Water harvesting through fog collectors: a review of conceptual, experimental and operational aspects

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Abstract

In water-scarce regions where fog is abundant, the population can rely on this resource to obtain fresh water. The potential to harvest fog is confirmed by Large Fog Collector projects worldwide, which are reviewed. Mostly maintenance issues due to environmental and complex social factors compromise the sustainability of such projects. The researchers endeavour to resolve these issues by developing enhanced materials, while others use biomimetic design, hence creating innovative collectors. The objective of this paper is to survey and review the state of the art and develop a framework of different types of innovative fog collectors, including conceptual, experimental and operational aspects.

Keywords: biomimicry; community-development; fog collection projects; water harvesting; unconventional water resources

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1 INTRODUCTION

The demand for fresh water rises, while the availability diminishes due to overpopulation, urban migration and human-made greenhouse emissions [1]. Globally, two billion people experience water stress daily whereof 1.1 billion, mostly settled in urban slums or remote arid areas, have merely 5 litres of water a day [2]. In order to fulfil daily basic water needs, each person should be provided with a minimum of 20 litres [2]. Isolated communities are usually not connected to a conventional water supply network whereas networks in urban slums are often in poor conditions and not adequately regulated by local governments [3]. In order to combat this threatening issue of water scarcity, alternatives such as desalination, rainwater collection and groundwater collection are being studied and implemented worldwide. When these alternatives are scarce or nonexistent, atmospheric water harvesting can be feasible. In fog-loaded (semi-)arid regions, inhabitants can fully or as a supplementary supply rely on fog collectors for drinking, agriculture and reforestation purposes [4]. The most prominent and largely installed collector is FogQuest's Large Fog Collector (LFC) [5]. Fog harvesting is a common practice in nature, and for enhancing the efficiency of human-made collectors, researchers are studying biomimicry, a promising research field defined as a solution for complex human design problems inspired by nature. [6]

The first scientifically documented feasibility study for collecting fog dates from 1903 conducted by Dr. Marloth in South Africa [7, 8]. Towards the end of the 1900s, fog collecting as a viable water resource has gained interest, and this is seen in the rise of publications, illustrated by Qadir *et al.* [9] in Figure 1. Dates of the publications on fog collecting reviewed for this paper are added to the graph.

The main objective of this paper is to survey and review state of the art and develop a framework of existing water harvesters with the focus on conceptual, experimental,] and operational aspects. Conceptual refers to parametrically designed prototypes, experimental to designs that are tested on full scale for scientific development and operational to collectors implemented within a community. The information on fog collection projects is scattered and this paper aims to fill this gap by analysing various collectors. Sections 2 to 5 of this survey and review effort are organized along the following questions: Globally, where are the most feasible fog collection regions? What are nature's fog collectors? What is the working mechanism of fog collectors? What is the role of the community for the success of LFC installations? Following the elaboration of the LFC projects, the sixth section provides a

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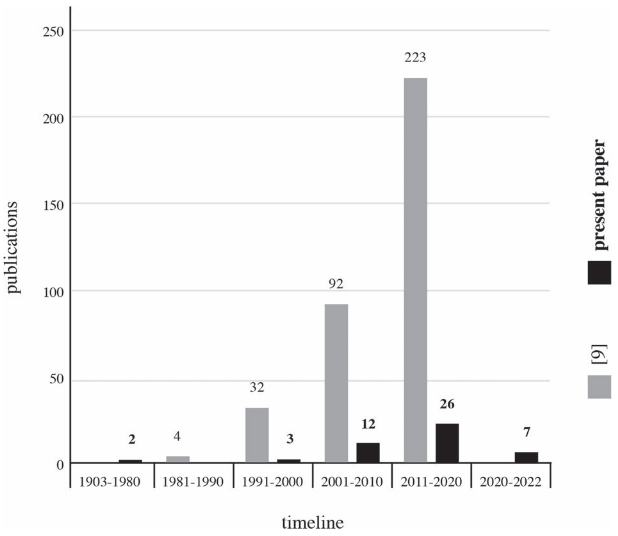


Figure 1. *Publications on the topic of fog collecting from 1981 to 2020. Adapted from [9]. Addition of publication dates reviewed for this paper from 1903 to 2022.*

comparative analysis of state-of-the-art mesh developments, alternative conceptual and experimental collectors and operational fog collection projects, with the LFC considered as traditional. To conclude, suggestions regarding future research towards efficient community-based, cost-effectiv and urban-integrated harvesters are provided. A combination of different methods is used: systematic literature reviews, comparative analysis, two expert interviews and a field visit.

2. FEASIBLE REGIONS FOR FOG COLLECTION

Fog precipitation is a local phenomenon, mostly thriving on slopes or summits of mountains and is generally a biodiversity wellspring [10]. By definition, fog is a cloud that touches the ground containing water particles from 1 to 40 microns. In the context of harvesting moisture from fog as a resource, three types are relevant: advection, orographic and radiation fog [5]. Advection fog is formed through warm, humid air masses moving horizontally over a cooler surface, such as the sea. Orographic fog is formed by humid air masses that move upward along the land acting as an orographic obstacle. At a certain height, the air expands. Both are characterized by relatively strong winds, whereas radiation fog, which is an accumulation of a large stable cold air mass formed during a cold period mostly situated inland, is characterized by a low wind speed making it the least interesting for harvest. [11] Aside from wind speed, which typically ranges from 2 to 12 m/s, the LWC (Liquid Water Content) is an important factor for fog collecting and is the amount and size of droplets in a cloud [5]. Along the coasts of South America, Africa and the Arabian Peninsula, various fog oases are found. These are characterized by aridity, but organisms survive through the presence of (seasonal) low stratocumulus [12, 13]. Moreover, tropical highlands that experience seasonal droughts, such as the Chiapas region in Mexico and the Philippines, can benefit from fog collection [14].

3 NATURE’S FOG COLLECTORS

Organisms living in places where water is scarce rely mostly on fog and have developed efficient ways to capture water out of the air. Natural fog collection occurs in trees, for example, in coniferous redwoods. The quantity of harvested water depends on the tree’s structure and the leaf’s wettability properties in relation to the present foggy wind. In advantageous conditions, little droplets coalesce on the leaves and fall on the ground through which the roots can absorb the droplets [10]. Ancient communities captured this fresh water by digging wells under the trees [15]. The Tillandsia landbeckii is known for being one of the sole organisms that thrives in the arid Atacama Desert by intercepting fog. The plant absorbs water through its fibre-like leaves, or trichomes, whereafter it is stored efficiently through its thick layer resulting in water losses close to zero [16, 17]. A cactus native to the Mexican desert has developed barbs on its spines facilitating the interception of droplets, whereafter they grow and move towards the base of the tip due to the Laplace pressure gradient and where they are absorbed by the cactus’ thick flesh [18].

Animals also have developed efficient ways to harvest moisture such as the fog basking ability of the Namib Desert beetle. Its back skin is made of alternating hydrophilic areas, whereon droplets congregate, and hydrophobic areas, allowing the droplets to funnel down to the beetle’s mouth [19]. A Lizard’s skin is likewise adapted to harvest water and funnel droplets into its mouth through open channels, which narrow down in the direction of the mouth. Water movement is achieved through capillary action [18]. This evolutionary intelligence is mostly researched by material scientists to develop efficient materials. Regarding fog collection, researching fabric material is important for enhancing the efficiency of fog-intercepting meshes.

