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Review

Fog Harvesting: An Effective Solution to the Water Scarcity Problem

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ABSTRACT

Fog harvesting, also known as fog collection, is a sustainable approach to addressing water scarcity which captures water droplets from fog, providing a renewable water source for water-scarce regions. The aim of this study is to give more background about fog harvesting by introducing fog harvesting systems, their advantages and disadvantages, real world and laboratory projects and efficiency. This study emphasizes fog harvesting's potential in arid regions with frequent fog occurrence, discusses working mechanisms, and explores nature-inspired and nanotechnology-based fog collectors. Local climate data's importance for feasibility assessment is highlighted, along with the vital role of community involvement for long-term success. Fog harvesting offers a promising and environmentally friendly solution to alleviate water scarcity challenges when combined with innovative strategies and community engagement. Real-world projects have shown that fog water collection can be an effective and sustainable solution, particularly in regions with persistent fog and limited water resources. However, more work is needed on innovative fog collectors and advanced materials to increase sustainability.

1. Introduction

In the modern world, there is an ever-increasing need for clean and sustainable water. Unfortunately, many regions struggle to meet the increasing demand for water, and in some areas, its inferior quality limits its usability [1]. There are several factors contributing to this global pressing issue, including rapid population growth, ineffective water management practices, and inadequate infrastructure. Moreover, the looming threat of climate change is expected to worsen the situation further [2, 3]. As a result, addressing the challenge of water scarcity and ensuring access to safe water for all is becoming increasingly critical. Sustainable water management practices and measures are urgently required to confront this growing crisis. Alternative water sources such as desalination, rainwater harvesting, groundwater collection, and fog harvesting are being studied and implemented worldwide to combat this issue [4, 5].

Fog harvesting, also known as fog collection, provides a renewable and sustainable water source for regions with limited access to conventional water supplies [6]. This technique is particularly vital for communities in arid or semi-arid regions and mountainous terrains, where traditional water sources such as rivers, lakes, and underground aquifers may be scarce or unreliable and where fog is a frequent occurrence [7]. These systems are installed in coastal and mountainous areas where fog presence is naturally high.

This technique involves the use of specialized nets or meshes, known as fog collectors or fog catchers, placed strategically in areas where fog

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formation is prevalent. These structures capture tiny water droplets suspended in the fog, which then accumulate and drip down into collection troughs. The collected water is then directed into storage tanks or reservoirs for immediate use or future distribution [8]. The effectiveness of fog harvesting systems largely depends on the design and efficiency of fog collectors [9]. However, the most commonly used for collectors, such as vertical mesh nets, have certain limitations. These collectors often experience reduced efficiency due to issues such as water droplet runoff, clogging, and low collection rates [10]. Consequently, there is a need for innovative techniques and materials that can overcome these limitations and improve the overall performance of fog collectors.

To address these challenges, researchers have explored various strategies to enhance fog collection efficiency [11–13]. Many researchers have focused on the optimization of the materials and coatings used in fog collection systems making it easy to harvest water under light fog conditions [14]. By developing hydrophilic-hydrophobic pattern coatings or modifying mesh surfaces, researchers have aimed to increase droplet capture rates and minimize water loss through runoff or evaporation [15, 16].

Additionally, advancements in fog characterization techniques have provided valuable insights into the properties of fog. Studying parameters such as fog droplet size distribution, fog density, and fog water content enables researchers to better understand fog behavior and optimize fog collection systems accordingly [17].

With the improvement of materials science, technology, and understanding of fog dynamics, fog harvesting has evolved significantly over the past few decades. Numerous experimental projects and real-world applications have been implemented in diverse geographical locations, from foggy coastal areas in Chile and Peru to mountainous regions in Morocco and Nepal. These projects vary in scale, ranging from small community-based initiatives to larger-scale installations supporting entire towns [18]. By examining these ongoing initiatives, we can gain valuable insights into the adaptability and potential limitations of fog water collection in various settings.

This study is aimed at exploring the principles, applications, challenges, and benefits of fog water collection, shedding light on its significance in addressing the global water crisis and promoting environmental conservation. The originality of this work is to raise awareness of the potential of fog harvesting as a sustainable and scalable solution to water scarcity problems by critically examining existing research, case studies, and real-world applications as well as literature.

