It was observed that the superhydrophobic surface would eventually eject the condensed and clumped water droplets on the hydrophilic bumps. In a dry environment, the biophilic surface outperformed the state-of-the-art superhydrophobic surface with an 184% heat transfer coefficient and a 349% water collection rate. Thus, dew harvesting represents a promising alternative as a supplementary water source. Dew water collected can be used for various purposes, including human consumption, crop irrigation, livestock feeding, recovery of native flora and fauna, and household water savings, etc. [71].

4. Conclusion

Water scarcity is a major global challenge, the diverse range of water harvesting techniques examined with the utilization of textile materials highlights the versatility and adaptability of these materials to overcome the shortage of water resources. It is an advancing step towards achieving environmental sustainability since it uses new renewable resources and reduces dependence on traditional water sources. Advancements in functionalization strategies such as surface modifications and coatings have significantly enhanced water capture capabilities, representing a substantial rise in improving the efficiency of water harvesting. This paper provides an overview of new sustainable solutions to overcome this issue including rainwater harvesting, seawater desalination, and innovative methods for harvesting water from the atmosphere. In addition, the combined designs of advanced textile technologies with water harvesting methods provide promising solutions for diverse climatic conditions in arid and semi-arid areas.

The paper illustrated various types of textile-based water harvesters used in water harvesting systems produced with specific materials and functional properties to enhance their performance. In seawater distillation systems, textiles are designed to promote condensation and collection of water under effect of solar energy. Rainwater harvesters are often designed to maximize the collection of rainwater by using specially engineered woven or nonwoven fabrics with filtration capabilities. Fog harvesters are mesh structures with enhanced surface wettability properties for the capture of fog droplets, the mesh collects fog droplets as they pass through, and gravity or other mechanisms help to direct the collected water into storage. Dew harvesters are designed to make dew droplets condense on the textile mesh harvester by creating conditions that make the textile's surface temperature lower than the dew point by using passive radiative cooling.

Hence, technical textiles represent a transformative approach to harvesting water, providing a sustainable and innovative path to overcome the problem of water scarcity. around the world.

Finally, researchers, academics, and industry players should consider and raise awareness about the importance of finding new sustainable sources of fresh water, which represents a qualitative rise in water resources management. More research work is needed for enhancing water harvesting efficiency using textile-based harvesters to widen their industrial application in the rural and urban societies.

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