Water Supply

Water Supply Vol 23 No 9, 3675 doi: 10.2166/ws.2023.217

Fog water harvesting potential and its use in supplementary irrigation of rainfed crops (winter wheat) in Abi-beyglu, Ardabil (Iran)

Amin Kanooni* and Mohammad Reza Kohan
Department of Water Engineering, University of Mohaghegh Ardabili, Ardabil, Iran
*Corresponding author. E-mail: amin.kanooni@uma.ac.ir

AK, 0000-0002-3415-1937

ABSTRACT

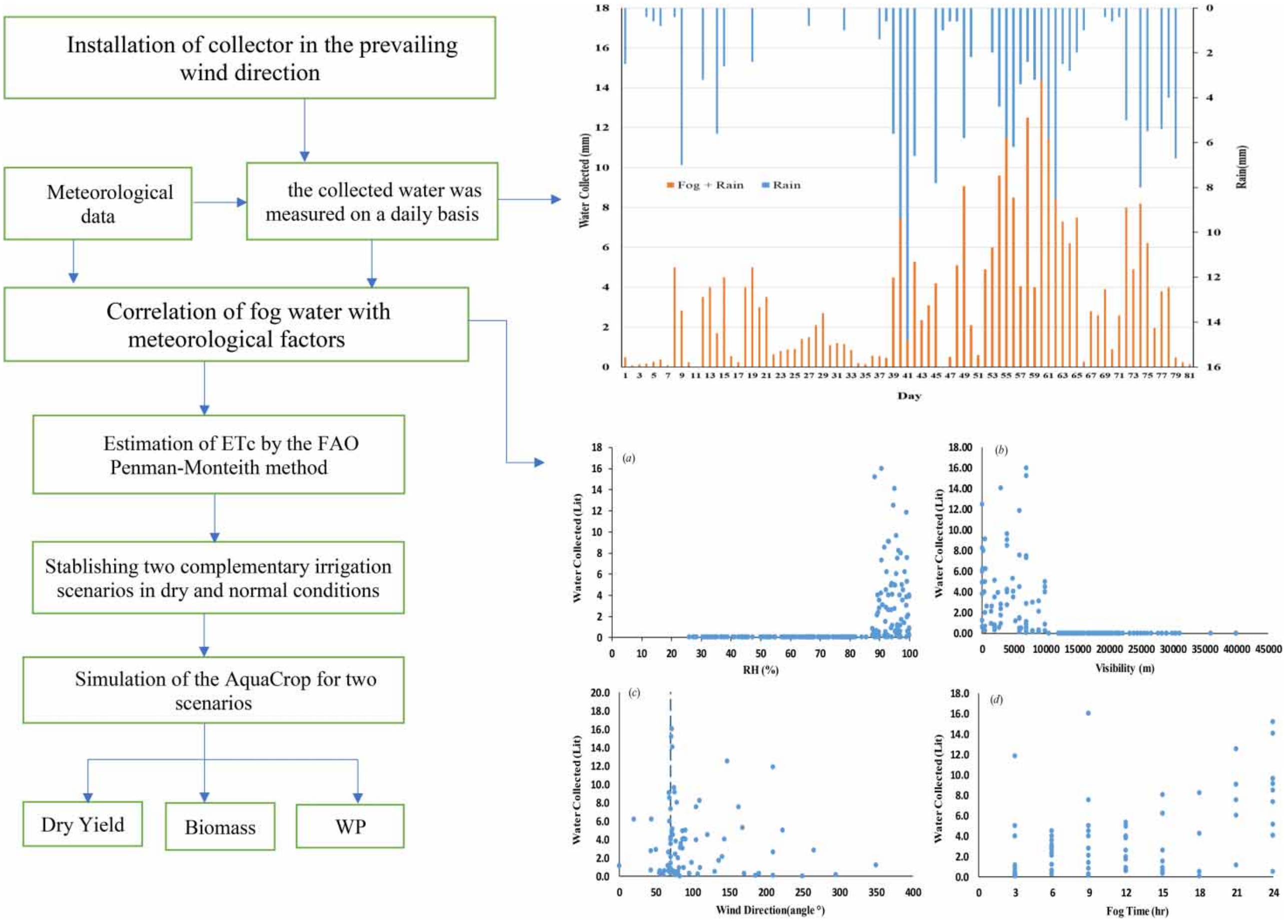
In arid and semi-arid areas where available water resources are very limited, the application of unconventional sources of water like the fog is of paramount importance. In this paper, the feasibility of using a standard fog collector (SFC) to collect fog water for complementary irrigation of rainfed wheat in the Abi-beyglu area was investigated. For this purpose, collected water volume was measured on a daily basis during fog time in 2021. The water demand of the winter wheat was estimated by the FAO Penman–Monteith equation under dry and normal conditions. Then the contribution of the collected water to supply the water demand of the wheat and the resultant increase in the yield under two different scenarios, namely complementary irrigation with 30 and 60 mm of collected water, was estimated using the AquaCrop model. Results showed that it is feasible to obtain an average water production of 3.6 L/m^2/day over the studied period. Upon irrigation with 30 and 60 mm of collected water under dry and normal conditions, 26 and 34% of the water deficiency for wheat farming was supplied, leading to increased crop yields by 0.6 and 1.7 ton/ha, respectively.

Key words: Abi-beyglu, feasibility, fog water, Raschel, supplementary irrigation

HIGHLIGHTS

- It is feasible to obtain an average water production of 3.6 L/m^2/day over the studied period.
- The meteorological parameters have a significant correlation with the water captured.
- The collected fog water represents a proper resource for supplying a part of the water demand for dry-farming.

GRAPHICAL ABSTRACT



1. INTRODUCTION

Fog water harvesting has been studied by numerous researchers thanks to its sustainability and low-cost features. In many foggy areas around the world where the rainfall is inadequate or not uniformly distributed, application of fog as an unconventional water resource can be seen as a suitable alternative for supplying water demands for drinking, farming, and/or forest rehabilitation. In drought-affected areas, provision of potable water is a major concern due to long distance from water resource, tough topography, and low quality of available resources or high cost of supplying water from alternative resources. In areas where water transmission is infeasible or rainfall deficiency/heterogeneity across different seasons is encountered, fog water collection can serve as an alternative for supplying the water demand of farmlands (Carrera-Villacrés *et al.* 2017).

Geographically speaking, fog water collection depends on such factors as height and topography. The topography and height play critical roles in the formation and guidance of fog. As a potential water resource, the fog is usually studied in high mountainous areas where the required conditions for fog formation are met (Klemm *et al.* 2012). As the height increases, air temperature drops followed by compaction of the air humidity content (Molina & Escobar 2008). This implies that the best position to install fog water collection facility is along the top line. Successful fog water collection projects have been installed at heights in the range of 400–1,000 m above mean sea level (MSL). Installation of collectors on high lands can enhance the water collection yield by up to 19 folds (Ritter *et al.* 2008). Another parameter to consider is the liquid water content (LWC), which refers to liquid water mass per unit volume. LWC is directly associated with the collected water. In general, sea fog or the radiation fog formed at low heights fails to exhibit adequate LWC. This implies the necessity of high mountains that can serve as a basis for the formation of high-LWC mountainous fog (Bruijnzeel *et al.* 2005). The fog frequency and duration are directly associated with the water collection yield. However, the fog is a seasonal and local phenomenon in most regions. In Chile, for example, fog time extends over virtually the entire year while Dhofar in Oman hosts the phenomenon for no more than 3 months a year (Schemenauer & Cereceda 1994b). Therefore, in order to plan and implement a fog water collection project, one needs to gather adequate data on the fog frequency, duration, and seasonal variations. This can be obtained from satellite images, synoptic stations, local reports, and, if none of this is available, interviews with local people (Fessehaye *et al.* 2015). Wind serves as the most important parameter contributing to successful implementation of fog water collection projects. As the wind speed increases, the fog flux passing over the collector surface increases, thereby increasing the water collection yield (Schemenauer & Joe 1989). When using flat collectors, both in research works and operating projects, the wind direction is of paramount importance as the collector surface must be normal to the wind direction. The wider the angular deviation of the collector surface out of the normal-to-wind direction, the lower the water yield, with a virtually zero yield when the collector surface is parallel to the wind direction (Estrela *et al.* 2009). Coastal areas are usually foggy but the wind speed may render inadequate to move the fog; that is, without adequate wind speed, a passive collector cannot function in practice. Therefore, before implementing a fog water collection project, one needs to evaluate local wind speed for successful operation of the system, configure the structures to minimize the loss across the system (Holmes *et al.* 2015), and consider dominant wind direction to determine installation direction of the collector (Schemenauer & Cereceda 1994a).