A Mini Database Based Review

In this section, the Web of Science (WOS) database was reviewed in terms of publication year, origin, highly cited papers and their motivation, and disciplinary categories for the "fog harvesting" keyword.

When the number of WOS publications is examined by year, it has been observed that interest in the subject has increased systematically in the last decade as seen in Figure 1.

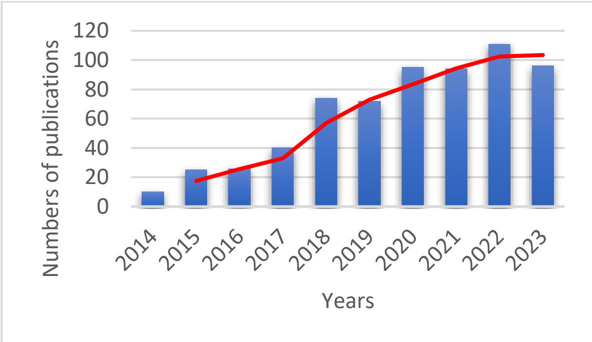

Figure 1. Numbers of publications by year

Considering the number of publications, the most published disciplinary categories (number of publications) according to WOS are as follows: Materials Science Multidisciplinary (206), Chemistry Physical (135), Chemistry Multidisciplinary (108), Nanoscience Nanotechnology (103), Physics Applied (85), Environmental Sciences (69), Water Resources (44), Engineering Chemical (42), Physics Condensed Matter (38), and Energy Fuels (37). As can be seen here, fog harvesting and technologies are a versatile and multidisciplinary subject.

The origins of the publications in the WOS database are listed as follow in the form of Country (publication number) as China (288), USA (122), England (42), South Korea (35), India (33), Germany (31), Australia (26), Saudi Arabia (23), France (22), and Canada (21). It can be concluded that significant parts of the studies are carried out by China and USA.

Yu et al. (2022) have provided in-depth information about design basics and production technologies of fog harvesting devices [19]. Tu et al. (2018) comprehensively reviewed current developments in atmospheric water harvesting technologies [20]. Song et al. (2023) conducted a comprehensive study on the controlled wettability of surfaces [21]. Wu et al. (2021) reviewed the recent advances in special membranes, which include both hydrophobic and hydrophilic structures, to control surface wettability [22]. Shi et al. (2021) focused on the membrane technologies for water harvesting [23]. A (PVA)/polypyrrole (PPy) based hydrogel membrane, which is effective in both fog collection and purification stages, has been developed. Yin et al. (2017) obtained a hybrid superhydrophobic-hydrophilic surface by coating the copper network with polytetrafluoroethylene nanoparticles [24].

Fathieh et al. (2018) designed a system to produce water from desert air [25]. LaPotin et al. (2019) and Zhou et al (2020) drew attention to absorbent materials that can be used in atmospheric water harvesting systems [26, 27]. Additionally, LaPotin et al. (2019) focused on modeling of a solar thermal water harvesting system in presence of adsorbent [26]. Kim et al. (2017) designed a metal-organic based porous framework that take up water from the atmosphere at ambient conditions [28].

The most cited fog harvesting papers in the WOS database were also examined. These studies can be summarized as reviewing current knowledge, focusing on wettability and surface properties, designing a system/device and modelling operating conditions as in seen in Table 1.

Table 1. The most cited papers and their motivations

Author (Year)	Reference	Working area
Yin et al. (2017)	[24]	Material
Fathieh et al. (2018)	[25]	Design
Tu et al. (2018)	[20]	Review
LaPotin et al. (2019)	[26]	Modelling
Kim et al. (2019)	[28]	Design
Zhou et al (2020)	[27]	Material
Wu et al. (2021)	[22]	Material
Shi et al. (2021)	[23]	Material
Yu et al. (2022)	[19]	Review
Song et al. (2023)	[21]	Material

2. The Principles of Fog Harvesting

2.1. Fog harvesting system

The principles of fog collection focus on capturing tiny water droplets from fog using specialized materials and surfaces. A basic fog harvesting system comprises fog collectors, collecting channels or troughs, storage tanks, and a distribution network. Depending on the intended use of the collected water, a treatment component may be included. The primary components of the system are the fog collectors, typically constructed from meshes made of materials like nylon, polyethylene, polypropylene, or high-density polyethylene. The material choice depends on factors such as cost, durability, and local availability [29].