4 FOG HARVESTING MECHANISM

Figure 2 illustrates the mechanism to yield fog by capturing droplets using a mesh placed perpendicularly to the fog-loaded wind. A part of the droplets carried by the wind collate on the mesh material and run down into the gutter. For optimal efficiency, fog waste must be kept to a minimum.

The most widely used interception mesh, called the Raschel Mesh (RM), is a food-safe mesh manufactured in Chile. Polypropylene or polyethylene fibres are triangularly woven consisting of a flat fibre of 1-mm wide and 0.1-mm thick resulting in a total covered surface (shading coefficient) of ~35%. The triangular pattern enables an efficient transport of droplets [20]. To ease runoff and obtain a shading coefficient of ~70%, a double layer able to move against each other is used. Aside from the LWC

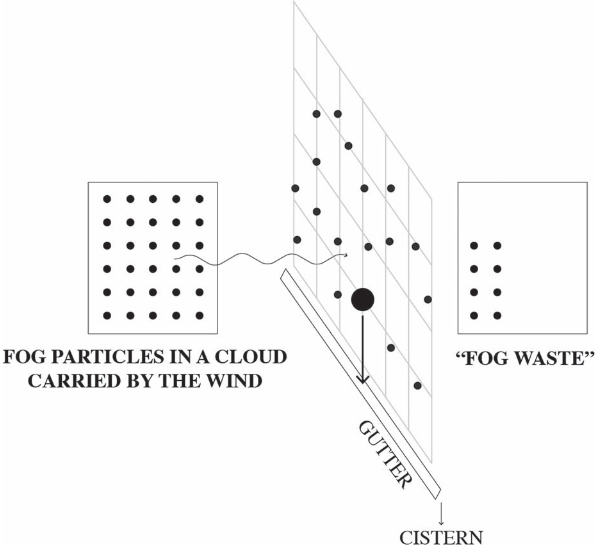


Figure 2. *Fog collection mechanism using a mesh to intercept fog particles.*

and the wind speed, the mesh's geometrical aspects and physical properties such as the surface wettability determine the collection rate [20, 21]. Thus, the thickness of the fibres and the percentage of the covered surface have a direct effect on the harvest efficiency. A smaller fibre size results in a better efficiency than one of 10 mm whereas the coverage of the surface cannot obstruct the wind completely to assure that the fog-loaded wind passes through [10]. The efficiency of the mesh is usually measured by the ratio of the amount of water that reached the gutter and the total amount of droplets that passed through the mesh over a defined period [22].

5 LARGE FOG COLLECTORS

An LFC (Figure 3) is a two-dimensional water harvesting mechanism with a flat frame of 4 × 10 m wherein a double RM is stretched. The frame is attached to two poles, anchored 2 m above the ground. These poles are strengthened by cables with turnbuckles that need to be strengthened or loosened depending on the climatic situation. The price for one LFC is US$1000–1500 [5]. Determined by the site and season, yearly averages of 3–10 l/m^2/day are obtained [20]. Due to the cables, the occupied ground surface is considerable resulting in the fact that LFCs can only be placed in areas where space is available. When multiple LFCs are installed in one place, two collectors share the middle pole, hence saving space.

5.1. Evaluation before implementation

Climatological and social parameters are evaluated before initiating a project. Preliminary tests with one or multiple Small Fog Collectors (SFCs) are executed over a certain period to estimate the amount of harvestable water. An SFC has a mesh area of 1 m^2 and should harvest approximately 1–10 l/m^2/day. [23] If a location is climatologically ideal, meaning positive harvest from the SFC(s), it does not assure an installment of LFCs. The commitment of the local communities must be evaluated, commonly through local non-governmental organizations (NGOs), because (they and) the locals need to maintain the collectors. Additionally, land ownership in the area should be revised [5].

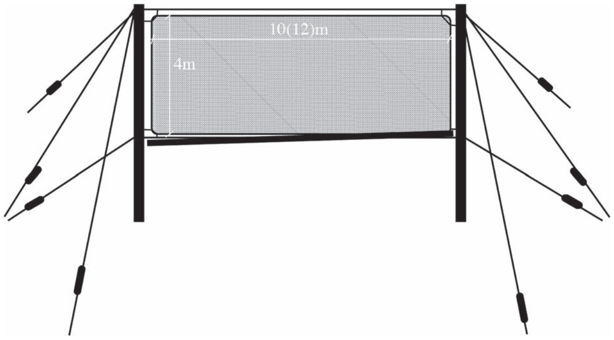


Figure 3. *Visualisation of a flat-framed Large Fog Collector with a total mesh surface of 40 (48) m^2.*

5.2. Operational community-engaged projects

Operational LFC projects intended for implementation in communities for drinking or growing crops are described and depicted in Figure 4, classified by continent and accompanied by their reason for failure or continuation and the number of implemented LFCs to perceive a scale of the project. Many additional installations have been carried out for scientific research, which are not incorporated. The current and past LFC installations demonstrate the high potential to supply rural communities with adequate amounts of water but show significant problems due to their lack of engineering and high-maintenance needs compromising the sustainability. Climatic issues refer mostly to breakage due to harsh weather conditions. This in combination with complex social issues ensuing poor maintenance and insufficient monitoring leads to deterioration of the collectors [24, 25].

5.2.1. *Successful projects*

In the Tojquia region in Guatemala, 42 LFCs supply 200 inhabitants with daily averages of 5 l/m^2/day during the dry winter season. The inauguration was in 2006 and according to FogQuest; the collectors were still carefully maintained in 2020 [26]. The construction was built with volunteers of the community whereafter a local village fund was founded to maintain the collectors [27]. The beneficiaries of the project are mostly women and girls, whom before would spend hours walking to collect water down the valley [28]. A small-scale project is found in a remote area in the Andes Mountains in Colombia. One collector with a mesh size of 25 m^2 delivers freshwater to a local school for irrigation purposes. The highest monthly average obtained was ∼2 l/m^2/day during a study period from May 2008 to February

