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Research History and Functional Systems of Fog Water Harvesting

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Water is among the top five global risks in terms of impacts translated through socio-economic and environmental challenges, influencing people's wellbeing. The situation is grim in water-scarce countries, which need to think and act beyond conventional water resources and tap unconventional water supplies to narrow the gap between water demand and supply. Among unconventional water resources, water embedded in fog is increasingly seen as a source of potable water in dry areas where fog is intense and prevalent. Although a low maintenance option and a green technology to supply freshwater, the potential to collect water from air through fog harvesting is by far under-explored. Based on the comprehensive analysis of fog water collection's research history since 1980, this study reveals that recent years have witnessed a sharp increase in research related to technological developments in fog collection systems. Also, there is an increased focus on associated policy and institutional aspects, economics, environmental dimensions, capacity building, community participation, and gender mainstreaming. In addition to research, fog water collection practice has also increased over time with emerging examples worldwide, notably from Canary Islands, Chile, Colombia, Eritrea, Ethiopia, Guatemala, Israel, Morocco, Namibia, Oman, Peru, and South Africa. The functional systems of fog water collection demonstrate community engagement, women empowerment, enhanced capacity and training, and active participation of local institutions as the key drivers for effective fog collection systems to provide a sustainable supply of freshwater to the associated communities.

Keywords: water scarcity, water quality, SDG 6, potable water, dry areas, unconventional water resources

INTRODUCTION

Five years into the 2030 Sustainable Development Agenda, the latest assessments suggest that most countries are not on track to achieve Sustainable Development Goal (SDG) six by 2030 [United Nations (UN), 2018], particularly those characterized as water scarce. Thus, access to and availability of water resources have become the key to ensuring water-related sustainable development across dry areas (Sultana, 2018; Guppy et al., 2019). The conventional water resources—snowfall, rainfall, river runoff, and easily accessible groundwater—are not enough to address growing freshwater demand in water-scarce areas (Mehta, 2003; Rijsberman, 2006; Falkenmark, 2018; UN-Water, 2020).

Demographic trends, future growth projections, and changing climate and rainfall patterns suggest that localized water scarcity will worsen in many regions, affecting even more area and

associated populations (Mekonnen and Hoekstra, 2016; Damania et al., 2017). Thus, water-scarce areas must sustainably access and utilize every available water resource augmentation option to minimize the water demand-supply gap that continues to grow. Unconventional water resources are an emerging opportunity for water resource augmentation in dry areas (Qadir et al., 2018; UN-Water, 2020). Amongst the unconventional water resources, the potential to recover water directly from fog is by far one of the most under-explored community-level water resource supply options.

Under pertinent conditions, the air at ground level may contain suspended water droplets with diameters ranging between 1 and 50 μm, generally understood as fog (Ritter et al., 2015). These suspended water droplets accumulate by creating a mass of humid air that could represent a valuable freshwater source, especially in arid environments. Fog is collected using a vertical mesh that intercepts the droplet stream (moist air stream), producing suspended water droplets' collision and coalescence. This water then runs down into a collection gutter and a storage tank or distribution system (Abdul-Wahab and Lea, 2008; Fessehaye et al., 2017).

There are different types of screen materials that can be used to develop the fog collectors consisting of vertical mesh, such as aluminum, plastic, plexiglass, and alloy nets (Abdul-Wahab et al., 2010; Azeem et al., 2020; Li et al., 2020). The geography and topography of potential fog harvesting sites need to be conducive to dense fog, especially in dry areas where rainfall events are sporadic. These conditions may include a high mountain range close to a coastline and perpendicular to the wind for optimal fog interception (Fessehaye et al., 2014).

In addition, bioinspired materials and surfaces are being developed to improve water supply and purification in a more environmentally sustainable manner. Bioinspired water collectors can be used to provide a supplemental source of water for communities in the arid regions where fog events and water condensation are common, such as coastal regions of Africa, the southwestern coast of South America, and the southwestern United States (Bhushan, 2019). In recent years, studies have also undertaken on bionic fog collection by developing specific materials for harvesting fog water in dry areas where fog intensity and events are common (Bai et al., 2018).

Fog water harvesting is a practical and, in certain circumstances, a cost-effective way to deliver freshwater directly to thousands of people living in rural communities (**Photo 1**; LeBoeuf and de la Jara, 2014). In addition to minimal operational and maintenance costs, fog water usually adheres to drinking quality standards—unless the fog collection sites are adjacent to urban areas that generate high amounts of emissions or air pollutants, which may end up in the fog (Nieberding et al., 2018).

As a green technology, fog harvesting is also an environmentally friendly intervention that does not rely on energy consumption nor has adverse environmental effects in surrounding areas. The atmospheric water represents only 0.001% of total water in the world and 0.04% of freshwater (Nasa Earth Observatory, 2010); thus, the amount of water that could be harvested through fog collection remains negligible. Similarly,

no adverse effects of fog water collection have been reported on local vegetation, insects, and the dependent ecosystems.