The most common type of fog collector in fog water harvesting is the vertical, rectangular panel, offering dimensions of approximately 4 meters in height and 10-12 meters in length, providing an extensive surface area for capturing fog droplets. For different applications, fog harvesting systems may use either standard fog collectors (SFC) or large fog collectors (LFC).

The SFC, with a fog-collecting area of 1.0 square meter, is primarily utilized for research purposes. Conversely, the LFC, boasting a panel surface area of 40 to 48 square meters, is extensively employed in various fog harvesting projects [30]. Fog collectors exhibit flexibility in terms of installation options, as they can be affixed to various support structures such as wooden or metal poles, concrete pillars, or existing buildings as shown in fog harvesting system in

Figure 2 [18]. The choice of support structure depends on factors such as terrain conditions, material availability, and local considerations [31]. Additionally, certain fog collectors are designed to be collapsible or portable, facilitating easy transport and installation. This portability allows for their disassembly and reassembly at different locations, making them well-suited for temporary deployments or research ventures [32].

2.2. Fog collection mechanism

The mechanism of fog collection involves two main stages: fog-capturing and liquid transport as shown in Figure 3 (a) and (b) respectively [33]. During the first stage, fog droplets are captured either during a fog event or through condensation on the solid mesh surface of the fog collector. This occurs through two mechanisms: capturing droplets from fog during a fogging event and collecting dew condensed on surfaces with temperatures below the atmospheric dew point [34].

As wind-driven fog passes through the strategically positioned mesh, the water droplets present in the fog deposit on the mesh surface [35]. Over time, these deposited droplets accumulate and combine to form larger ones, which then fall under gravity into the trough below the panel. Alternatively, when the surface temperature drops below the dew point of the surrounding air, water vapor in the atmosphere condenses into droplets on the surface. Fog collectors designed to promote condensation effectively capture this dew, which eventually accumulates and flows into collection points [9, 34].

In the second stage, the captured water droplets need to be efficiently transported from the mesh surface to a central collection point, such as a trough or gutter, from where they can be directed to storage tanks or reservoirs. This liquid transport is primarily achieved through gravity-driven flow. As water droplets accumulate and coalesce on the mesh surface, they gain sufficient mass to overcome the surface tension and flow down the mesh under the force of gravity [9, 36]. The mesh is strategically designed to allow water to flow towards the collection channels, ensuring a steady and controlled movement of the captured water [37].

The collecting channels or troughs are positioned below the fog collector panel to catch the falling water droplets. These channels are designed to efficiently channel the water towards a centralized point, where it can be collected and further directed for storage or distribution.