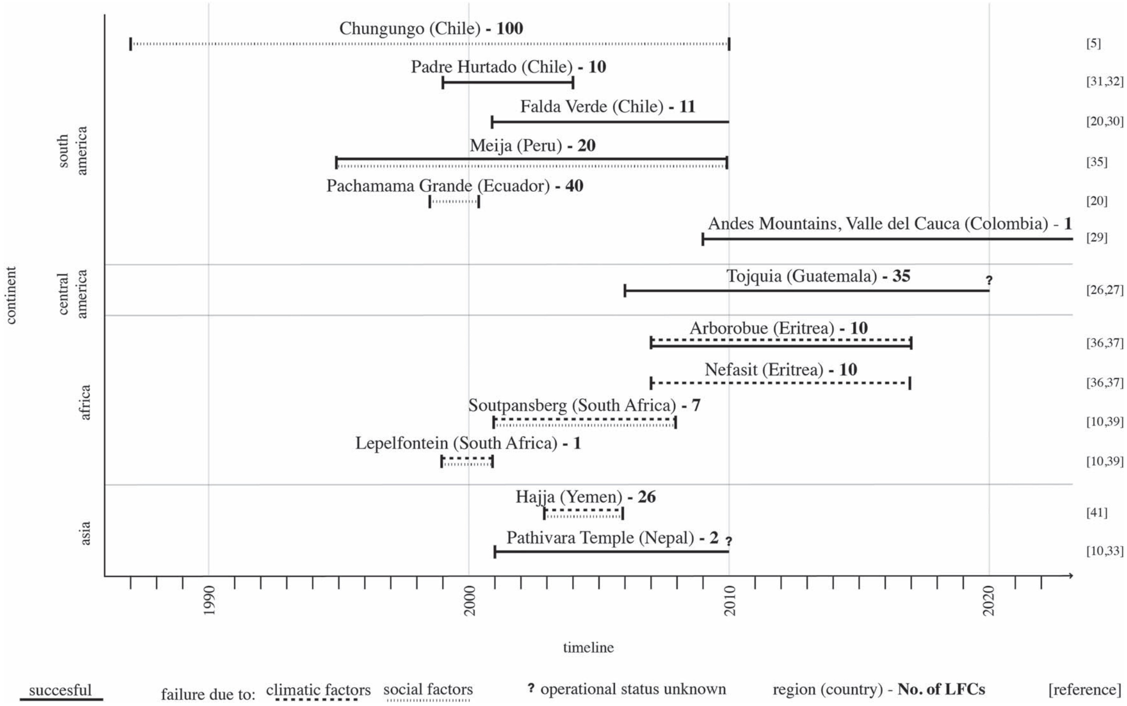


Figure 4. *Selected operational Large Fog Collector projects in Africa, Asia, Central America and South America appointed with their main reason for failure (climatic or social) or continuation and the number of implemented LFCs.*

2009. Afterwards, the collector was built, with a strongly engaged community resulting in a request for additional LFCs [29].

In spite of fog being difficult to predict, this is an economic and ecologic resource from which enterprises and organizations can benefit. Moreover, when the water supply for the local population is delivered by conventional means, their domestic water supply is not affected during fog-scarce periods, generally resulting in a strong involvement of the employees for managing and maintaining the collectors. In the rural village Falda Verde (Chile), 11 LFCs supplied the irrigation of commercial *aloe vera* from 2001. An annual average of 1.5 l/m^2/day was determined by SFCs prior to the installation of the LFCs [20, 30]. In 1999, ten collectors were placed to supply a sanctuary, in Padre Hurtado, Chile, providing up to 5 l/m^2/day [31, 32]. In Nepal, the Pathivara Temple is supplied with ~6.3 l/m^2/day of fog water (no specifications of data found) from two collectors from 2001 onwards [10, 33].

5.2.2. *Past projects*

A research project in the 1980s led to the first large-scale fog collection project worldwide in a small Chilean fisher village, Chungungo, using 100 LFCs of 48 m^2 overlooking the village. The collectors harvested an average of 15 000 l/day (~3 l/m^2/day) over a 10-year period flowing directly into the village and supplying 300 inhabitants [5, 10]. This generated a visible increase in economic resources [20]. The community managed the system, but after administrative problems, growth of the permanent population pressuring the water system, absent funds, storms destroying the LFC's rigid 2D structure and the mesh if not regulated properly, and a pending request for a connection to a conventional pipeline, the system was slowly neglected. During the project, the unreliability of fog water in some period led to the supplementation with truck-delivered water, as it was done before and soon enough it switched back to this expensive resource [34, 35]. A reforestation project to rehabilitate the Lomas' ecosystem in Meija (Peru) was established in 1995 with 20 LFCs. The water was also used by neighbouring farms. After the reforestation project came to a successful end in 2010, harvesting an annual average of 7.5 l/m^2/day, the lack of involvement of the local communities to adapt the collectors resulted in degradation [35]. Considerable amounts of up to 12 l/m^2/day on foggy days were measured in the mountainous region Pachamama Grande (Ecuador), where 40 collectors operated from 1995–1997. The large-scale project quickly degraded due to the lack of technical skills of the local NGO [20].

Insufficient maintenance and monitoring in combination with extreme weather quickly results in damaged collectors [10]. In Eritrea, the local population often depends on various unstable water resources such as unsafe shallow wells and truck-delivered water. In the small rural villages Nefasit and Arborobue, 10 LFCs were installed at each location in 2007 to supply local schools nearby [36]. Feasibility studies demonstrated annual averages of 1.4 l/m^2/day (Nefasit) and 3.1 l/m^2/day (Arborobue) [37]. Both projects were abandoned due to gale winds despite the strong commitment in Arborobue, where the RM was replaced several times and ultimately even replaced to a resistant German ITV mesh [37]. Extreme wind speeds also affected two projects in

Lepelfontein and Soutpansberg (South Africa), where annual averages of 4 l/m^2/day were measured [38]. In Lepelfontein, one collector with a mesh surface of 70 m^2 supplied a local community from 1999 to 2001, and in Soutpansberg, seven collectors supplied a local school from 2001 to 2008 [10, 39]. Furthermore, collectors in South Africa suffer from vandalism [40]. After obtaining positive results of 4.5 l/m^2/day over a 3-month period in a small village in Western Yemen, 26 LFCs were inaugurated in 2003. After 3 years, strong winds destroyed the midscale project [41].

5.3. Sustainability issues

The sustainability of a project mostly depends on the beneficiaries' commitment to maintaining and monitoring the collectors [10]. The communities' commitment decreases when climatic-related problems occur, especially when they were not motivated nor prepared for this alternative. Experience revealed that individually owned and/or self-bought collectors accomplish a higher degree of commitment [42], because generally, a community consists of different families. This suggests that there is no direct ownership and no feeling of responsibility on an individual level causing conflicts, abandonment or both. Besides, some locals do not possess economic and technical resources nor spare time whereas the collectors demand daily surveillance [25]. The role of a local NGO is therefore crucial to introduce and inform the beneficiaries about the fog harvesting mechanism through a public programme with great sensitivity to local traditions. After the collectors are handed over to the community, NGOs are expected to assist and conduct routine evaluations, but these are often irregular or obsolete [43]. In most cases, governmental aid is required for subsidies and leadership [14]. However, multiple fog-loaded arid regions are prone to governmental restrictions because they do not consider fog collection to be a national water policy, ergo, do not provide action plans [44].

6 ALTERNATIVE FOG COLLECTORS

New designs are emerging to harvest atmospheric moisture. These are based on the LFC, the knowledge of the local population living in fog-loaded areas and fog-basking organisms, fusing into sustainable community-based collectors. By learning from previous mistakes, introducing new materials and developing low-maintenance designs, alternative mesh and collector concepts solve some common issues seen in the LFC projects. All collectors described operate with a mesh and are passive, using merely natural driven forces without requiring external energy. Additionally, a common innovative design aspect is that they all use a three-dimensional design whereas the LFC has a two-dimensional set-up catching water from one direction, while the wind direction can be variable [45].

6.1. Mesh research

Only ∼2% of the total moisture passing the RM is harvested and the efficiency decreases remarkably due to factors such as clogging, coalescence of droplets and loss of droplets re-joining the wind [46]. Experimental research by Rajaram *et al.* [47] illustrates the great potential for improvement of the RM by applying coatings and changing geometrical features. The tests revealed that a reduction in fibre size and an increase in filament distance yields ∼50% more. A superhydrophobic coating increased the contact angle yielding by an additional 50% [47].