The scientific interest in studying and measuring fog as a natural water resource started in the early 1900s. One of the first documented experiments to investigate fog feasibility as an alternative water resource was undertaken between 1901 and 1904 in South Africa (Olivier, 2002). Significant developments in fog collection have occurred since then. In the last decades, there has been an increasing number of research studies addressing such aspects of fog harvesting as technical features, policy and institutions, gender, community development, economics, capacity building, and its possible environmental impacts (Fessehaye et al., 2014; Qadir et al., 2018; Azeem et al., 2020; Li et al., 2020). Similarly, the number of operational fog water collection systems has also increased over time, with examples of functional systems emerging worldwide.

To date, there is no comprehensive assessment available on the thematic focus and timeline of the research conducted on different aspects of fog water collection. Furthermore, information on successful examples of fog water collection systems is fragmented. This paper aims to fill these gaps. It presents the research history of fog water collection, segregated by decade since 1980, and categorizes publications by the specific aspects of fog water collection they address. This paper also presents five examples of functional systems of fog water collection—"bright spots"—along with specific information on each case's critical technical and operational aspects. These aspects for each case include (1) site and community characterization, (2) gender mainstreaming and community engagement, (3) operational elements, and (4) stakeholder involvement. This paper does not address the history of engineering and technical developments around fog collection systems as excellent reviews (Klemm et al., 2012; Fessehaye et al., 2014; Bhushan, 2019) on these aspects are already available in the literature.

RESEARCH HISTORY OF FOG WATER COLLECTION

In the literature search process, academic publications about fog water harvesting were identified using critical literary databases—Google Scholar, Web of Science, and Science Direct—and scientific journals, books, as well as conference and workshop proceedings. The search phrases used in the study were: "fog water," "fog water harvesting," "fog collectors," "fog collection," and "fog water collection." The articles included in the literature search were written in English and published between 1981 and 2020. Following a systematic representation, these articles were organized by their decade of publication: 1981–1990, 1991–2000, 2001–2010, and 2011–2020. Any other publications outside of the parameters mentioned above were not included in this study.

The articles' titles, abstracts, and contents were individually evaluated to confirm their relevance based on the following topics: technical and operational aspects, history of the technology, policy and institutional dimensions, gender-related aspects, community involvement and development, economic

PHOTO 1 | Fog water collection systems (Credit: Aqualonis).

and financial aspects, and capacity building and environmental trade-offs. In many cases, articles addressed more than one topic.

These publications' technical features referred to the relevance, applicability, and improvements to the fog water quality and collection technologies. History referred to the evolution of fog collection processes and review of case studies. Policy and institutional dimensions included policies on fog water collection and relevant organizations, particularly local institutions, in fog collection projects. Gender aspects focused on the role of women in fog water collection processes and potential improvements in their lives due to fog water harvesting. Community involvement included the participation of associated communities in fog collection systems. Economic and financial aspects referred to the related costs and financial analysis based on the design, size, type, and dimensions of the fog collection mesh as well as operation and maintenance of the fog collection systems. Capacity building highlighted the consideration of education and training to support the sustainability of the fog collection systems. Environmental trade-offs included environmental impacts and ecological studies related to fog water harvesting, such as fog water quality related to atmospheric emissions and pollution.

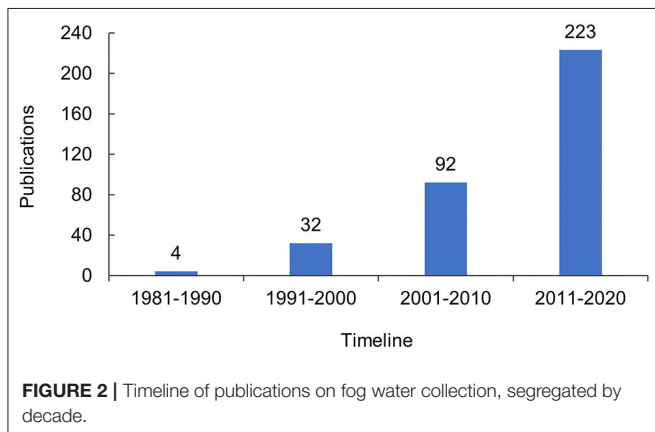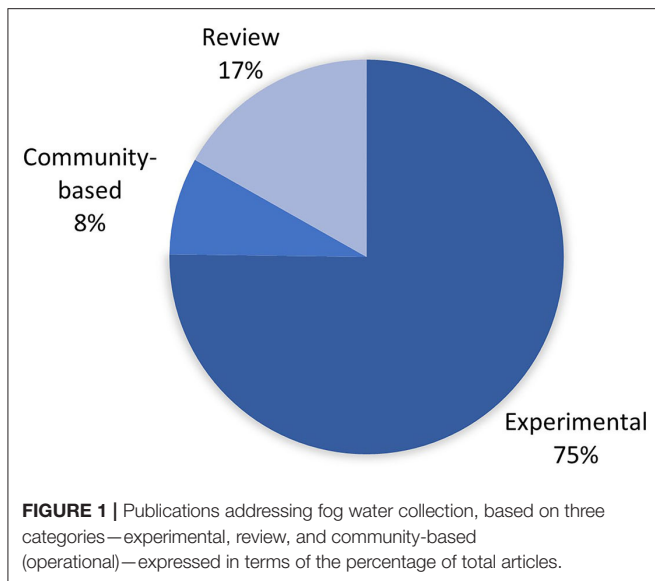The publications were individually classified under one of the three categories: experimental, operational, or review. The experimental group included pilot or controlled-environment studies of fog collection technologies as well as fog water quality and fog harvesting simulations or modeling of the experimental results. Operational referred to publications based on large projects implemented at the community level for several years. The review category included publications based on desk studies that involved several past case studies and reviewed various aspects of the fog harvesting projects.