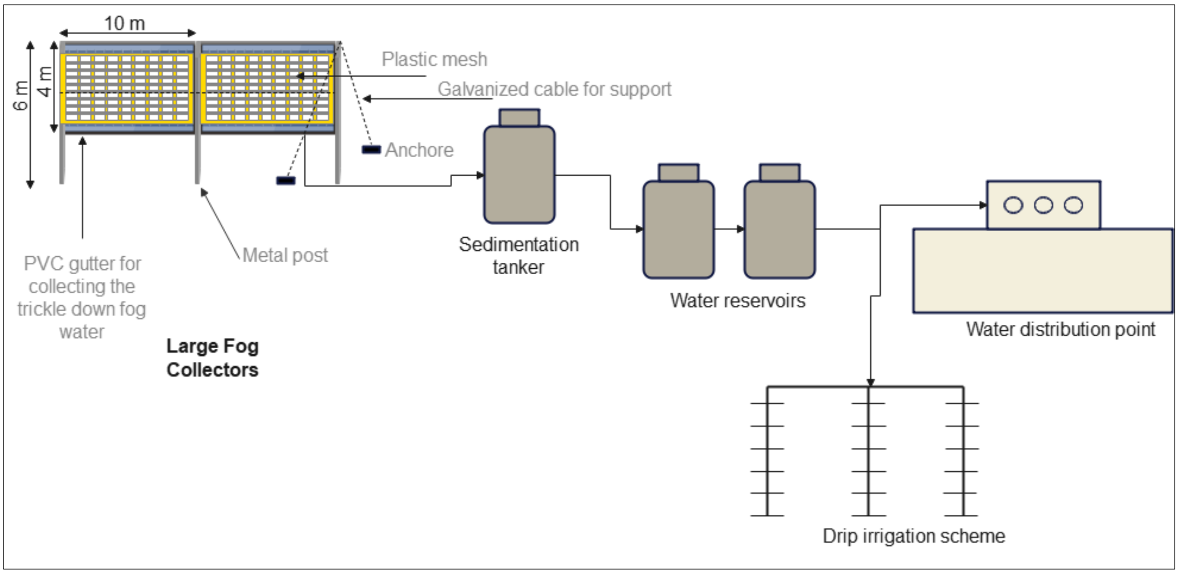

Figure 2. Fog harvesting system [18]

The efficiency of fog collection depends on various factors, including the wettability and topography of the surface, the air-liquid fraction, and the drop mobility derived from the optimization of superhydrophobic properties [37]. Properly designing and managing these aspects contribute to maximizing water yield and optimizing the overall performance of the fog harvesting system.

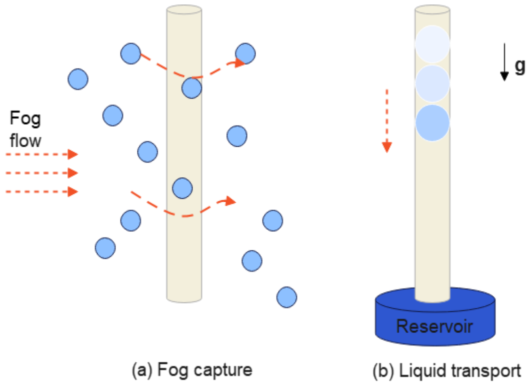

Figure 3. Schematics of the two key steps of fog collection. (a) Fog capture process. (b) Captured liquid transport process [33].

3. Advantages of Fog Water Collection

Fog water collection offers several compelling advantages as a viable and sustainable water resource, making it an increasingly popular solution in regions facing water scarcity challenges. One of its primary benefits is the provision of an alternative water source, reducing reliance on traditional sources such as groundwater. As climate change and increasing demand put pressure on conventional water supplies, fog water collection offers a complementary and reliable source, particularly in areas where fog is a frequent occurrence.

The simplicity and low operating costs associated with fog water collection technology make it an attractive option for communities with limited financial resources. The infrastructure required is minimal, and the systems are easy to maintain, enabling cost-effective implementation and operation. This affordability enhances accessibility, making fog water collection a feasible option for marginalized communities and remote areas where establishing extensive water infrastructure may not be practical or economically viable [19].

Moreover, fog water's inherent cleanliness and freedom from pollutants make it a valuable resource for various applications, including domestic use, irrigation, and livestock watering. In comparison to other water sources that may require extensive treatment, fog water often meets high-quality standards directly after collection, saving costs and effort in purification processes.

Fog water collection's suitability in arid and semi-arid regions is particularly advantageous, where rainfall is scarce, and traditional water sources may be unreliable. By harnessing fog, communities in these regions can enhance their water security, ensuring a steady supply even during prolonged dry periods [38].

The versatility of fog water collection is reflected in its diverse design options. From traditional mesh-based fog collectors to cutting-edge systems featuring advanced materials and technologies, fog water collection can be tailored to suit specific environmental conditions and water demands. The adaptability of these designs ensures efficiency and effectiveness across various geographical locations [39].

As a sustainable and environmentally friendly solution, fog water collection operates on natural processes without the need for energy-intensive infrastructure or chemical treatments [40]. This aspect aligns with global efforts towards sustainable water management and conservation, contributing to environmental preservation and reduced carbon footprints [29].

Fog water collection's capacity to supplement existing water supplies, such as rainwater harvesting or groundwater pumping, adds an additional layer of resilience to water management strategies. By diversifying water sources, communities can better withstand fluctuations in rainfall patterns and other climate-related uncertainties.

Moreover, fog water collection supports reforestation efforts, providing water to ridge lines and mountainous regions where importing water from conventional sources may be impractical. This promotes forest growth and ecological restoration, contributing to ecosystem health and biodiversity conservation [35].