Specific climate conditions demand specific mesh characteristics, and the inflexibility of the RM has proven not to be suitable for very windy locations. The mesh is also prone to damaging under high UV radiation [25]. In general, the RM has a lifespan of 5–10 years (excluding environmental damage) whereas three-dimensional nets are estimated to have a lifespan of 20 years. Still, these technologies hold a considerable disadvantage, which is their high cost, making the RM more suitable for underprivileged communities [24, 44]. In South Africa, a co-knit mesh of stainless steel, for strength, and polypropylene yarn, for an efficient harvest, has successfully been tested [20]. Fernandez *et al.* [48] performed comparative studies of three different mesh types regarding wind speeds on four locations in California (USA). Each site included four SFCs, one with a double-layered RM, one with a hydrophobic coated stainless steel mesh (MIT-14) and lastly two with a 3D spacer fabric deployed horizontally and vertically, respectively (FogHa-Tin). The results revealed that, under similar conditions, the meshes showed inconsistent results. Nonetheless, compared to the RM, the FogHa-Tin produced better results at lower wind speeds and the MIT-14 produced better results at all wind speeds [48]. Apropos to this, Schunk *et al.* [49] performed studies to determine the most durable meshes at high wind speeds. Three-dimensional spacer fabrics, entailing more efficient run-off and coalescence of droplets, showed better results than woven fabrics such as the RM [49]. Lummerich and Tiedemann [50] performed a comparative analysis of three full-scale collectors with three-dimensional meshes alongside a traditional SFC in field conditions in the outskirts of Lima. The 'Eiffel', constructed with two separate layers of RM and additional strips in between, produced most water. The 'Harp' and 'Diagonal Harp' consisted of a metal frame wherein vertical and diagonal, respectively, rubber strings were attached and produced similar results as the SFC [50]. The fog harp, designed by Shi *et al.* [51], contains an array of vertical wires. Woven meshes tend to clog and lose droplets whereas the metallic wires ensure an efficient water yield and efficient drainage harvesting three times more [51]. Azeem *et al.* [17] reported multilayer harp collectors with four or five layers achieved the maximal aerodynamic collection efficiency, which is the unperturbed flow of fog droplets carried by the wind that could reach the wires. Under optimized geometrical conditions, experimental studies revealed that this harp collects four times more than the SFC [17].

A notable water harvesting feature seen in nature is (super)hydrophobicity [52]. By studying the effect of hydrophilic and hydrophobic coatings on wires, Azeem *et al.* [21] concluded that the latter improved the collection rate of vertical harps. American engineer Bhushan developed a conceptual design of a biomimetic three-dimensional mesh with water-harvesting cones

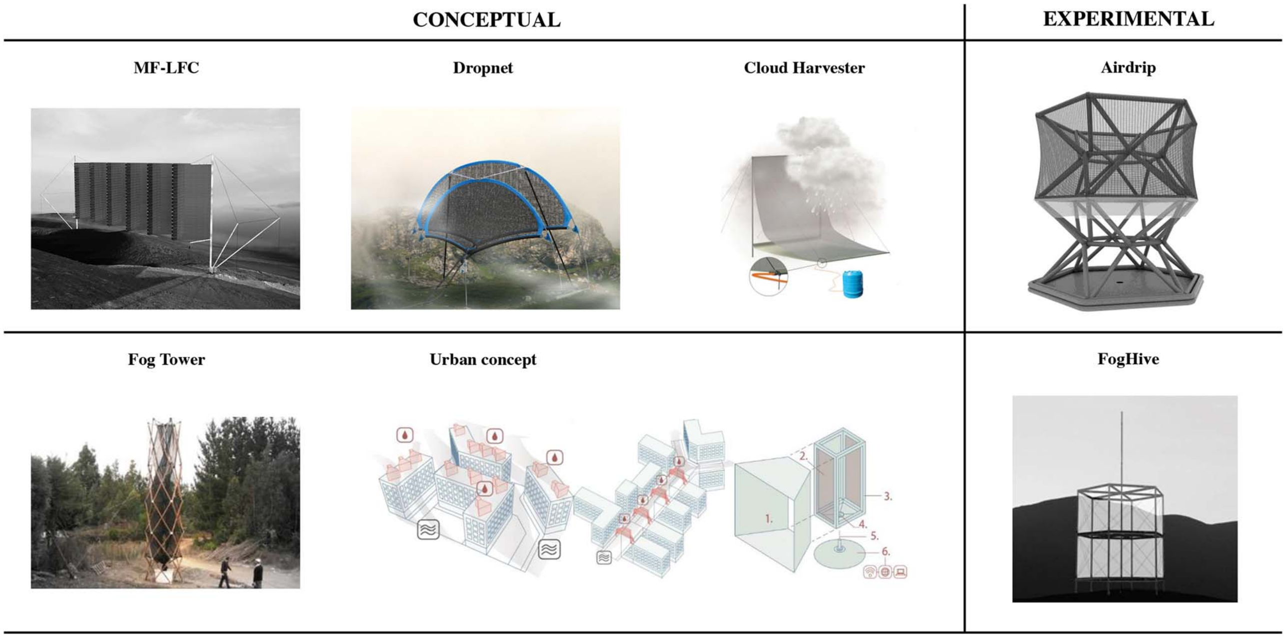


Figure 5. *Visualisation and pictures of conceptual fog collectors with their source of Copyright: MF-LFC [25], Dropnet [54], Cloud Harvester [55], Fog Tower [57], Urban concept [58] and experimental fog collectors: Airdrip [13], FogHive [59].*

resembling a cactus. Metallic cones are attached to a metallic surface that consists of alternating hydrophilic and hydrophobic areas inspired by the Namib Desert Beetle's back, and openings for the wind to pass through [18]. Another distinct conceptual mesh design is a simplification of a spiny cactus to a two-dimensional mesh made from waxed paper kirigami (variation on origami). Preliminary tests illustrated that the collection rates are higher than those of harps at a lower cost [53].

6.2. Conceptual and experimental

Figure 5 visualizes conceptual and experimental fog collectors.

6.2.1. *Conceptual*

Developed by Chilean researchers is the MF-LFC, which is a conceptual design derived from the traditional LFC optimizing its weak characteristics such as breakage and high maintenance by dividing the mesh surface. This modification decreases the stress on the mesh fibres and ultimately decreases the need for constant regulation under extreme weather. Moreover, decreasing the mesh surface is an element used by all described conceptual, experimental and operational designs to reduce breakage and maintenance needs. The collector has a three-dimensional modular funnel (MF) structure and the appearance of a half-open harmonica with individual frames placed at 60-degree angles facing each other towards the predominant wind. Each frame is filled with a double layer RM and individually anchored into the ground. Theoretically, the collection efficiency is increased from the LFC's 26% to 64% [25].

Dropnet is a tent-like structure with a parabolic-formed mesh developed by Höhler. Six square metres of RM is tensed around aluminium prebend poles catching droplets multi-directionally. The prototype is constructed in the same way a typical camping tent is, anchored 90 cm above ground level. In favourable climatic conditions, Dropnet is predicted to harvest up to 2 l/day. Through plastic foundations, the structure is flexible and can adapt to strong winds [54]. A beneficial application could be for urgent small-scale supplies in post-disaster areas, where conventional networks or trucks are not within reach.