To analyze trends of the fog harvesting research, a database was created with the following information: title, author(s), year of publication, and citation details, together with the area, country, and region of the study.

Analysis of the studies on different aspects of fog water collection reveals 351 publications since 1980. Of these publications, 75% are based on experimental studies, 17% are classified as review publications, and only 8% are based on operational projects implemented on a long-term basis at the community level (**Figure 1**). This indicates that while fog water collection is relatively new to the scientific literature, there is a clear need for more research to analyze grounded case studies.

Temporal assessment of the fog water collection publications suggests a trend of a consistent increase in the number of articles published. For example, only four publications addressed fog water collection between 1981 and 1990, but 32 between 1991

FIGURE 1 | Publications addressing fog water collection, based on three categories—experimental, review, and community-based (operational)—expressed in terms of the percentage of total articles.

FIGURE 2 | Timeline of publications on fog water collection, segregated by decade.

FIGURE 3 | Publications organized by theme and decade. In cases where a publication addresses more than one theme, it was added to more than one relevant group.

and 2000. The number of publications tripled to 92 between 2001 and 2010 and rose to 223 between 2011 and 2020 (**Figure 2**). This trend reveals that there is a growing interest in fog water collection among researchers, particularly in addressing water resource management in water-scarce areas, in both technical and non-technical aspects of fog water collection.

While reviewing these publications' scope, we found that the majority addressed technical aspects of fog water collection systems. Until 2000, the research on other aspects of fog water collection (history, policy and institutions, gender-related, community engagement, economic, capacity building, and environmental trade-offs) received relatively little attention from scientists. Since 2000, there has been an increasing number of publications based on studies that addressed one or more of the following aspects: policy and institutions, gender, community development, economics, capacity building, and environmental trade-offs (**Figure 3**). It is essential to see that the total number of publications displayed in **Figure 3** exceeds the total number of publications on fog water collection (351 publications) analyzed in this study. This is because some studies addressed more than
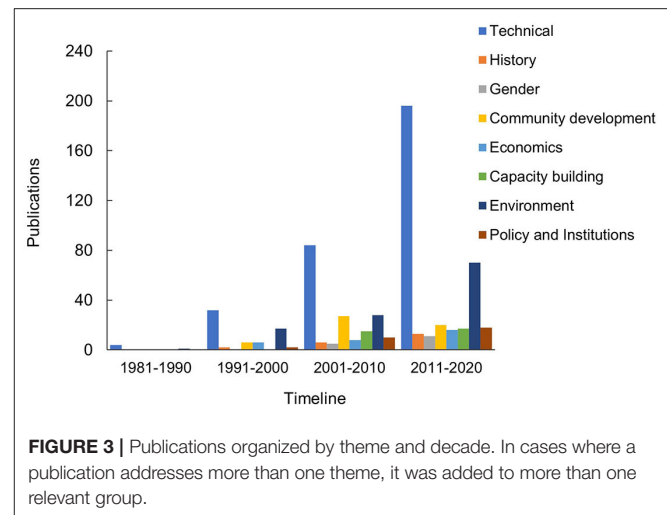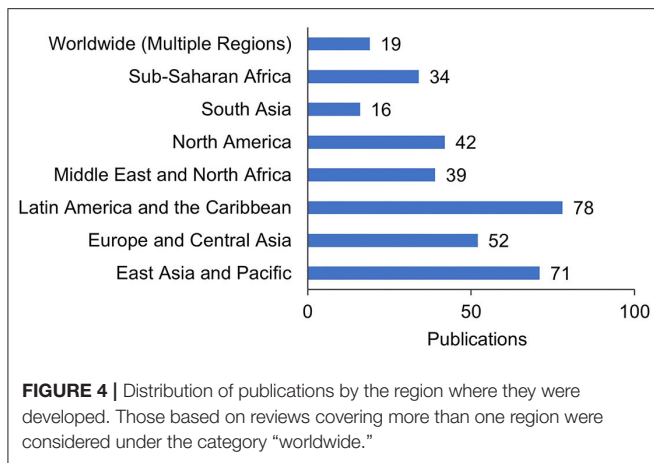
one aspect of fog water collection systems. Thus, in cases where a publication addressed more than one aspect, it was added to more than one, but relevant thematic groups.