Properly designed fog water collection systems can produce water that meets drinking water standards set by organizations like the World Health Organization (WHO) [41]. This ensures that the collected water is safe for consumption, further enhancing its value as a reliable and potable water source for communities.

4. Real-World Fog Harvesting Projects

Real-world fog harvesting projects have demonstrated the practicality and potential of this technology in providing a sustainable water source in regions facing water scarcity. Governments, NGOs, and researchers collaborate to implement fog harvesting systems and study their effectiveness in different climatic conditions [34].

Table 2. Number of foggy days for some countries [18, 42]

Countries	Foggy days per year
Cape Verde, Serra Malgagueta	365
Peru, Mejia	210
Canary Islands, Tenerife	354
Chile, Alto Patache	365
Eritrea, Arborobu	166
Guatemala, Tojquian	210
S. Africa, Lepelfontain	184
Yemen, Hajja	121
Ecuador, P. Grande	210
Nepal, Pathivara	122
Spain, Valencia	142
Eritrea, Nefasit	90
S Africa, Soutpansbergn	200
Chile, El Tofo	365
Chile, Padre Hurtado	365
Colombia, Andres Mountain	210
Chile, Falda Verde	365

One notable project is the Fog Quest organization's initiatives, which have been successfully implemented in countries like Chile, Nepal, and Eritrea. Table 2 and Figure 4 show some of the countries that successfully established fog collection projects together with amount of fog collected per area per day. These projects have used from 10 to 100 fog collectors and have shown success even in areas with minimal annual precipitation, as low as 1 mm per year [18, 42].

In Chile, fog water collection has been instrumental in providing water for irrigation and reforestation projects in one of the world's driest regions, Cerro Talinay [43]. Similarly, in Morocco, the village of Boutmezguida has witnessed increased crop yields and improved livelihoods through fog water collection for irrigation and livestock watering [40]. Peru's village of Huancavelica has benefited from improved access to safe drinking water through fog water collection, enhancing the community's well-being [44].

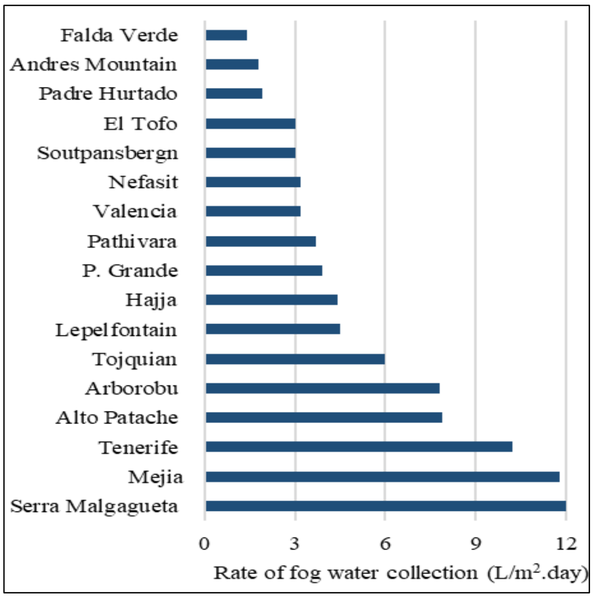

Figure 4. Rate of fog collected (L/(m^2.day)) for the countries that utilized the technology of fog collection. [18,42]

Other real-world projects have showcased innovative approaches to fog water collection. For instance, the Warka Tower project in Ethiopia utilizes a unique fog collector design inspired by local flora, providing drinking water to rural communities and earning recognition for its ingenuity [32].

In addition to Fog Quest's efforts, various experiments and research projects in Chile, Spain, and Oman have explored different fog water collector designs and their feasibility in supplementing existing water sources [44].

These studies have further demonstrated the potential of fog water collection as a sustainable and affordable solution, particularly in arid and semi-arid regions where fog is abundant. Figure 5 shows a map of potential areas for fog harvesting in the world [45].

Figure 5. The map illustrates areas where fog collection has been successful, currently successful, and potential for future success [45].

Croatia, in Southern Europe, has also successfully implemented fog water collection on Mount Velebit, highlighting the potential of fog as a significant water source, especially during dry summer seasons. Spain has maintained a fog collection network since 2003, covering a vast area along the eastern fringe of the Iberian Peninsula, further establishing fog water as a valuable resource in the western Mediterranean basin [44].