The Cloud Harvester has a particular shape, designed by Choiniere-Shields. A stainless steel mesh with one side attached a few centimetres above the ground covering a part horizontally, continuing vertically, with the other side attached at a height of 1.8 m, theoretically harvests ∼1.1 l/m^2, or 45.6 l, per hour in optimal climatic conditions. Considering only 10% of this quantity, one mesh would harvest 5 l/h. Under the collecting mesh, a tarp is placed, inclined to the direction of the water tank serving as an impermeable layer to catch the droplets and whereon dew formation is possible. Because of the simplicity of the structure, the mesh is made affordable with a total cost, production and construction of US\$165.85. Supposedly, the conceptual design is expected to have similar collection efficiency as the LFC at a lower cost and smaller in size [55, 56]. A great advantage is the small size of the collector enabling it for implementation in metropolitan areas. While the LFCs are intended for long-term commitment, have the potential of harvesting large amounts of water, but require basic knowledge of technical tools and skills, Dropnet and Cloud Harvester, which are ready-made, easy to transport, and lightweight, serve more as a temporary supply.

Chilean researchers developed the Fog Tower. The collector uses the same mesh (RM) as the LFC but is designed as a three-dimensional tower of 10–20 m, depending on the communities' needs. The structure was physically built in 2008 measuring almost 10 m in height with a diameter of 2 m consisting of a wooden spiralling frame. The RM is attached to the interior of the structure on multiple points accomplishing a higher resistance to strong winds. The tower requires solid foundations, but the structure is lightweight and flexible making it foldable and easy to transport. The fog tower theoretically harvests 100–300 l/day, which is similar to the LFC but occupies around ten times less of the ground surface [57]. However, comparing these conceptual designs to the operational LFC in terms of collection efficiency can be misleading because it is imperative to test and validate the collectors in similar field conditions.

Italian researchers designed an urban fog collector. A water-harvesting cube intercepts moisture with its two parallel sides filled with a mesh. No specifications of a mesh are provided but the researchers declare that further research should determine the most efficient mesh for this prototype. In front, an MF is placed to direct the fog-loaded wind and a wind vane assures the most efficient wind speed. In densely built-up cities, the wind is obstructed and deviated by the buildings, thus the collectors would be placed on roofs and in the upper street valleys where greater foggy wind speeds are found [58]. This concept is the sole example that aims to tackle the problem of the high need for urban collectors that can be placed in densely built-up metropolitan areas.

6.2.2. *Experimental*

Airdrip is a validated concept of a three-dimensional fog mechanism with an innovative structural feature being the lightweight polyhedral air-frame system and the size ratio of the water yielding mesh which is placed multidirectional to capture fog from all sides in the Atacama Desert. The designers observed various organisms living in foggy arid climates and concluded that hydrophobic materials and harvesting water from all wind-faced directions are crucial for an innovative design. A prototype was built in Coquimbo, Chile, and has the potential to harvest around six times more than the flat framed LFC. The price for one collector is US$1850 [13].

The prototype is derived from FogHive and uses the same mesh. A hydrophobic polyethylene textile is a light-coloured mesh that decreases the temperature surface while its three-dimensional built-up makes it resistant to strong winds. FogHive is designed in a hexagonal form serving as a pavilion for shade for animals and people. Three sides that are in the direction of the most prevailing fog-loaded wind are covered with the white mesh, whereas the other sides are covered with a shading mesh. The lightweight and deployable mecanoo structure is constructed with aluminium, galvanized steel or timber [59, 60]. Both three-dimensional designs strongly differ from the traditional flat frame and are fixed alone standing collectors. Their application could be a central meeting point within a community providing both water and shade.

6.3. Operational

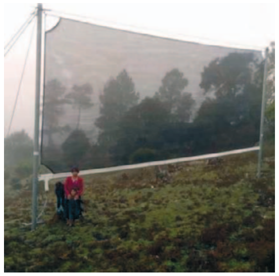
The following described projects are or have been working within a community. A comparison is made in Table 1. However, it is important to convey that every collector has been implemented in a distinct area, coming with different (dis)advantages for each location.

6.3.1. *CloudFisher*

In Southwest Morocco, LFCs for rural Berber communities of Aït Baamrane were damaged several times due to strong winds. The collectors, placed uphill from the villages, were maintained daily by locals [61]. Their strong commitment motivated the non-profit organization Dar Si Hmad for Development, Education and Culture (DSH) and German engineers of Wasserstiftung to seek a solution. Preliminary experiments with more resistant material [49] ultimately led to the creation of a new design named CloudFisher (CF) in 2013 [61]. Twenty-five kilometres of pipelines connect 31 CFs and cisterns to 15 villages downhill. Potable water is delivered to 1250 inhabitants, with a daily supply of 18 l/person, a school and agriculture, making it the most productive and durable fog collection project globally. An average of 22 l/m^2/day is collected on fog days [62, 63]. Operational installations are found in Morocco, Tanzania and Bolivia, and additional projects are underway. In terms of mechanism, and contrary to the LFC where the 40-m^2 mesh is solely connected to its frame at the corners, a big CF consists of four separate frames, each with a mesh surface of 13.5 m^2 connected to the steel frame through multiple bungee holders facilitating to tense the mesh, decreasing the need for constant regulation and resulting in a resistance to winds up to 120 km/h. To enhance its resistance and efficiency even more, a plastic grid is placed on the mesh to prevent the surface from bulging and losing droplets. The total net surface is 54 m^2, and each frame has support poles anchored into the ground [63–65]. Whereas the structure is two dimensional, the innovative spacer fabric, which is a food-safe and UV-resistant mesh with monofilaments woven into interconnected helixes, is three-dimensional rendering a more efficient harvest. Because of the variable sized openings of the mesh, the fog passes through easily while the three-dimensional aspect facilitates the coalescence and run-off of droplets ultimately decreasing the potential for droplets to re-join the wind. Yet, the price is considerably higher compared to the RM [61].

Two models exist, a big (height: 6 m) or mini (height: 3 m) CF, and depending on the soil wherein it will be placed, concrete or peg fastenings are available. Before committing completely, an SFC variant with the CF's technology is offered for US$910 [63–65]. The main drawback of this collector is its high initial cost of US$13 000 for one CF. Nonetheless, an average of 1200 l/day on foggy days is harvested in Morocco whereas the LFC only harvests a general average of 200 l/day but costs around 13 times less [61]. For the price of one CF, eight LFCs could be purchased with a theoretical harvest of 1600 l but eight times the space is required. Considering the expected durability and low maintenance needs of the CF, the investment could render a lower price

Table 1. *Comparison of operational fog collectors that are implemented within a community for domestic, agricultural and/or reforestation purposes: LFC, CloudFisher, Niebla, Nieblagua and Warka Water*

	LFC	**CloudFisher**	**Nieblagua**	**Niebla**	**Warka Water**
Average water harvest	200 l/day	1200 l/day	11 000–25 000 l/year from 5 to 6 RAAs	21 l/day	Theoretically 40–80 l/day
Structure	Fixed	Fixed	Fixed	Flexible (tensegrity)	Flexible
Form	2D	2D	3D cuboid	3D triangular ground surface	3D circular
Dimensions (length × width × **height)** [m]	(10 × 6) m	(9 × 6) m	(2 × 0.8 × 4) m	(3 × 3 × 3) m	Height: 9 m
Total net surface [m^2]	40 m^2	54 m^2	36 m^2 whereof 12 m^2 on interior (double layer on front and sides)	27 m^2	/
Ground surface [m^2]	56 m^2 *	36 m^2 **	1.60 m^2	4.5 m^2	/
Cost [US$]	US$1000–1500	US$13 000	/	US$400	/
Mesh material	RM	Spacer fabric	Polyethylene	Polypropylene monofilaments	Polyester
Purpose	Domestic supply, reforestation, agriculture	Domestic supply, agriculture	Reforestation	Domestic supply, agriculture	Domestic supply, agriculture
					
Reference	(Picture Copyright FogQuest [5])	[61–67] (Picture Copyright aqualonis [63])	[68] Field visit and expert interview (Picture from authors)	[69, 70] Expert interview (Picture Copyright Tómas Garay Ávila https://www.instagram.com/niebla.agua/)	[56, 71, 72] (Picture Copyright Warka Water [71]).