Despite a growing interest in exploring the non-technical facets of fog water collection in recent years (Klemm et al., 2012; Dodson and Bargach, 2015; Fessehaye et al., 2017; Farnum, 2018; Qadir et al., 2018), the publications on technical research remain higher than the publications on research surrounding non-technical factors. However, the gap between the number of academic publications addressing technical and non-technical aspects of fog water collection has narrowed over the years, and this trend is expected to continue.

Considering the geographical distribution of fog water harvesting projects and studies, **Figure 4** presents the distribution of publications by their region of origin. The number of studies per region, in descending order: Latin America and the Caribbean (78), East Asia and Pacific (71), Europe and Central Asia (52), North America (42), Middle East and North Africa (39), Sub-Saharan Africa (34), and South Asia (16). Some of the articles were under "worldwide" (19) as they were review articles covering more than one region. Within a region, most of the studies are concentrated in specific geographic and topographic areas determined by the occurrence of fog events. For example, multiple research sites are in Chile, Peru, South Africa, Morocco, China, the USA, and Spain (Canary Islands).

FUNCTIONAL SYSTEMS OF FOG WATER COLLECTION

Site selection is the key to effective fog water collection and starts with the following two major assessment parameters. First, identification of potable water demand in areas where available water resources are far away and time consuming, or where alternate sources, such as water tankers, are prohibitively expensive. Second, meteorological data of the target areas supports that fog intensity and duration are suitable for

FIGURE 4 | Distribution of publications by the region where they were developed. Those based on reviews covering more than one region were considered under the category "worldwide."

implementing fog water collection systems (Batisha, 2015). Based on these considerations, multiple sites worldwide have been identified and established to collect fog water for potable uses and, to a limited extent, for livestock and agriculture.

Fog water collection projects have been undertaken in several countries, including Namibia (Shanyengana et al., 2002), South Africa (Olivier, 2004), Saudi Arabia (Gandhidasan and Abualhamayel, 2007; Al-Hassan, 2009), Egypt (Harb et al., 2016; Salem et al., 2017), Azerbaijan (Meunier and Beysens, 2016), Ethiopia (FogQuest, 2017a), Sultanate of Oman (Abdul-Wahab and Lea, 2008), Israel (FogQuest, 2017a), Colombia (García-Ubaque et al., 2013), Chile (FogQuest, 2017a), and the Canary Islands (Marzol, 2002), among others.

In most fog water collection projects, the type of fog reported is advection fog (Fessehaye et al., 2014), formed by the contact of moist, warm wind on a cool surface, producing vapor condensation in small, suspended droplets in the air. Advection fog usually appears where warm tropical air touches the oceans' cooler surface, providing a layer of fog that later rises due to its temperature.

While there are several examples of fog water harvesting functional systems, there are also fog harvesting projects that have not been implemented successfully due to particular social, economic, and political challenges. The reasons reported for unsuccessful projects include a lack of community engagement and gender mainstreaming, limited funding and lack of financial feasibility mechanism, inadequate local stakeholder management, low equipment maintenance, and social instability in the project area. Some fog water collection projects in Chile, Nepal, Dominican Republic, Ecuador, Yemen, Guatemala, and Haiti were terminated at different implementation stages due to at least one of these factors (FogQuest, 2017b).

The following are five examples of functional fog water collection systems, termed "bright spots," drawn from different parts of the world. These examples seek to showcase that fog water collection can increase water availability for associated communities where this valuable resource is available. The key aspects of functional systems of fog water collection in Guatemala, Eritrea, Chile, Peru, and Morocco are summarized in **Table 1**.

Guatemala: La Ventosa and Tojquia

La Ventosa and Tojquia are small, isolated, rural villages located in the Cuchumatanes Mountain range in Guatemala's western highlands, at an elevation of 3,300 m above sea level. The weather conditions are characterized by two seasons: dry season runs from November to April, while the wet season starts from May and ends at the end of October. Fog events are frequent in the dry season allowing the community to use collected fog water as a new potable water source. During the wet season, rooftop rainwater harvesting is practiced using containers and filters (Schemenauer et al., 2007). La Ventosa has a population of 60 people, while approximately 50 families live in Tojquia. Both communities have the prevailing Mayan culture, which is based on cultural and linguistic heritage and characteristic of one of the most important ancient civilizations inhabited in the Americas. There are sensitivities to photography and videography since they are perceived as potential culture appropriation (Schemenauer et al., 2007). The spoken language is almost exclusively Mam, except for a few women who can speak Spanish. Some men also talk in Spanish due to the migration for seasonal labor. Formal schooling ends at the age of 12, with low or nonexistent female attendance. Thus, illiteracy rates in the area are high.