Although fog water harvesting is expanding in different countries around the world, its application has roots in the old age. In the ancient age, fog and dew water harvesting had been common in coastal/mountainous and desert areas, respectively. For example, honey comb structures and stone cones with heights of up to 10 m had been used to collect dew water in ancient Palestine and Crimea, respectively (Nelson 2003). For years, this has been the only way to supply drinking water for humans and animals in the Canary Islands, Antofagasta (Chile), and mountains of Oman (Schemenauer & Cereceda 1994b). In the recent years, numerous studies have been performed to investigate the water harvested from the fog around the world, a summary of which is presented in Table 1. In these studies, various collectors (*e.g.*, SFC, LFC, QFC, Juvik, and Harp) were used under different topographic and height conditions to evaluate potential yield of fog water collection in different areas. According to the results of these studies, average water yield of different collectors ranges within 0.16–10 L/m^2/day. In the meantime, yields of as high as 30 L/m^2/day were recorded by an omnidirectional SFC in Oman (Schemenauer & Cereceda 1994b). Similar values have been reported for other collectors.

The applications of fog water mainly include the needs related to drinking and rehabilitation of forest areas. In the meantime, it has been used for agricultural applications in limited cases. The reason behind the limited use of fog water for agricultural applications is the relatively large water demand of the agricultural sector. Nevertheless, the fog water can be used for complementary irrigation of rainfed lands. Estrela *et al.* (2009) used the water collected by a passive large fog collector (LFC) to rehabilitate a forest area in the mountains of Valencia. They could collect water at an average rate of 3.3 L/m^2/day. Results showed that micro irrigation of a segment of the forest rehabilitation seedlings for a short period of time enhances the survival rate and yield of the planted species. Another piece of research was done at the Marsa Matrouh Agricultural Research Center in Egypt by Harb *et al.* (2016) who investigated the effects of using the collected water from two fog water collectors (51 m^2 single-layer and bilayer propylene meshes with shading coefficients of 50 and 70%, respectively) in drip irrigation. Acknowledging the higher water captured from the bilayer propylene mesh, the resultant peanut yield and yield components were significantly different from those of the other collector. Carrera-Villacrés *et al.* (2017) used a fog water collection system to supply a part of the water demand for agricultural crops (especially the corn). They reported fog water yields of 5–20/m^2/day for different days in a year. Results showed that the collected water can be devised to supply some 5% of the water demand for agricultural crops. In their studies in the San Cristóbal Island (Ecuador), Echeverria *et al.* (2020) installed two SFCs with shading coefficients of 50 and 35% at a height of 600 m. The water yield by the two SFCs was measured at 7.9 and 5.9 mm/day. They then presented the required number of collectors for satisfying 25 and 15% of the irrigation water deficiency in normal and dry years, respectively.

Inappropriate management of fresh water resources, especially the groundwater, drought and climate change (in the recent years) have led to a reduction in water resources, as reflected by the significant decline of groundwater table, which is the most prominent source of water. The urban population of the world who suffer from water scarcity is projected to increase from 933 million (*i.e.*, one-third of total urban population in the world) in 2016 to 1.693–2.373 billion individuals in 2050 (some 50% of the world population) (He *et al.* 2021). The Middle East has been constantly hit by drought since after 1998, defining the worst drought period in the past 900 years, according to NASA (NASA 2016). Having such a vision in mind, competitions on water resource governance in these regions will be definitely boosted, thereby weakening the

Table 1 | A summary of fog water harvesting studies implemented around the world

Country	Altitude (m)	Collector type	Average Water Collected (L/m^2/day)	Reference
Chile (Chungungo)	780	LFC	4	Cereceda *et al.* (1992)
Chile (Chungungo)	780	LFC	3	Schemenauer & Cereceda (1994b)
Peru	*	SFC	9	Schemenauer & Cereceda (1994b)
Oman (Dhofar)	900–1,000	SFC	30	Schemenauer & Cereceda (1995)
Nepal	2,000, 3,500	SFC	10.7	Mac Quarrie *et al.* (2001)
South Africa (JP Tshanowa, Lepelfontein)	1,004,100	LFC	2–4.6	Olivier & De Rautenbach (2002)
Namibia (Gobabeb, Klipneus, Swartbank)	408,352,464	SFC	0.51 & 3.31 & 2.39	Shanyengana *et al.* (2002)
South Africa (Cape Columbine)	200	SFC	5.7	Olivier (2002)
Nepal	1,980	LFC	6.75	Karkee (2005)
USA (Monterey)	397	SFC	1.17	Ruiz (2005)
Oman (Dhofar)	1,000	AC filter- green and aluminum shade mesh (LFC)	12.9 & 11.4 & 9.8	Abdul-Wahab *et al.* (2007)
Iran (Mashhad)	1,800	cylindrical harp-wire	0.53	Mousavi-baygi (2008)
Spain (Tenerife)	842	SFC	9.5	Marzol (2008)
Morocco (Boutmezguida)	1,225	SFC	7.1	Marzol & Sánchez (2008)
Canary Islands	1,270	QFC	0.2 & 5.0	Ritter *et al.* (2008)
Colombia (Roldanillo)	1,850	SFC	4.2	Molina & Escobar (2008)
Spain (Valencia)	971	Juvik and LFC	3.3	Estrela *et al.* (2009)
Kingdom of Saudi Arabia (Asir)	2,260–3,200	SFC	6.2 & 3.3	Al-hassan (2009)
Colombia (Andes Mountain)	2,600–2,800	SFC	2	Escobar *et al.* (2010)
Kingdom of Saudi Arabia (Asir)	*	SFC	6.05 & 5	Gandhidasan & Abualhamayel (2012)
Morocco (Boutmezguida)	1,225	LFC	10.5	Dodson & Bargach (2015)
Ecuador (Galte)	3,500	SFC	5–10	Carrera-Villacrés *et al.* (2017)
Kingdom of Saudi Arabia (Asir)	2,200	SFC	6.7	Algarni (2018)
Chile (Antofagasta)	1,000	SFC	0.16–0.37	Carvajal *et al.* (2022)

agriculture, worsening social constructs, encouraging urbanization of rural communities, increasing insecurity, contributing to instability, and finally triggering water wars. Due to low rainfall and inappropriate temporal and spatial distribution of the rainfall, Iran has been listed under arid and semi-arid regions, making it one of the most vulnerable areas to climate change (Al-Mandhari 2019). Given the population growth, expanded urbanization, and development of industrial and agricultural sectors, the demand for water is escalating in Iran. Preservation of existing water resources and search for alternative ones (*e.g.*, air humidity, fog, etc.) are important measures of water resource management, which have been regarded by practitioners during the recent past. Considering the geographic position of the Ardabil Plain, which is overwhelmed by highly humid winds from the Caspian Sea that pull down stratus clouds (low-altitude) toward the ground surface, thereby lowering the air temperature, fog formation is a common phenomenon in the Abi-beyglu area (where the fog from the Caspian Sea enters the Ardabil Plain). This highlights the necessity of paying attention to fog water collection for various purposes.