In summary, real-world fog harvesting projects have shown that fog water collection can be an effective and sustainable solution, particularly in regions with persistent fog and limited water resources. While challenges such as proper design, maintenance, and local climate conditions exist, the success of these initiatives underscores the importance of fog water collection in addressing water scarcity and improving the quality of life for communities worldwide.

As technology and understanding continue to advance, fog water harvesting will likely play an increasingly vital role in water resource management and environmental conservation efforts.

5. Challenges and Limitations

Fog water collection, while holding significant promise as a solution to water scarcity, presents several challenges and limitations that must be carefully considered for successful implementation. One of the primary constraints of fog harvesting is its dependence on the availability of suitable fog. This technique thrives in regions with frequent and dense fog occurrences, limiting its applicability to areas with such favorable meteorological conditions. Consequently, fog water collection may not be viable in regions with low fog frequency, making it essential to carefully assess the feasibility of fog harvesting projects based on local climate data.

Maintenance emerges as a critical challenge in sustaining efficient fog collectors. The delicate nature of fog-catching infrastructure exposes it to damage caused by strong winds, intense sunlight, and other environmental factors. Regular maintenance becomes imperative to ensure the longevity and effectiveness of fog collectors. However, the logistical difficulty and associated costs of maintaining fog collection systems can pose significant barriers, particularly for remote or economically challenged regions [40].

Moreover, the collection efficiency of fog harvesting systems can be influenced by multiple variables. The size and design of the mesh, wind speed and direction, and the presence of airborne pollutants and dust can all impact the rate at which water droplets are captured from the fog [6]. Consequently, achieving consistent and optimal collection rates may prove challenging, necessitating careful design and monitoring of fog collectors.

Water quality is another crucial aspect to consider in fog water collection. Fog water can be susceptible to contamination by airborne pollutants, including industrial emissions and particulate matter. The presence of pollutants can affect the suitability of the collected water for direct human consumption, requiring proper treatment before use. Ensuring water quality compliance becomes essential to safeguarding the health of the communities relying on fog harvesting as a freshwater source [41].

The cost of implementing and maintaining fog water collection systems poses a significant limitation to its widespread adoption. The initial investment and ongoing expenses associated with fog collectors may not be financially feasible for all regions, particularly in areas with limited resources or competing priorities. Addressing cost concerns may require innovative financing models and exploring partnerships with governmental, non-governmental, or private entities.

Additionally, fog harvesting heavily relies on specific atmospheric conditions, necessitating high humidity and wind speeds for effective water droplet capture. This inherent reliance on environmental factors may limit the applicability of fog water collection in regions with comparatively lower humidity or calmer winds.
Community involvement and education play a pivotal role in the success of fog harvesting projects. The motivation, training, and active participation of local populations are key factors in ensuring the long-term sustainability of fog collection initiatives. Inadequate engagement with the local community can undermine the effectiveness and acceptance of fog water collection systems [46].

Despite these challenges, successful fog harvesting projects have demonstrated their feasibility in regions with favorable climatic conditions, particularly in arid and semi-arid areas with persistent fog. Ongoing research and technological advancements aim to optimize fog collector designs and overcome limitations, making fog water collection a viable and sustainable option for addressing water scarcity challenges in select geographical locations. Careful planning, innovative approaches, and collaboration between stakeholders are essential to unlocking the full potential of fog harvesting as an environmentally friendly and locally appropriate water supply solution.

6. Enhancing Fog Collection Efficiency

Enhancing the efficiency of fog collection is a critical aspect of making fog water harvesting a reliable and sustainable source of fresh water. Researchers and engineers have explored various innovative approaches to optimize fog collectors and maximize water yield [47]. Some of these methods are inspired by nature, while others involve improved design configurations and material selection [48].

Bioinspired surfaces have been a focal point of research in enhancing fog collection efficiency. By emulating the fog-collecting characteristics of creatures like beetles, cacti, and trees, researchers have developed novel fog collector designs. Nanocones decorated with a 3D fiber network, beetle-inspired and cactus-inspired surfaces, and tree-shaped hierarchical cones on superhydrophobic films are some examples of bioinspired fog-collecting surfaces. These bioinspired structures promote water droplet condensation and facilitate more efficient water collection [49].