Language, illiteracy, and cultural differences in the area were initial concerns to harness project implementation scope. For example, it is inappropriate for a male outsider to interact with a local female in the absence of a male family member (Schemenauer et al., 2007). Such issues were addressed through the community members' active involvement for the willingness to cooperate in harnessing the potential of fog water collection.

In the indigenous Guatemalan societies, women perform traditional house chores and participate in agricultural work, including collecting and transporting water. Women carry water containers by balancing them in their heads, walking long distances from the springs to Tojquia and La Ventosa. The outfit worn is like the daily traditional ankle-length skirt and plastic slippers, making the hike even more difficult. It was found that a greater cross-cultural understanding and targeting of gender-specific needs were required for the project to succeed in these villages (Schemenauer et al., 2007). Building trustworthy and respectful relations with community members and families improved the sustainability and success of fog water collection in these villages. Respecting and acknowledging the cultural aspects and traditions in place and including the beneficiaries from the project's planning stages enhanced local involvement, capacity building, and leadership within the community. Simultaneously, public approval of the technology made it possible to integrate and complement traditional and external knowledge (Schemenauer et al., 2016).

Fog collection systems have been installed and operated for more than 12 years in these communities. The project started with four Large Fog Collectors (LFCs) in La Ventosa in 2005; four LFCs were installed in Tojquia in 2006; and later, men and women from the village completed the installation of five new LFCs in collaboration with FogQuest (FogQuest, 2018). In total, 35 LFCs have been installed. A total of 1,640 m^2 of LFC

TABLE 1 | Summary of key aspects of functional systems of fog water collection.

Country	Site characterization	Gender and community aspects	Technical and stakeholders' aspects	Trade-offs
Guatemala	La Ventosa and Tojquia are small, isolated, rural villages at an elevation of 3,300 m above sea level near the top of Cuchumatanes Mountain.	Water collection is a women's assigned task. High levels of cross-cultural understanding and addressing gender-specific needs are vital for project's success.	A total of 1,640 m^2 of mesh collects water at daily average of 8.5 m^3. Collaborative efforts amongst stakeholders have led the success of this project.	Community engagement, capacity building, collaborative work, and active participation of local institutions and leaders.
Eritrea	Small settlements of Arborobue (827 people) at 2,085 m above sea level, and Nefasit (3,990 people) at 1,725 m above sea level.	Water access is limited due to the topography. Water collection is the responsibility of women and girls, which restricts their development.	In Arborobue, the average daily fog water collection is 3.1 L/m^2 and it is 1.4 L/m^2 in Nefasit. Trained community members have made committees to manage fog collection systems.	Due to economic limitations, initial costs need to be subsidized by external organizations. Community participation and education in fog water collection are key for project sustainability.
Chile	Falda Verde is 5 km north of the city of Chañaral and 1.5 km to the coastal line in Chile (altitude 600 m above sea level; annual average precipitation of 30 mm).	The community created an association to install the fog collectors to sustainably improve the local economy.	The project is based on 14 LFCs, a piping network and water storage with an average daily collection at 1 m^3. This project received support from multiple stakeholders.	Some of the domestic water needs of the communities are covered by municipal services. This project provides communities with the opportunity to use fog water for other purposes.
Peru	Villa Maria del Triunfo is in the outskirts of Lima, at 294 m above sea level. At least 35% of people are abysmal and lack access to water.	Most of the inhabitants receive water by delivery trucks, with significant concerns regarding unaffordable prices and water quality.	The project daily collects 300–400 L of water per collector during right fog conditions. A local NGO and the community are the primary stakeholders.	The community is supported and encouraged by the local NGO, which triggers this project's success.
Morocco	Aït Baamrane region of the Anti-Atlas range in Southwest Morocco, on top of Mount Boutmezguida, at an altitude of 1,225 m above sea level.	Gender inequality and cultural norms restricted initial female involvement in the project. The project has explicitly addressed gender concerns.	Multiple institutional collaboration leads to developing the world's most extensive functional fog collection system with a daily water supply of up to 22 L/m^2 of mesh.	Positive impacts in the community by the active engagement of women. The community is involved in the system's maintenance, having a sense of ownership of the project.

mesh collects a daily average of 8,500 L (8.5 m³) of water during the dry season, i.e., about 5 L/m² of mesh (Schemenauer et al., 2016).

Collaborative efforts among stakeholders have led to the success of this project. The project idea was initially introduced by FogQuest (http://www.fogquest.org/) and supported by local people and leadership and funding entities. Additionally, the local community created a water committee for project management to oversee the maintenance of the fog water collection system (Schemenauer et al., 2016).