Obviously, one can store large amounts of water by collecting fog as it passes the region, with the stored water then used to supply a part of the farming or even drinking water demands for local villagers.

2. MATERIALS AND METHODS

2.1. Study area

With an approximate area of 140,000 ha, the Ardabil Plain is delineated by 48°10′E–48°30′E and also 38°7′N to 38°23′N, Ardabil Province, Iran, at an average height of 1,330 m from MSL. Because of its geographical location, the plain exhibits special meteorological features including long freezing winters coupled with relatively moderate summers. According to long-term stats acquired at Ardabil Synoptic Station (39-year data), the area has experienced a minimum, maximum, and average temperature of −33.8, 39.8, and 9.2 °C. Average relative humidity (RH) is 71% and average annual rainfall is reportedly 293.3 mm, of which only 7% falls in the summer when the agricultural water demand is maximal – a fact that characterizes the region as a semi-arid area. Located in the Ardabil Plain, the Abi-beyglu area is the earliest location through which the Caspian humidity front flows into the Ardabil Plain. It is dominated by rainfed agriculture. Information received from the Ardabil Agriculture Organization show that some 80% of the lands in this region are dedicated to rainfed farming of crops. Barley and lentils are the main dry-farmed agricultural products of the region.

In order to evaluate fog water collection potential of the study area, first, appropriate location was identified as the point where the fog flowed from the Caspian Sea into the Ardabil Plain, and three SFCs were installed at (38°17′17″N, 48°34′11″E). This paper reports the results from Raschel-mesh collectors, which have been used as reference SFC in many researches. This collector makes use of a bilayer polypropylene mesh with a shading coefficient of 35%; it is made up of equilateral triangles with side lengths of 9 and 5 mm with stripes of 2 mm in width and 0.1 mm in thickness. Thanks to their low cost, availability, and high resistance to sunlight, polypropylene and polyethylene meshes are the materials of choice for most fog water collection projects. The considered collector model was used as a reference to compare the results to those of other projects performed around the world and evaluate the efficiency against other types of collectors. According to the standards mentioned in Schemenauer & Cereceda (1994a), the collectors were made into 1 × 1 m dimensions and a height of 2 m, and then deployed. In order to guide the collected water to the storage tank, a gutter, which was a segment of a polyethylene pipe, was employed at a slope of 2%. Droplets were drained through a plastic hose that connected the gutter end to a storage tank. Although the test site was selected to be right at the entrance of the humidity fronts from the Caspian Sea to the Ardabil Plain, the collectors were finally installed at a small distance to the top line of the highlands adjacent to the Ardabil Plain near the city of Abi-beyglu to account for particular security issues and facilitate access to the research site, thereby easing the measurements. Figure 1 shows the location map of the Ardabil Plain and the site of experiment.

2.2. Meteorological data

The required meteorological data (including temperature, RH, wind speed and prevailing direction, evaporation, and rainfall) during 1997–2021 from the Abi-beyglu weather station and during 2003–2021 from the Ardabil Airport synoptic station (such as monthly foggy and sunny days) were prepared. Noteworthily, 3-h average values of the considered parameters over the research period (April to December 2021) were also retrieved from the Ardabil Airport Synoptic Station and used in the analyses.

2.3. Methodology

Once finished with installing the collectors in the prevailing wind direction, the collected water was measured on a daily basis for about 8 months from April 10, 2021 to November 21, 2021. The passive fog water collectors work with a simple mechanism with no need to energy or any costly operation. In such systems, small particles of fog hit the collector surface and, upon deposit at the collector surface, join together to form larger droplets. When the droplet size reaches a critical level, it falls into the gutter placed in the bottom of the collector with the help of the gravity, from where the water is then guided to the storage tank. Theoretical fog water yield can be estimated through the following equation (Ritter *et al.* 2008):

$$q = 3.6 \times \mathrm{LWC} \times A \times \eta_{\mathrm{Coll}} \times u \tag{1}$$

where q is the collected fog water (l/h), LWC is the liquid water content (gr/m^3), A is the cross section of collector (m^2), u is the wind speed (m/s), and η_{Coll} is the collector efficiency.

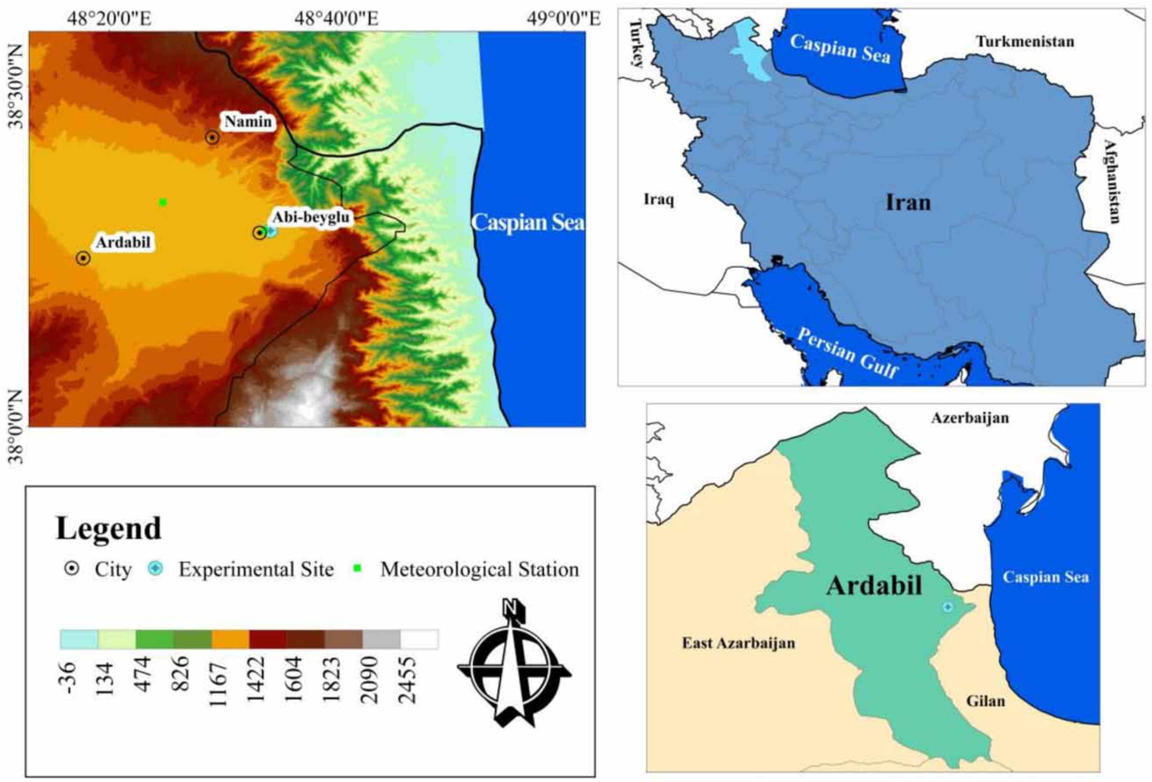


Figure 1 | Location of the experimental site and meteorological stations.