*Calculated by assuming that each erected cable at the corners is placed on 45° degree at a 2 m distance resulting in a ground surface occupancy of (14 × 4) m. **Calculated by assuming that each erected cable is placed in front and behind a big CF at a 2-m distance resulting in a ground surface of (9 × 4) m.

over time. However, this is purely theoretical because long-term testing of the two collectors under equal conditions has not been undertaken (yet). The commitment of the inhabitants and the NGO DSH has generated an exceptional social and economic impact, especially influencing gender inequality issues. As seen in many other remote communities, women and girls are the main water gatherers and spend hours walking to nearby valleys or open wells, retaining them from pursuing other productive activities and going to school, respectively. They are thus the primary beneficiaries of a water harvesting project. In Morocco, the older Berber women are assigned to survey and report on the CFs' water problems by using their smartphone. By giving responsibility on management and training low-literate women to use information and communication technologies, some traditional and institutional discrimination issues are addressed [66, 67].

6.3.2. *Nieblagua*

Nieblagua is a Canarian company. Most of the information below is obtained during a field visit and expert interviews with the founder Ricardo H. Gil Casanova, and through the website www.nieblagua.com. The fog collector RAA (Spanish: Recogedores de Aguas Atmosféricas) is a three-dimensional metal cuboid wrapped with a green double layer of polyethylene mesh. A biomimetic feature is implemented through the placement of additional meshes within the cuboid stacked hierarchically resembling a tree's structure minimizing its fog waste. A second is the green-coloured mesh, which serves as a means of visually merging into forest regions. A collecting tray is installed under the structure which is connected to a cistern with tubes. Evidently, the mesh is an obstruction to the wind flow. Unlike the LFC where the mesh is applied when the poles are up implying difficulties to attach the corners to the structure, an innovative feature is that the RAA's mesh is easily applied when the structure is not up yet using simple strip cable zip ties. The cost-effectiveness and simplicity of the structure are also advantages requiring merely two people to build five to six collectors in 1 week. Other advantages are its small ground surface area of 1.60 m^2 and the absence of cables. However, the structure is still fixed and needs to be placed with robust foundations, such as the LFCs. Multiple installations are found on the Canary Islands. Each location contains five to six individual RAA collectors placed side by side and collectively harvest 11 000 to 25 000 l/year. Most projects are intended for reforestation, and when using it for drinking, filtration is added [68].

6.3.3. *Niebla*

Niebla is a fog collector designed by Tómas Garay Ávila. In Caldera, a deserted area in Northern Chile, four collectors alongside each other were installed in 2017 by and for the Colla community with national funds. According to Garay, through an expert interview, the communication with the community was challenging, and he spent years gaining trust and introducing the fog harvesting mechanism to them. The structure is based on tensegrity, which is an architectural principle of components under tension. The collector is easy to transport and construct and requires a minimum of maintenance owing to its flexible structure. To keep it low-cost and low-tech, material that is easy to find is used such as PVC tubes for the structure and metal cables to keep the structure in place. Instead of using the Chilean RM, a more robust mesh of monofilaments is used. A total of 27-m^2 mesh is loosely attached through multiple holders within the tensed network, allowing the mesh to fluctuate and reducing the tendency of breakage under harsh weather conditions. In Caldera, an average of 20 l/day is accumulated by one collector during the winter fog season. A unique feature of this design is that the fluctuating mesh allows intercepted droplets blown off by winds to be recovered. Coalesced droplets can also roll down the mesh as typically observed. A plastic slab catches all the mesh-intercepted droplets, covering an area greater than the ground surface of the collector, and is directed to a gutter connected to a cistern. The relatively small-scale three-dimensional collector with a size of 3 m in all directions has an aesthetic outlook. While the collector is currently in exploratory phase collecting water to supply one person, Garay intends to build NIEBLAs for domestic and agricultural use for rural families. With national funding, the collector could also serve as a refuge for people and animals seeking shade in the Atacama Desert on routes that are used by the rural population moving daily with their animals, enhancing the quality of their trips, and providing potable water [69, 70].

6.3.4. *Warka Water*

The Warka Water Tower is a freestanding cylindrical wooden collector developed by architect Arturo Vittori to harvest fog, rain, and dew using a polyester mesh similar to the RM. The prototype is in exploratory phase intending to obtain a daily average of 40–80 l. The innovation of the 9-m-high tower lays in the fact that it is prefabricated, lightweight (80 kg), quickly built and easy to maintain through a minimal knowledge of tools. Moreover, it uses recyclable and local materials such as bamboo and is designed to be operated and owned by the locals [56, 71]. The fog-collecting mechanism and materials of the tower are inspired by organisms' hydrophobic or hydrophilic surfaces, or both, such as the Namib beetle's back, lotus flower leaves, spider webs and cacti. A promising first and second of 12 designs have already been constructed in Ethiopia and Cameroon, respectively. The price of the collector is unknown because of its large dependence on local materials, workforces and remoteness of the area [71]. A large canopy can be added around the structure for community gathering events [72], implicating that one Warka Tower is aimed for placement within and for the entire community living in fog-loaded areas, excluding the need for extensive pipelines, whereas the LFCs are mostly placed uphill near beneficiary villages.

7 DISCUSSIONS AND CONCLUSIONS

Water is a vital resource for all living creatures. Fog is essential for natural organisms to survive in arid climates, and researchers have learned a lot about this evolutionary phenomenon. Fog harvesting, being relatively new, clearly has great potential with an exciting interdisciplinarity blending biomimicry, indigenous knowledge, sociology, engineering and sciences. The search for innovative designs and low-cost and low-maintenance materials is an ongoing process enhancing this sustainable humanitarian technology. Bio-inspired research for ameliorating meshes as well as structures is still underexplored, nonetheless, with a great range of possibilities. Multiple projects of FogQuest and alternative fog collectors are described each with their merits and weaknesses but showing their exceptional ability as an alternative water resource. Most of these projects are intended for placement in specific rural fog-loaded areas where the population needs to rely on unreliable expensive truck-delivered water or where they need to spend full days walking to open wells or river basins. Besides, collecting possible contaminated water results in a high number of water-borne diseases and other health issues, hence the large benefits of fog collection for underprivileged communities. To conclude, some suggestions for future research are discussed. First, various factors need to be considered before implementing collectors within a community. The absent participation of communities, and obsolete local NGOs has a great influence on the failure of a project, calling for focused research to develop an adapted approach to communicate and educate rural people in need. Second, although the conceptual designs are more flexible and constructed with lightweight materials, studies show that strong winds require more robust structures, exposing the need for more extensive experiments in remote areas. Third, due to climate change and urbanization, water scarcity is becoming a bigger problem in arid metropolitan areas. One-third of the urban population, or 993 million, already experiences water stress [73]. Therefore, research towards urban-integrated fog collectors is highly recommended, especially in vulnerable urban areas. Lastly, collecting rainwater is a common practice for people living in rainy areas, regardless of their status. The average or wealthier population that are connected to a conventional water network living in fog-loaded arid regions do not profit from atmospheric moisture, which is a lost opportunity, mostly because they do not feel nor consider water scarcity to be a problem. Integrating this alternative as a (complementary) water resource into moderate households, with the help of governmental regulations, creates a sustainable freshwater supply and ultimately a sustainable future, and could positively change the opinion of the less fortunate.