Safe access to drinking water, education, and capacity development were the main benefits reported from the fog water projects. The four critical elements identified were: adaptation of the project to community needs and idiosyncrasies (community development); co-creation and transfer of technology and management of fog collection systems (capacity building); collaborative work and community engagement; and active participation of local organizations and leaders. The long-term sustainability of these fog collection projects in La Ventosa and Tojquia areas hinges on obtaining further funding. Even though the local community currently manages the project, securing financial support from local institutions and the government remains a challenge (Schemenauer et al., 2016).

Eritrea: Arborobue and Nefasit

About 70% of Eritrea is hot and arid, with an average annual rainfall of less than 350 mm. To alleviate local water scarcity, a fog water harvesting project was implemented in two villages: Arborobue and Nefasit. The population of the Arborobue is 827 people, and it is located at 2,085 m above sea level, while Nefasit has a population of 3,990 and the village is located at 1,725 m above sea level. The main economic activity in both villages is daily labor, with only 10–15% of the population working in agriculture and small businesses. The fog collection period in these communities runs from September to December. The community uses water stored during these months as a drinking water source during the remaining part of the year (Fessehaye et al., 2017).

Access to water is limited in these communities due to the area's topography, making it difficult and expensive to design water distribution systems. The utility prices for conventional water distribution in rural zones of Eritrea range from $1.7 and $3.3 per m³ of water delivered (Fessehaye et al., 2017). Where there is no water delivery, or when the communities cannot afford it, water collection falls to women and girls' responsibilities, who are required to walk long distances to fetch water, restricting their human and social development.

Fog collection systems were initially installed in 2007. Each system consisted of 10 LFCs with 40 m^2 of mesh (10 × 4 m) along with one sedimentation tank with a capacity of 2 m^3; a water storage system for 13 m^3 water; and a distribution point with a pipeline network of 552 m that delivers water by gravity. Energy is not required at any stage of the process. In Arborobue, the average daily fog collection rate is 3.1 L/m^2, while in Nefasit it stands at 1.4 L/m^2. In a subsequent stage of the project implementation, locally trained experts could expand the system with the installation of 10 additional LFCs to the distribution network in Arborobue (Fessehaye et al., 2017).

In the initial stages of these projects, the governmental and non-governmental institutions and experts implemented and managed the fog collection systems along with training of the local community to maintain and optimize the fog collection process. Such activity went to the point that the communities could make beneficial modifications to some LFCs to withstand high winds. They also established water committees to manage the system more effectively. The committees consist of elected community members and a hired local operator who oversees and operates the water collection and distribution.

Although the communities receive economic support from governmental institutions, such support needs to continue to keep the fog water collection systems functional. Besides, financial support from the government or international donor organizations is also required to out-scale the technology to other suitable locations, where initial costs need to be subsidized through funds.

In Nefasit and Arborobue, communities consider that the significance of fog harvesting lies in its safety and simplicity, and durability in harsh weather conditions such as strong winds. As community involvement is vital from planning to implementation, continuous education of the population about the potential of this unconventional water resource is also essential. In Eritrea, communities reflected that a significant part of the people in other similar communities does not understand or know about fog harvesting and its advantages (Fessehaye et al., 2017), which inevitably hinders the out-scaling of these types of projects.

Chile: Falda Verde

With 5 km north of Chañaral and 1.5 km from Chile's coast, Falda Verde is at an altitude of 600 m above sea level. The area receives annual average precipitation of 30 mm (Carter et al., 2007; Correggiari et al., 2017). Because of the arid conditions of Chañaral, the community suffers from limited access to clean water. The community created an association to engage in the fog collection project, named Atacama Fog Collection Group. It consists of 20 fishers who at least completed high school and were keen to diversify their incomes. With fishing as their main economic activity, they wanted to install fog collectors to water plants and enhance food production. The group has been together since 2001 with a firm commitment to the project. Their families do not participate directly in the project, and their wives usually work in household chores (Carter et al., 2007; FogQuest, 2009).

The fog water collection project consisted of 10 LFCs with mesh surfaces between 40 and 48 m^2 with a daily supply of 600 L of clean water. In 2005, the system was expanded with four new LFCs along with a piping network and new water storage facilities to increase the average daily collection rate to 1,000 L (Correggiari et al., 2017). There have not been reported cultural barriers as the initiative went through a bottom-up approach. This makes the community familiar with the technology, leading to easier adoption and effective implementation.

The local economy has significantly improved after years of running the fog water collectors. Initially, the community produced tomatoes, pumpkins, potatoes, corn, and olives (Carter et al., 2007). Lately, the community has been benefiting from tourism and Aloe Vera production. Seeing the benefits from the fog water collection projects, the Catholic University of the North is developing educational programs to support fog collection systems for research and food production in the region (Universidad Católica del Norte, 2017). Chile is among one of the first countries to develop local expertise on fog water collection.