A collector can never harvest the entire LWC of the flowing air. In order to evaluate the fraction of the passing flux that is absorbed by a fog water collector, one can use the collector efficiency (η_{Coll}), which has been defined as the ratio of the collected water per unit surface area of the collector to the passing flux across the cross section.

In order to investigate the applicability of the collected water for supplying a part of the water demand for a major rainfed crop (*i.e.*, wheat), first, the wheat water demand was estimated by the FAO Penman–Monteith equation, followed by calculating the contribution of the collected water into the supply of the demanded water for wheat. The following equation calculates water demand of a plant:

$$I_n = \mathrm{ET}_c - P_e \tag{2}$$

$$\mathrm{ET}_c = K_c \times \mathrm{ET}_0 \tag{3}$$

where I_n is the net irrigation demand, P_e is the effective rainfall, ET_c is the crop evapotranspiration, ET_0 is the reference evapotranspiration, and K_c denotes the plant coefficient. ET_0 can be obtained from the following formula (Allen *et al.* 1998):

$$ET_0 = \frac{0.408\Delta(R_n - G) + \gamma(900/(T + 273))u_2(e_s - e_a)}{\Delta + \gamma(1 + 0.34u_2)} \tag{4}$$

where ET_0 is the reference evapotranspiration [mm/day], Rn is the net radiation at the crop surface [MJ/m^2/day], G is the soil heat flux density [MJ/m^2/day], T is the mean daily air temperature at 2 m height [°C], u_2 is the wind speed at 2 m height [m/s], es is the saturation vapor pressure [kPa], ea is the actual vapor pressure [kPa], Δ is the slope of vapor pressure curve [kPa/°C], and γ is the psychrometric constant [kPa/°C]. For more information on the above parameters, one can refer to FAO Publication No. 56 (Allen *et al.* 1998).

Next, the effects of the collected water on increasing yield and water productivity of the wheat were assessed by AquaCrop software. The AquaCrop presents a simple yet powerful model that can be used for a wide spectrum of different weather conditions and crops, including vegetables and cereals. Being prepared based on the revised version of the FAO paper No. 33, this model simulates the plant growth and yield as functions of input data including meteorological parameters, soil characteristics, and applied managerial measures (*i.e.*, mulching, irrigation, fertilization, etc.) (Steduto *et al.* 2009). The AquaCrop model has been used in many investigations around the world, with its ability to simulate the growth and yield of crops proven through multiple calibration and validation studies (Todorovic *et al.* 2009).

2.3.1. Aquacrop parameterization

To simulate the AquaCrop model, irrigation data, soil characteristics, crop parameters, farm conditions and management parameters were used based on the calendar-day mode. Soil data were obtained from local information and daily measured data of temperature, humidity, wind speed and solar radiation at the Abi-beyglu meteorological station were used to determine daily evapotranspiration of the crop. The parameterized AquaCrop model was used to simulate soil water content, CC, biomass and grain yield for wheat.

3. RESULTS AND DISCUSSION

Simultaneously with the measurement of the collected water, possible occurrence of fog was recorded by the operator. Investigating the data on fog occurrence at the site of collectors and controlling them against the data received from the Ardabil Airport Synoptic Station, it was figured out that the two sites are completely identical in terms of fog occurrence and meteorological properties. Knowing that the collected fog water is a function of meteorological factors, we began by analyzing the meteorological parameters affecting the fog water collection at the research site followed by investigating the relationship between the collected water and these parameters. Afterwards, water demand of a major rainfed crop in the region (namely wheat) was calculated and yield improvement was investigated under various scenarios involving complementary irrigation with the collected water.

3.1. Analysis of meteorological parameters

The Abi-beyglu Weather Station is the closest of the kind to the research site, where considered meteorological parameters are measured and recorded. This station is located at 38°16′54″N, 48°33′29″E. Table 1 presents monthly average values of the meteorological parameters at this station. As observed, maximum percent rainfalls occur in May and November (14.4%), while the minimum occurs in August (2%). Moreover, the highest and lowest seasonal rainfalls occur in fall and summer (34.2 and 11.6%, respectively). The table further presents the number of foggy days at the Ardabil Airport Synoptic Station. Accordingly, the highest fog frequency was observed in September followed by October and then December (12.7, 11.7, and 11.6%, respectively), while the lowest fog frequency was seen in June followed by July and then August (5, 5.6, and 6.1%, respectively). On the other hand, seasonally speaking, the highest fog frequency (*i.e.*, 48%) occurred in fall. According to the results, on average, the study area experiences a total of 145 foggy days a year (covering more than one-third of the year). Therefore, it can be said that the average number of foggy days that occurs during agricultural activities is 83 days. The fog frequency indicates the inflow of the humidity front from the Caspian Sea toward the study area clearly. It is worth noting that the fog frequency data are based on the stats recorded at the Ardabil Airport Synoptic Station, and the fact that the study area is where the humidity front from the Caspian Sea flows into the region coupled with local observations indicate that the fog frequency is higher at the research site rather than the Ardabil Airport Synoptic Station.

In order to compile wind information across the region, long-term data on wind speed and direction at the Ardabil Airport Synoptic Station was retrieved and analyzed.

Annual average speed of the prevailing wind was calculated at 3.7 m/s. the east wind (the one that originates in the east and blows in a westward direction) exhibits the highest annual speed. A wind rose diagram in WRPLOT was used to demonstrate the prevailing winds graphically. Figure 2 shows the wind rose diagram and annual wind frequency at the Ardabil Airport Synoptic Station. As is evident from the figure, the prevailing wind in the region is the east wind, which is responsible for 70% of total annual wind frequency. Also known as the Caspian Wind, this wind transports the humidity from the Caspian Sea into the Ardabil Plain.

We further plotted seasonal wind rose diagrams of the data at the Ardabil Airport Synoptic Station, which is not presented in this paper to keep it neat. Investigation of the seasonal wind rose diagrams showed that the east wind retains its prevalence across the region in all seasons. Indeed, the east wind comprises 95, 90, 60, and 55% of the wind flows in spring, summer, fall, and winter, respectively, making it the prevailing wind system in the region. On the other hand, the east winds exhibit

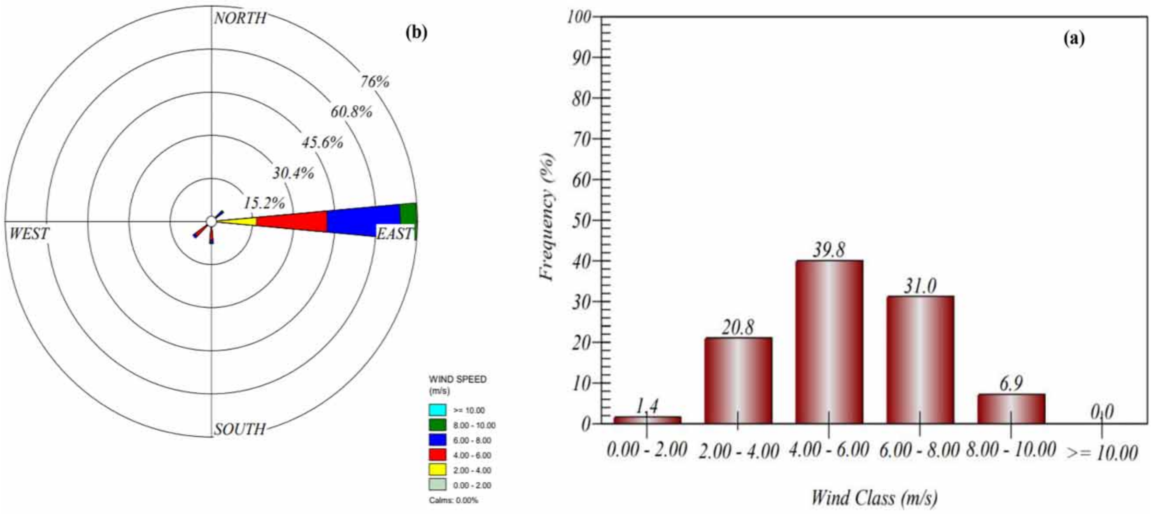


Figure 2 | Frequency of annual wind speed (a) and wind rose (b) at the synoptic station of Ardabil Airport.

significantly higher speeds in the summer rather than the spring, fall, and winter. In the winter, the south and southwest winds blow at higher speeds than the east winds. Considering what was mentioned above, maximum utility of the humidity from the Caspian Sea, as the main source of humidity in the region, occurs in spring and fall.