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REFERENCES

[1] Kummu M, Ward PJ, de Moel H, Varis O. Is physical water scarcity a new phenomenon? Global assessment of water shortage over the last two millennia. *Environ Res Lett* 2010;**5**:034006.

[2] UNDP. Human Development Report. *Beyond scarcity: power, poverty and the global water crisis*. New York: UNDP, 2006. 2006.

[3] Modéer U. Climate smart water management is fundamental for sustainable development. 2020. https://www.undp.org/blog/climate-smart-water-management-fundamental-sustainable-development (25 March 2022, date last accessed).

[4] Domen JK, Stringfellow WT, Camarillo MK, Gulati S. Fog water as an alternative and sustainable water resource. *Clean Techn Environ Policy* 2014;**16**:235–49.

[5] Schemenauer RS, Cereceda P, Osses P. *FogQuest Fog Water Collection Manual*. 2022.

[6] Pawlyn M. *Biomimicry in Architecture*. London: Riba Publishing, 2011.

[7] Marloth R. Results of experiments on Table Mountain for ascertaining the amount of moisture deposited from the south-east clouds. *Trans SA Phil Soc* 1903;**14**:403–8.

[8] Marloth R. Results of further experiments on Table Mountain for ascertaining the amount of moisture deposited from the southeast clouds. *Trans SA Phil Soc* 1905;**16**:97–105.

[9] Qadir M, Jiménez GC, Farnum RL, Trautwein P. Research history and functional systems of fog water harvesting. *Front Water* 2021;**3**:37.

[10] Fessehaye M, Abdul-Wahab SA, Savage MJ *et al.* Fog-water collection for community use. *Renew Sust Energ Rev* 2014;**29**:52–62.

[11] Eugster W. *Fog Research DIE ERDE* 2008;**139**:1–10.

[12] Balaguer L, Arroyo-García R, Jiménez P *et al.* Forest restoration in a fog oasis: evidence indicates need for cultural awareness in constructing the reference. *PLoS One* 2011;**6**:e23004.

[13] Suau C, Zappulla C. AIRDRIP© pneumatic fog collector for rural and urban environments in arid lands. *JMEST* 2015;**2**:1936–42.

[14] Zamani N, Maleki M, Eslamian F. Fog water harvesting investigation as a water supply resource in arid and semi-arid areas. *Water Product J* 2021;**1**:43–52.

[15] Abdul-Wahab SA, Al-Hinai H, Al-Najar KA *et al.* Fog and rain water collection from trees in the Dhofar region in the Sultanate of Oman. *J Eng Res* 2009;**6**:51–8.

[16] Koch MA, Kleinpeter D, Auer E *et al.* Living at the dry limits: ecological genetics of Tillandsia landbeckii Lomas in the Chilean Atacama Desert. *Plant Syst Evol* 2019;**305**:1041–53.

[17] Azeem M, Guérin A, Dumais T *et al.* Optimal Design of Multilayer fog collectors. *ACS Appl Mater Interfaces* 2020;**12**:7736–43.

[18] Bhushan B. Design of water harvesting towers and projections for water collection from fog and condensation. *Philos Trans Royal Soc A* 2020;**378**:20190440.

[19] Mazzoleni I. *Architecture Follows Nature-Biomimetic Principles for Innovative Design*. Boca Raton: CRC Press, 2013.

[20] Klemm O, Schemenauer RS, Lummerich A *et al.* Fog as a fresh-water resource: overview and perspectives. *Ambio* 2012;**41**:221–34.

[21] Azeem M, Noman M, Petru M *et al.* Surface wettability of vertical harps for fog collection. *Surf Interfaces* 2022;**30**:101842.

[22] Montecinos S, Carvajal D, Cereceda P, Concha M. Collection efficiency of fog events. *Atmos Res* 2018;**209**:163–9.

[23] Schemenauer RS, Cereceda P. Fog collection's role in water planning for developing countries. *J Nat Resourc Forum* 1994b;**18**:91–100.

[24] Azeem M, Noman MT, Wiener J *et al.* Structural design of efficient fog collectors: a review. *Environ Technol Innovation* 2020;**20**:101169.

[25] Holmes R, Rivera J D D, de la Jara E. Large fog collectors: new strategies for collection efficiency and structural response to wind pressure. *Atmos Res* 2015;**151**:236–49.

[26] FogQuest. New video update from Guatemala. 2020. http://www.fogquest.org/new-video-update-from-guatemala/ (13 July 2022, date last accessed).

[27] Schemenauer RS, Zanetta N, Rosato M *et al.* 2016. The Tojquia, Guatemala Fog Collection Project 2006 to 2016. In Błaś M, Sobik M (eds). *Proceedings of the 7th International Conference on Fog, Fog Collection and Dew*. Wroclaw.

[28] García JL, Schemenauer R, Rosato M *et al.* 2004. Guatemala Fog Collection Project, 2004. 2004. In *Proceedings of the 3th International Conference on Fog, Fog Collection and Dew, Cape Town*.

[29] Escobar CM, Lopez A, Aristizabal HF *et al.* 2010. Operational fog collection and its role in environmental education and social reintegration: A case study in Colombia. In *Proceedings of the 5th International Conference on Fog, Fog Collection and Dew*. Münster.

[30] Carter V, Schemenauer R, Osses P *et al.* 2007. The Atacama Desert Fog Collection Project at Falda Verde, Chile. In *Proceedings of the 4th International Conference on Fog, Fog collection and Dew*. La Serena.

[31] Osses P, Schemenauer RS, Cereceda P *et al.* Los atrapanieblas del Santuario Padre Hurtado y sus proyecciones en el combate a la desertificación. *RGNG* 2000;**27**:61–7.

[32] FogQuest. Chile PADRE HURTADO. 2009. http://www.fogquest.org/project-information/projects/chile-padre-hurtado/ (12 April 2022, date last accessed).

[33] FogQuest. Nepal. 2012. http://www.fogquest.org/project-information/current-projects/nepal/ (14 April 2022, date last accessed).

[34] de la Lastra C. *Report on the Fog-Collecting Project in Chungungo: Assessment of the Feasibility of Assuring its Sustainability*. Ottawa, Canada: International Development Research Centre (IDRC), 2002.

[35] Correggiari M, Castelli G, Bresci E, Salbitano F. 2017. Fog Collection and Participatory Approach for Water Management and Local Development: Practical Reflections from Case Studies in the Atacama Drylands. In Ouessar M, Gabriels D, Tsunekawa A, Evett S (eds). *Water and Land Security in Drylands*. Cham: Springer International Publishing.