Peru: Villa Maria del Triunfo

At 294 m above sea level, the fog water collection site is at Villa Maria del Triunfo on the outskirts of Peru's capital city, Lima. Around 400,000 people live in this area, with at least 35% of the population lacking access to safe water and living in extreme poverty (Creating Water Foundation, 2017). These are isolated suburban people not connected to the main water supply networks. Most of the inhabitants receive water by delivery trucks and face concerns about the water price and its quality. In these municipalities, the price for water delivery is about ten times greater than the conventional network supply. The delivery is irregular and unscheduled. Also, the quality of the water delivered by trucks warrants that it must be boiled before being consumed, which increases the household's energy expenses (Creating Water Foundation, 2016).

The local NGO called Peruvians without Water, the Creating Water Foundation, and the local community are the main stakeholders in the fog water collection project. The community was interested in participating from the project's onset, and the community people of all ages and genders have assumed essential roles in the implementation (Creating Water Foundation, 2016). The Creating Water Foundation provided the required technical knowledge and led the fog collection process's construction and implementation. The knowledge transfer to the community-supported capacity building regarding operation and maintenance to ensure fog water collection sustainability. The community has been highly supported and encouraged by the Peruvians Without Water, which serves as the key link between the community and the Creating Water Foundation.

The project collects water around 300–400 L/day per collector under conducive fog water collection conditions. Fog water collection systems address some of the community's main concerns: water quality, food security, and utility costs.

Morocco: Aït Baamrane

The fog collection project is installed on top of Mount Boutmezguida at an altitude of 1,225 m above sea level in the

Aït Baamrane region of the Anti-Atlas range in Southwest Morocco. The arid ecosystem receives an annual rainfall of only 112 mm but experiences frequent fog events at an average of 143 days a year. Fog events mostly occur during the wet season between December and June. Just 35 km from the Atlantic Ocean coastline, the area receives stratocumulus clouds created jointly by the Azores anticyclone and a cold current from the Canary Islands. The resulting fog is thick and ideal for water collection (Dodson, 2014; Dar Si, 2017).

Most of the inhabitants near the Mount Boutmezguida fog water collection site are Berbers—indigenous people. The Berber people are a socio-economically marginalized population. The villages close to the fog water collection project typically lack established public services such as water, sanitation, health, education, and financial opportunities (Dodson, 2014).

With gender inequality, the male segment of the society dominates the political scene and labor force. The school enrolment and literacy rates are highly skewed toward men. Cultural norms restrict female behavior in traveling, communicating with non-family members, and attending educational or healthcare centers. Limited economic opportunities in rural areas have driven remittance labor patterns, with males migrating to urban centers and females taking on increased household responsibilities as de facto single mothers. While women seemingly gain some power in men's absence, male-dominated systems continue to dominate behavior and decision-making processes, affecting female participation and involvement in community-related work, including water resource management.

Dar Si Hmad, a local non-profit organization, has explicitly tackled gender issues in the fog collection project, conducting regular community surveys and capacity building programs around the water supply. Co-educational curriculum trains young children in ecosystem science and technology, while capacity-building training and literacy workshops are often held for women in fog water villages. Through these initiatives, fog water collection has gone beyond the necessary water supply to be a driver of gender equity and sustainable development. This work has not been without drawbacks (Farnum, 2018). Still, multiple success stories demonstrate the potential of unconventional water resources, such as fog water, to stimulate spinoff projects and create positive externalities.

The fog collection network in the area is based on CloudFisher technology. Over the years, a combination of fog water collection technology and research has achieved community development through enhanced access to clean water and sanitation in marginalized rural Berber communities (Dodson, 2014; Dodson and Bargach, 2015). The first fog nets based on the FogQuest principle were installed and inaugurated in 2015, with an estimated daily per capita water capacity of 10–15 L, providing water to 400 people in the community. This equates to a daily water supply of 4–6 m^3 (4,000–6,000 L). The Water Foundation (http://www.wasserstiftung.de/), installed the first CloudFisher, developed by Aqualonis (https://www.aqualonis.com/), on Mount Boutmezguida in 2013 in collaboration with Dar Si Hmad. The Water Foundation and the Technical University of Munich collaborated to test 10 different fog net fabrics over 18 months. The material with the highest daily average yield harvested fog at 22 L/m^2.

In response to maintenance issues, stemming primarily from strong winds resulting in torn nets and water loss, the Water Foundation evaluated various mesh types and structures for durability. The Technical University of Munich measured the yield quantities, while Dar Si Hmad provided logistical and workforce support. The resulting system is resistant to winds up to 120 km/h (Dar Si, 2017). The installation of new fog collection nets has expanded the water supply to meet about 1,000 villagers' water needs. There are plans for a permaculture farm and a training center entirely focused on fog water.