3.2. Quantity of collected water

Upon installing the collectors, collected water volume was measured on a daily basis for a total of 225 days from April 10, 2021 to November 21, 2021, of which 81 days were identified as foggy. A cumulative amount of 289 L of water was collected during the entire measurement period. Given the number of foggy days, average daily water yield was calculated at 3.6 L/m^2/day, with the lowest and highest water yields of 0.2 and 16 L/m^2/day, respectively. Figure 3 shows the collected water (fog + rain) and rainfall data in different months. Accordingly, maximum water collection occurred in October (146 L), which corresponded to the maximum fog frequency as well (Table 2).

Figure 4 demonstrates the collected water and rainfall data in foggy days. Total rainfall during the entire measurement period was 209.5 mm, 173 mm of which occurred in foggy days. Therefore, the collected water was 167% of the rainfall.

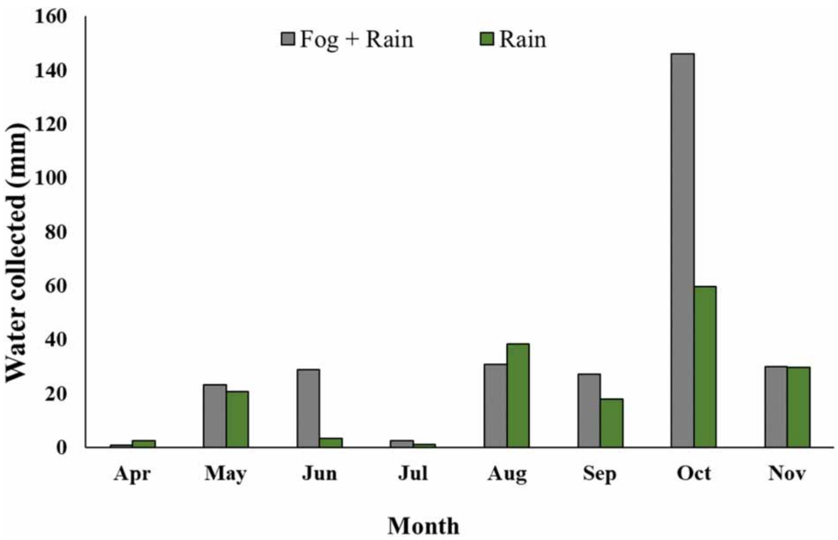


Figure 3 | Monthly comparison of collected water and rainfall during foggy times.

Table 2 | Monthly average of meteorological parameters during the statistical period

Month	Mean minimum temperature (°C)	Mean maximum temperature (°C)	Relative humidity (%)	Mean wind speed at 2 m height (m/s)	Precipitation (mm)	Evaporation (mm)	Monthly sun hours (h)	Wind direction (degree)	N. Foggy days
January	−6.0	4.8	76	3.5	20.5	0.8	160	168	10
February	−6.1	4.6	78	3.6	35.5	0.7	149	133	11
March	−2.6	3.1	76	4.0	29	0.7	169	125	13
April	1.2	12.9	75	3.8	34.2	49.4	196	88	13
May	5.1	16.7	77	3.5	50.2	122.3	252	88	10
June	8.1	20.6	75	4.1	20.1	176.6	296	88	7
July	11.3	22.3	73	4.5	10.1	210.5	292	85	8
August	11.6	23.7	72	4.3	7.2	218.8	288	85	9
September	10.0	20.7	81	3.7	23.2	136.9	217	85	18
October	6.2	17.9	80	3.3	38.4	97.4	181	85	17
November	1.5	12.4	79	3.0	50.4	54	147	101	17
December	−3.7	6.9	77	2.9	30.9	19.2	145	199	13

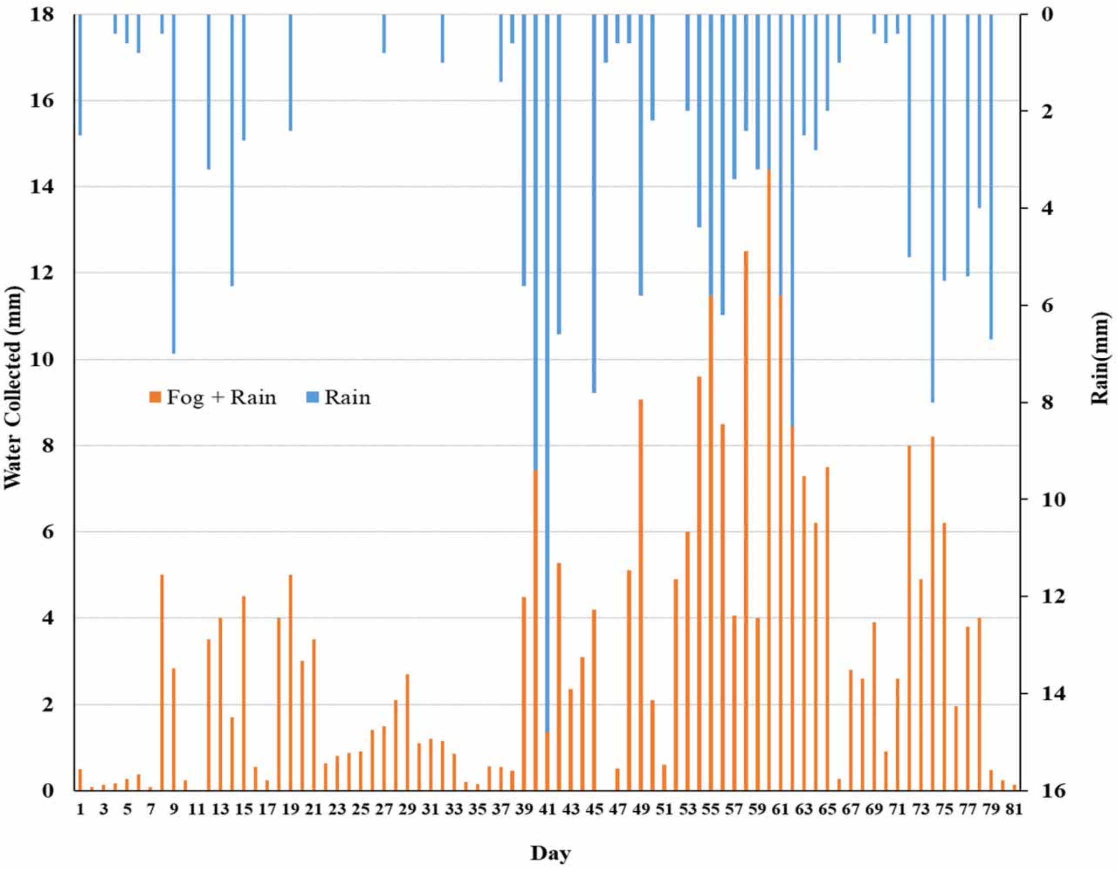


Figure 4 | Daily amounts of collected water and rainfall during the study period.