[36] Fessehaye M, Abdul-Wahab SA, Savage MJ *et al.* The potential for scaling up a fog collection system on the eastern escarpment of Eritrea. *Mt Res Dev* 2015;**35**:365–73.

[37] Fessehaye M, Abdul-Wahab SA, Savage MJ *et al.* Assessment of fog-water collection on the eastern escarpment of Eritrea. *Water Int* 2017;**42**:1022–36.

[38] Olivier J, Van Heerden J, DeW JC. Et al. *Fog as an Alternative Water Resource* .

[39] Olivier J, de Rautenbach CJ. The implementation of fog water collection systems in South Africa. *Atmos Res* 2002;**64**:227–38.

[40] van Heerden J, Olivier J, Van Schalkwyk L. 2010. Fog Water Systems in South Africa: An Update. In *Proceedings of the 5th International Conference on Fog, Fog Collection and Dew*. Münster.

[41] FogQuest. Yemen HAJJA/MABIJAN. 2009. http://www.fogquest.org/project-information/projects/yemen-hajjamabijan/ (8 April 2022, date last accessed).

[42] Sivanappan RK. 2006. Rain Water Harvesting, Conservation and Management Strategies for Urban and Rural Sectors. In *National Seminar on Rainwater Harvesting and Water Management*. Nagpur.

[43] Batisha AF. Feasibility and sustainability of fog harvesting. *Sustain Water Qual Ecol* 2015;**6**:1–10.

[44] Qadir M, Jiménez G, Farnum R *et al.* Fog water collection: challenges beyond technology. *Water* 2018;**10**:372.

[45] Juvik J, Nullet D. Comments on 'a proposed standard fog collector for use in high-elevation regions. *J Appl Meteorol* 1995;**34**:2108–10.

[46] Park KC, Chhatre SS, Srinivasan S *et al.* Optimal Design of Permeable Fiber Network Structures for fog harvesting. *Langmuir* 2013;**29**:13269–77.

[47] Rajaram M, Heng X, Oza M, Luo C. Enhancement of fog-collection efficiency of a Raschel mesh using surface coatings and local geometric changes. *Colloids Surf A Physicochem Engg Asp* 2016;**508**:218–29.

[48] Fernandez DM, Torregrosa A, Weiss-Penzias PS *et al.* Fog water collection effectiveness: mesh Intercomparisons. *Aerosol Air Qual Res* 2018;**18**:270–83.

[49] Schunk C, Trautwein P, Hruschka H *et al.* Testing water yield, efficiency of different meshes and water quality with a novel fog collector for high wind speeds. *Aerosol Air Qual Res* 2018;**18**:240–53.

[50] Lummerich A, Tiedemann KJ. Fog harvesting on the verge of economic competitiveness. *Erdkunde* 2011;**65**:305–6.

[51] Shi W, Anderson MJ, Tulkoff JB *et al.* Fog harvesting with harps. *ACS Appl Mater Interfaces* 2018;**10**:11979–86.

[52] Korkmaz S, Kariper İA. Fog harvesting against water shortage. *Environ Chem Lett* 2020;**18**:361–75.

[53] Bai H, Zhao T, Wang X *et al.* Cactus kirigami for efficient fog harvesting: simplifying 3D cactus into 2D paper art. *J Mater Chem A* 2020;**8**:13452–8.

[54] Höhler I. 2010. DROPNET Fog Collection and Lightweight Construction. In *Knowledge Collaboration & Learning for Sustainable Innovation ERSCP-EMSU conference*. Delft.

[55] Choiniere-Shields E. The cloud harvester catches and stores fresh water from fog. 2013. https://inhabitat.com/httpinhabitat-comwp-adminpost-phppost519497actioneditmessage1/cloud-harvester-2/ (17 December 2021, date last accessed).

[56] Jarimi H, Powell R, Riffat S. Review of sustainable methods for atmospheric water harvesting. *Int J Low-Carbon Technol* 2020;**15**:253–76.

[57] Fernández González A, Ortega GS. Coastal Fog Tower – Design and Fabrication Process of a Vertical Fog Capture Device. In *Proceedings of the 22th Conference of the Iberoamerican Society of Digital Graphics*. São Carlos, 2018.

[58] Fernandez G, Morichi G, Bandeira CL. 2019. Exploring fog harvesting nature-based solution tensile membrane structures towards sustainable development in the Italian urban context. In *Proceedings of the TensiNet Symposium*. Milan.

[59] Suau C. 2012. 3D Fog Collection along the Coastal Atacama Desert. In *Proceedings of the 28th International PLEA Conference - Opportunities, Limits and Needs*. Lima.

[60] Suau C. 2010. Fog Collection and Sustainable Architecture in Atacama Coast. In *Proceedings of the 5th International Conference on Fog, Fog Collection and Dew*. Münster.

[61] Farnum RL. 2022. Fog Harvesting. In Qadir M, Smakhtin V, Koo-Oshima S, Guenther E (eds). *Unconventional Water Resources*. Switzerland: Springer.

[62] Wasserstiftung. Morocco Mount Boutmezguida. 2022. https://www.wasserstiftung.de/en/morocco-mount-boutmezguida/ (18 July 2022, date last accessed).

[63] aqualonis. Fog harvesting. 2021. https://www.aqualonis.com (18 December 2021, date last accessed).

[64] fognetalliance. CloudFisher. 2021. https://www.fognetalliance.org/cloudfisher (18 December 2021, date last accessed).

[65] Murray-Nag B. CloudFisher turns fog into drinking water in Morocco's driest regions. 2017. https://www.designboom.com/technology/cloudfisher-fog-net-water-foundation-02-02-17/ (18 December 2021, date last accessed).

[66] Dodson LL. *A foggy desert: Equitable information flow for a fogwater system in southwest Morocco*. Ph.D. Thesis,. Boulder: University of Colorado, 2014.

[67] Dodson LL, Bargach J. Harvesting fresh water from fog in rural Morocco: research and impact Dar Si Hmad's Fogwater project in Aït Baamrane. *Procedia Eng* 2015;**107**:186–93.

[68] Nieblagua. Nieblagua Captación de aguas atmosféricas. 2018. https://www.nieblagua.com/ (25 July 2022, date last accessed).

[69] Neira CM. Atacama tierra de emprendedores: Tomás Garay, emprendiendo con conciencia en la crisis hídrica. 2016. https://www.elquehaydecierto.cl/noticia/sociedad/atacama-tierra-de-emprendedores-tomas-garay-emprendiendo-con-conciencia-en-la-crisi (16 July 2022, date last accessed).

[70] Creativo C. Diseñador chileno crea atrapanieblas tridimensional Para enfrentar la escasez de agua. 2016. https://campuscreativo.cl/disenado

r-chileno-crea-atrapanieblas-tridimensional-para-enfrentar-la-escasez-de-agua/ (16 July 2022, date last accessed).

[71] Warka Water. Warka tower. 2021. https://www.dropbox.com/s/fkndnqmnzcl52pz/WW_PR_WTower_210530_WP_08.pdf?dl=0 (18 December 2021, date last accessed).

[72] Kakade S, Kumar Pandit T, Patel S *et al. Warka Water Tower : an innovative water harvesting technique from thin air*. Bachelor Thesis,. Mumbai: University of Mumbai, 2018.

[73] He C, Liu Z, Wu J *et al.* Future global urban water scarcity and potential solutions. *Nat Commun* 2021;**12**:4667.