Moreover, nanotechnology has contributed to advancements in fog collection efficiency. The introduction of nanowire structures on cone tips and wettable gradient microchannels has shown promising results in improving water harvesting efficiency [7, 49]. By incorporating superhydrophobic nanowires, Sarracenia-inspired microchannels, and spider-inspired wetting gradients, researchers have achieved a confined effect and ultrafast water transport, further enhancing the fog collection process.

Integration of multiple bioinspired surfaces has also been explored to achieve high fog harvest efficiency. Combining the fog-collecting characteristics of various creatures in an integrated fog collector system maximizes water droplet capture and enhances overall water yield [50].

In addition to surface design, fog collector placement plays a crucial role in optimizing water capture rates. Installing fog collectors perpendicular to the prevailing wind direction allows for the maximum interception of fog, ensuring efficient water collection [43, 51].

Mesh material optimization is another key strategy. Selecting mesh material with a pore size of 0.2 to 0.4 mm strikes a balance between capturing fog droplets effectively and allowing sufficient air passage, reducing clogging and improving overall collection efficiency [52]. Furthermore, it has also been reported that fog harps demonstrate a significantly higher number of droplets sliding down the harvester compared to meshes [53]. This observation reveals a key advantage of fine-scale harps in avoiding the clogging problem frequently encountered with fine meshes. The increased number of droplets sliding down the harp's surface ensures a continuous and efficient fog water collection process.

To mitigate the impact of wind on fog collectors, the installation of windbreaks has been proposed [30]. These barriers reduce wind speed and turbulence around the fog collector, creating a calmer environment that enhances water droplet capture rates during windy conditions.

Furthermore, proper water storage and protection are essential to maintain water quality and quantity [46]. Storing the collected fog water in clean, covered containers shielded from sunlight prevents contamination and evaporation, ensuring the water remains suitable for various uses.

Additionally, advancements in 3D printing technology have led to the development of new fog collectors with innovative designs as in seen in Figure 6. For instance, 3D-printed fog collectors with cactus-inspired spine structures and peristome-like arc-pitted grooves have shown impressive efficiency in capturing fog water [54].

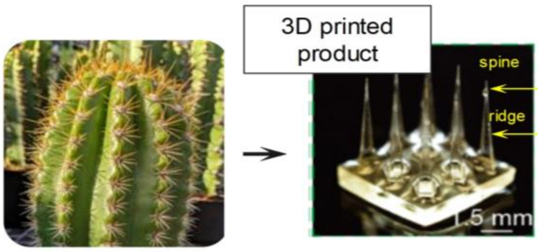

Figure 6. Bioinspired 3D product design of the fog-collection structure [54]

By integrating these approaches and continually exploring advancements in materials, design, and fog characterization techniques, fog water collection can be significantly enhanced. Such improvements have the potential to make fog harvesting a more reliable and scalable solution for addressing water scarcity in foggy environments.

7. Consclusion

In conclusion, fog harvesting presents a promising solution to the pressing issue of water scarcity and the need for sustainable water sources. By capturing water droplets from fog, this renewable and eco-friendly technique offers a reliable water supply, especially in arid regions with frequent fog occurrences.

Despite challenges such as fog availability, maintenance costs, and water quality concerns, ongoing research and technological advancements continue to enhance fog collection efficiency. Innovations inspired by nature, nanotechnology, optimized materials, and improved designs contribute to maximizing water yield and economic viability.

Real-world fog harvesting projects and laboratory researches have demonstrated the effectiveness of this approach in providing sustainable water access to communities facing water scarcity. Collaboration between stakeholders and local community involvement are vital for successful implementation.

Fog harvesting’s potential to shape a more water-secure world is undeniable. By embracing this eco-friendly solution and fostering innovation, we can move towards a sustainable future where clean water access is a fundamental human right for all.

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The Declaration of Ethics Committee Approval

This study does not require ethics committee permission or any special permission.

The Declaration of Research and Publication Ethics

The authors of the paper declare that they comply with the scientific, ethical and quotation rules of SAUJS in all processes of the paper and that they do not make any falsification on the data collected. In addition, they declare that Sakarya University Journal of Science and its editorial board have no responsibility for any ethical violations that may be encountered, and that this study has not been evaluated in any academic publication environment other than Sakarya University Journal of Science.

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