Peak rainfall was recorded in October. According to the figure, it can be stipulated that the water yield varies over different months. On particular days, there has been some water yield although no rainfall occurred, which is an indication of foggy condition. On some other days, the collected water exceeded the rainfall (October) due to simultaneous occurrence of rainfall and fog, which has contributed to the collection of excessive water. On the other hand, there are cases where the collected water is less than the rainfall (August), which can be a result of multitudes of causes, including too high wind speeds. Indeed, too high wind speeds reduce the water yield of the collector. It is worth noting that, in two cases, despite high rainfalls, the collected water volume is reportedly lower than reality due to measurement errors caused by overflowing of the water storage tank.

3.3. Fog water quality

Quality of collected water depends on local environmental conditions, and possible contamination of the collector surface with dust, insects, and birds' droppings. Although the fog water was expected to be pure, of high quality, and free of any chemical contamination, qualitative assessment of the water was performed through chemical analysis of the collected fog water at Central Laboratory of University of Mohaghegh Ardabili and comparing the results to the standard levels set by WHO (WHO 1993). Table 3 shows a comparison of the qualitative parameters of the fog water. The collected water was found to be highly pure with very low concentrations of sulfate, nitrate, phosphate, sodium, calcium, magnesium, and potassium. Moreover, the very low TDS levels indicated the absence of any industrial activity in the vicinity of the research site.

3.4. Correlation of extracted water with meteorological factors

As it blows to hit the collector surface, the flow of fog is affected by a number of factors including the meteorological factors. In order to investigate the meteorological factors affecting the water yield, correlational analyses were performed between different meteorological parameters and the water yield in SPSS 26. Table 4 reports the correlation coefficient of the water yield of the Raschel-mesh collectors to different meteorological parameters.

Investigation of the correlation coefficient of the extracted water to meteorological parameters show that, among different parameters, significant correlations were observed between the extracted water and visibility (Visibility), temperature (T), rainfall (Rainfall), RH, evaporation (Evaporation), fog time (Fog time), and temperature difference between the dew point and dry air ($T - T_{\mathrm{dew}}$) at a significance level of 0.01. On the other hand, no significant correlation was observed between the extracted water and the dew point and wind speed and direction. Visibility, evaporation, and temperature difference between the dew point and dry air exhibited negative correlations to the water yield, while rainfall, RH, and fog time were found to be positively correlated to the water yield. Of the pool of different parameters, the rainfall and evaporation exhibited the highest and lowest significant correlations to the water yield, respectively. An important point to note was the insignificance of the correlation of the wind speed and direction to the extracted water. As we know, wind is a crucial parameter affecting the fog water collection yield, with an expectedly direct association between them. However, as is seen from the results, they exhibit no significant correlation. The same outcome has been reported by Ritter *et al.* (2015) and Carrera-Villacrés *et al.* (2020). With increasing wind speed up to about 4 m/s, the collection efficiency increases non-linearly,

Table 3 | Chemical analyses of collected fog water

Tests	Results of fog water (mg/L)	Maximum allowed value (mg/L)
PH	6.81	6.5–8
EC	0.0065	–
TDS	45	1,000
SO_4	2.43	50
NO_3	2.12	50
PO_4	1.02	–
Na	1.8	200
K	0.89	–
Ca	4.4	200
Mg	3.2	125
HCO_3	1.6	–
Cl	3	250

Table 4 | Correlation coefficient of meteorological parameters with the collected water

	Water Collected	**Wind Speed**	**Wind Direction**	**Visibility**	**T**	**T_{dew}**	**Rainfall**	**RH**	**Evaporation**	**Fog time**	**$(T–T_{dew})$**
Water Collected	1.000	0.111	0.001	−0.550**	−0.338**	0.059	.622**	.464**	−0.241**	.475**	−0.423**
Wind Speed	0.111	1.000	−0.429**	0.181	.435**	.309**	−0.066	−0.268*	0.200	.101	.259*
Wind Direction	0.001	−0.429**	1.00	−0.033	−0.087	−0.167	.081	.273*	−0.161	−0.162	.096
Visibility	−0.550**	0.181	−0.033	1.000	.397**	−0.226**	−0.059	−0.726**	.228**	−0.353**	.633**
T	−0.338**	.435**	−0.087	.397**	1.000	.503**	−0.231*	−0.606**	.678**	−0.245*	.665**
T_{dew}	0.059	.309**	−0.167	.226**	.503**	1.000	−0.159	.299**	.277**	−0.099	−0.311**
Rainfall	.622**	−0.066	0.081	−0.059	−0.231*	−0.159	1.000	.089	−0.037	.326**	−0.145
RH	.464**	−0.268*	.273*	−0.726**	−0.606**	.299**	.089	1.000	−0.470**	−0.072	−0.925**
Evaporation	−0.241**	0.200	−0.161	.228**	.678**	.277**	−0.037	−0.470**	1.000	−0.247*	.506**
Fog time	.475**	0.101	−0.162	−0.353**	−0.245*	−0.099	.326**	−0.072	−0.247*	1.000	−0.251*
$(T–T_{dew})$	−0.423**	.259*	0.096	.633**	.665**	−0.311**	−0.145	−0.925**	.506**	−0.251*	1.000

**Correlation is significant at the 0.01 level (two-tailed).

*Correlation is significant at the 0.05 level (two-tailed).

but at higher speeds, the collection efficiency does not change significantly (Regalado & Ritter 2016). In this research, in more than 77% of the conditions, the wind has occurred with a speed higher than 4 m/s (Figure 2), which does not have a significant effect on the water collection efficiency. This issue was also identified in the statistical correlation between wind speed and the amount of collected water.

In order to obtain a better understanding about the association of different meteorological parameters with fog water collection yield, corresponding plots to different parameters are presented in Figure 5.

According to Figure 5(a), for the most part, fog is formed at relative humidities above 90%, which shows that the air is nearly saturated with humidity when the fog forms. Visibility is another parameter affecting the fog water collection yield. That is, as the visibility decreases, LWC increases. Increased LWC because of increased flux of fog per unit area results in increased fog water collection yield. Figure 5(b) shows the relationship between these two parameters. As observed, water collection by the collector occurs when the horizontal visibility is below 10,000 m. Of course, it should be noted that a fog-free rainfall may not reduce the horizontal visibility significantly but introduces some error into the measurement data as the rainfall and fog contributions were not separated in this study. Wind direction with respect to the fog collector affects the water yield. As mentioned earlier, the collectors were installed in the direction of the prevailing wind in the region. According to Figure 5(c), when the wind direction was perpendicular to the surface of the collector (or the deviation angle was small), the water yield was relatively high. In the cases where the water yield was high despite a large deviation between the wind direction and the collector direction, the main contributor to the collected water was the rainfall.

At the weather station, fog time was recorded once every three hours. Accordingly, the corresponding plot (Figure 5(d)) demonstrates the collected water versus fog time in multiples of 3 h. Except for a few exceptions (corresponding to simultaneous occurrence of fog and rainfall), higher water yields were observed with longer fog times. The fog time affects the water yield directly. Obviously, the longer the fog time the longer the available time for water collection, leading to a higher water yield.