In January 2017, the expansion of CloudFisher technology was launched, and 15 additional fog collectors were installed in collaboration with local construction companies, organized by the Dar Si Hmad Foundation. With 1,682 m^2 of mesh space, this is the world's most extensive operational fog collection system. The Water Foundation, which is responsible for the project, commissioned Aqualonis with the project's implementation. In addition to Water Foundation, other stakeholders also participated in this project, such as local communities and researchers from the University of La Laguna and other institutions (Dar Si, 2017).

By addressing specific cultural challenges on women's participation in the project, most women and children reflected the community's positive impacts. As a result, women spend less time and labor on water collection chores and undertake various cultural, economic, educational, and recreational activities. Children are also beneficiaries as they receive environmental education in natural resources management, climate change adaptation, and unconventional water resources management. The associated community at large has a sense of ownership over the project. There are water tariffs on fog water, which help households monitor their resource use and create a communal fund for upkeep (Dar Si, 2017).

Several donor organizations have provided funds, contributing to financial support and further access to research and ideas for improvement in fog collection systems. Although there is still some funding available to run the project, the economic trade-offs continue to be a concern as the new CloudFisher technology's cost is high. Overall, the project has been a big success, sustainably supplying potable water in enough quantities to about 1,000 villagers. While not a problem-free initiative, this is the most extensive fog-harvesting system representing truly a "bright spot" in both unconventional water supply techniques and locally led development interventions.

CONCLUSIONS AND PERSPECTIVES

Amid increasing water scarcity, fog water harvesting has gained attention in academic research and community-based applications on the ground in the past three decades. Over 350 publications have addressed fog water collection from the atmosphere. The literature review reveals that most of the studies focused on technical features, with a few studies addressing the importance of gender mainstreaming and community-led

development and addressing the critical role of relevant policies and supportive institutions to promote and support fog water collection systems. Although no adverse environmental effects of fog water harvesting have been reported on local vegetation, insects, and the ecosystem at large, there is a need to undertake studies on the governance and transboundary implications of fog water collection systems.

As localized water scarcity is worsening in many regions, the operational examples of fog water collection highlight the importance of harvested fog water for the associated people's benefits. The beneficial effects can be enhanced by engaging the communities and their leadership, addressing local water needs, ensuring water security, mainstreaming gender roles and responsibilities, and accessing and using appropriate technologies. Such benefits warrant community-based work, multi-stakeholder participation, private-sector engagement, and government support, particularly local government, and its related institutions.

Even though the number of fog water collection projects has grown over time, there remains a tremendous potential for further development. Several of these projects could not continue operations over the long run due to specific social, economic, and political challenges. Also, weak local institutions, limited or no private-sector engagement, unclear stakeholder responsibilities, funding uncertainties, and lack of support from local government have had a severe negative impact on fog water collection projects. If not addressed under specific situations, such factors result in disruptions and, in extreme cases, failures.

With a comprehensive approach to addressing water scarcity, there is an opportunity to explore and harness fog water collection potential in dry areas with frequent fog events throughout the year. This can be achieved by incorporating fog water collection as one of the water resources management strategies in the national water policies and implementing action plans in countries where biophysical conditions are conducive for fog water collection. Such adjustments to the national water policies supported by pertinent investment and financing action plans should be backed by comparing the value proposition of fog water collection systems to other possible water sources in terms of economic, societal, social, educational, environmental, and health trade-offs.

Capacity needs assessments and need-focused capacity building would be crucial in planning and executing sustainable community-based fog collection systems. Although technological developments in fog collection systems have received continued attention, it is essential to keep this momentum up and enhance interest within the relevant research community. For example, organizations like FogQuest (http://www.fogquest.org/) and FogNet Alliance (https://www.fognetalliance.org/) have demonstrated the importance of fog harvesting knowledge and best practices by identifying pertinent innovations and their implementation through functional networks of researchers, water professionals, communities, local institutions, and governmental and non-governmental organizations. A key element would be greater awareness among potential donors and the private sector's active engagement to fast-track and sustain fog water collection systems.

As our typical practices relying on conventional water supplies are not enough when facing today's water shortages, it is time to think beyond rivers, pipes, wells, and pumps. As concerns over water scarcity continue to grow, the "bright spots" of fog water harvesting systems shed light on how creative responses to resource stresses can alleviate tensions and support water-related sustainable development. This is crucially important in an era when achieving water-related sustainable development is a grand challenge for countries where communities suffer water shortages [United Nations (UN), 2018] while the potential to recover water from air remains under-explored (UN-Water, 2020). The international research community needs to continue to explore these systems and other unconventional approaches to water collection to best address water scarcity while supporting equity around our planet's most precise resource.

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The initial work on the data collection and write-up was undertaken jointly by MQ and GJ followed by further input from RF and PT. MQ coordinated this process. The final draft was written by all authors.

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