As the vapor rises to higher altitudes at lower temperatures, the moisture content of the air compacts to form fog. In other words, as the temperature decreases to the dew point, the air moisture is compacted and saturated, and this is the point where

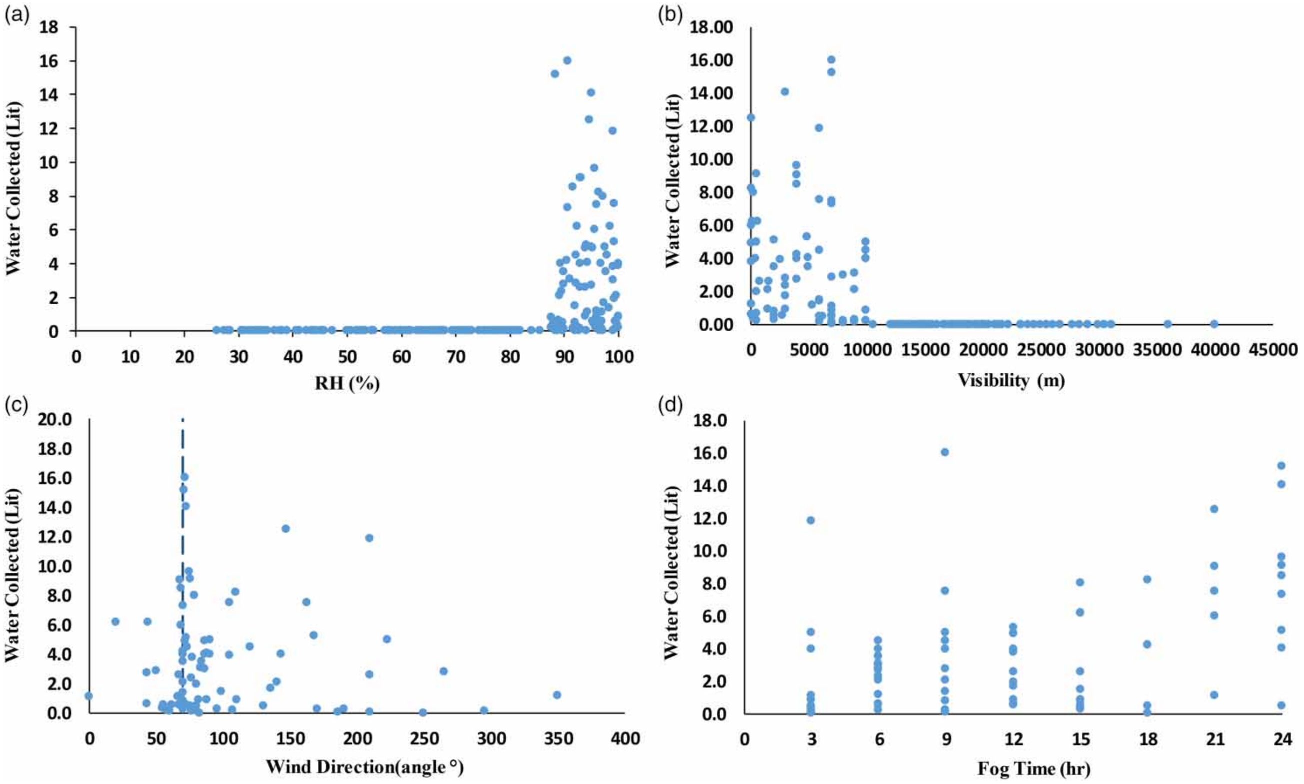


Figure 5 | The relationship between meteorological parameters and the amount of collected water.

fog is formed. Figure 6(a) shows variations of air temperature and dew point temperature over the measurement period. When the air is saturated with humidity, temperature difference between dew point and dry air reaches zero. Since humidity-saturated air is a precondition for fog formation, the temperature difference between dew point and dry air becomes zero or close to zero. Frequent occurrence of fog during the measurement period is evident on Figure 6(a) at the points where the curves of the dry air temperature and dew point intersect. Figure 6(b) shows the relations between fog water collection yield and temperature difference between dew point and dry air. As is evident, fog water collection yield was higher at lower $T - T_{dew}$ levels.

3.5. Contribution of collected water to supply water demand and increase yield of wheat

In order to investigate the contribution of collected water to supply water demand and its effect on the yield of wheat, we began by calculating the water demand for the wheat from the regional meteorological data using the FAO Penman–Monteith equation for dry and normal conditions. Figure 7 shows the water demand for the wheat coupled with effective monthly rainfall in the study area under both conditions. Although total rainfall was higher in normal condition rather than dry condition,

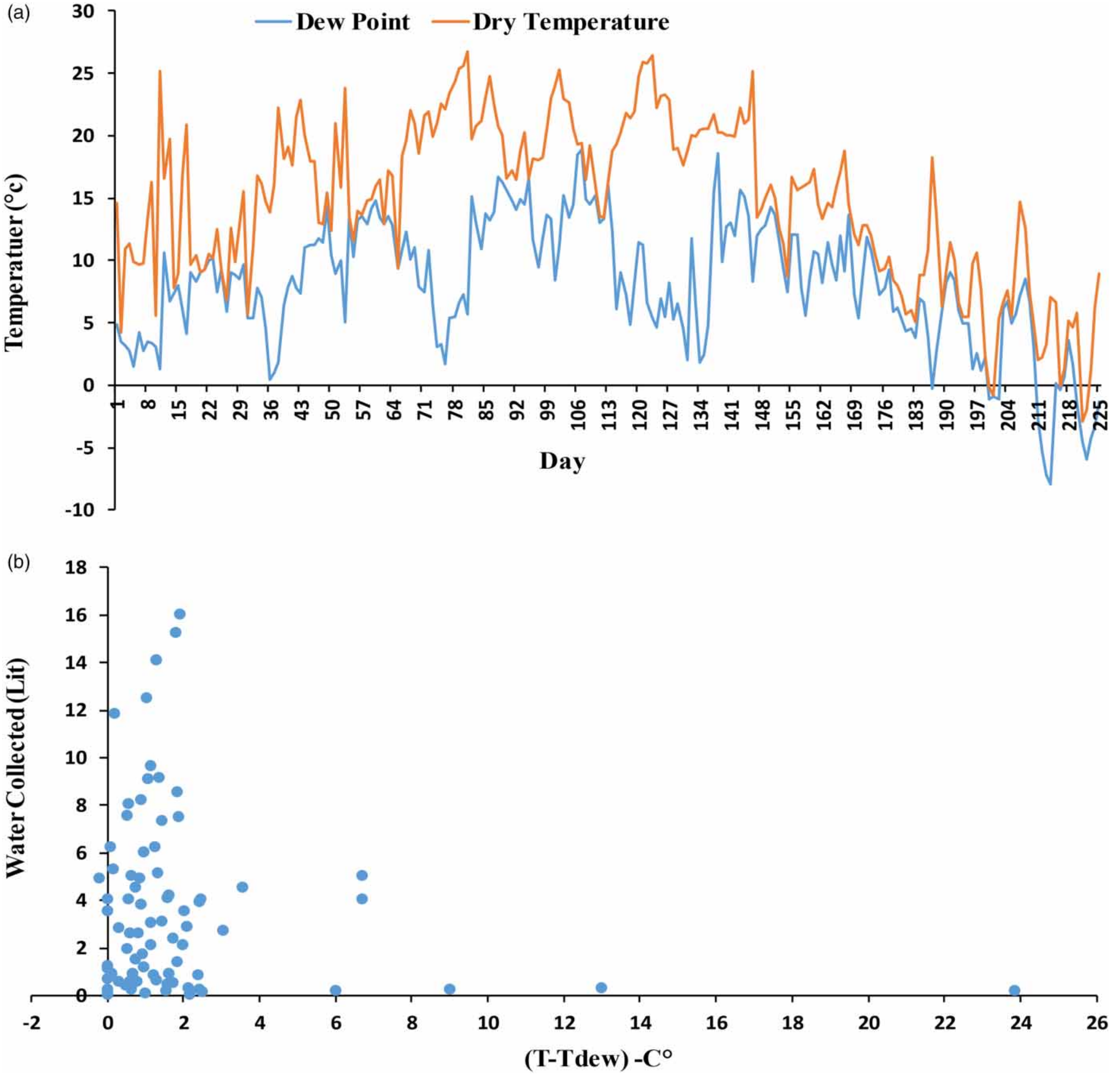


Figure 6 | Dry temperature and dew point temperature during the study period (a), the relationship between the collected water and the difference between dry temperature and dew point temperature (b).

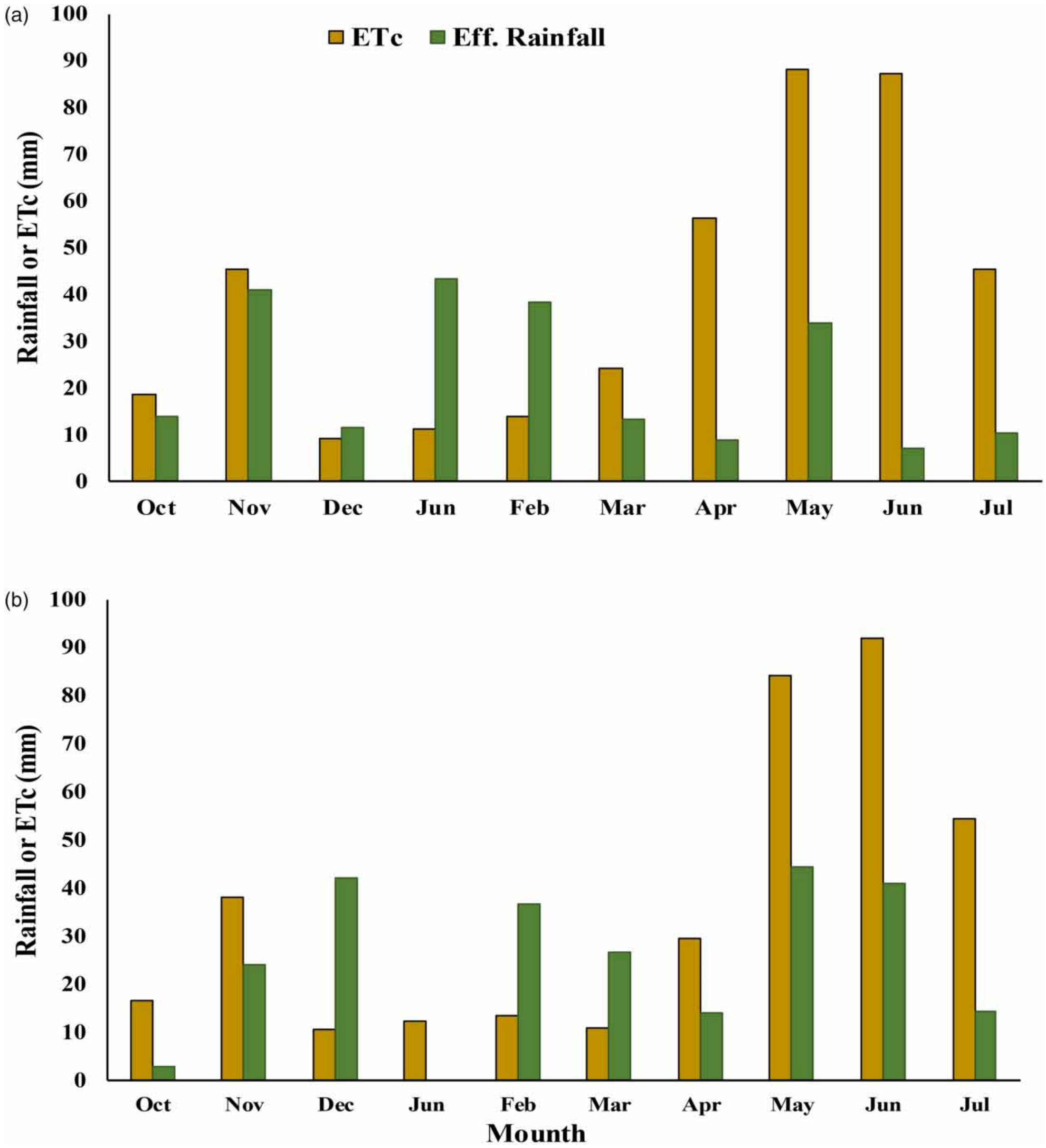


Figure 7 | Monthly variations of wheat evapotranspiration and effective rainfall in dry (a) and normal (b) scenarios.

the water deficiency is evident in both cases due to non-uniform distribution of rainfall events during the growth period of wheat. This water deficiency is intensified during the last 4 months of the growth period, which includes the sensitive stage of flowering, in the dry condition. Supplying the water demand of the wheat from rainfall was insufficient during April, May, June and July under both normal and dry conditions. Total water demand by the wheat during its growth period in dry and normal condition was calculated at 399.4 and 361.6 mm, respectively. After writing down the effective rainfall, the irrigation water demands reached 177.7 and 115.3 mm, respectively.

Considering potential occurrence of the fog in the region and the achieved average water yield by the Raschel water collectors, supplying water for complementary irrigation of the wheat was feasible. This was done under two irrigation scenarios. In scenario I, two complementary irrigations were applied to supply the wheat with 60 mm of water during the flowering stage in dry condition. In scenario II, however, one complementary irrigation was applied to supply the wheat with 30 mm of water during the flowering stage in normal condition. Complementary irrigation of the wheat with 30 and 60 mm of water in normal- and dry-condition scenarios could supply the crop with 26 and 34% of its water deficiency, respectively. According to the average collected water (3.6 L/m^2/day), by installing 36 LFCs (with dimensions of 48 m^2), the water needed for supplementary irrigation in the dry scenario can be supplied. Of course, as mentioned earlier, by installing the collectors at higher altitudes, the collection efficiency can be increased up to 19 times. Nevertheless, assuming a 5-fold increase in water collection efficiency, the number of LFCs required will be 7.

In order to investigate the effect of complementary irrigation in the two mentioned scenarios on the yield and yield components of wheat, AquaCrop model was utilized. Calibration of the AquaCrop model was conducted on the basis of the data collected from the region, in-person interviews with farming experts, and the data extracted from test farms, indicating that this model can well simulate the wheat yield and yield components. The conservative and non-conservative parameters of the crop are shown in Table 5.

Table 6 lists the parameters related to wheat production under the two scenarios. Dry yield increased by 1.7 and 0.6 ton/ha under the dry and normal scenarios, respectively, highlighting the positive effects of complementary irrigation on wheat production in the region. This improvement was also evident in water productivity levels, which increased by 0.38 and 0.08 kg/m^3 under the dry and normal scenarios, respectively.

3.6. Uncertainties governing the fog water extraction

The potential of fog water collection varies depending on the meteorological parameters and the design of the harvesting system. Meteorological parameters cannot be controlled. Therefore, for good design to maximize collection capabilities, it is necessary to measure them more accurately. Air temperature and RH can be mentioned among the meteorological parameters effective in the formation of fog. As the RH increases and the temperature decreases to the dew point temperature, the water vapor in the atmosphere condenses and fog is formed. The number of foggy days indicates the suitable conditions of temperature and RH in the region. In addition to the number of foggy days, wind speed and its direction are also considered key parameters in water collection. So that if there is no wind, the fog drops will not be transported. If the wind speed is not enough, the collection efficiency will also decrease.

The wind increases the collected water in two ways: (1) It causes the transfer of suspended fog drops toward the collector. Therefore, as the wind speed increases, the fog flux entering the collector also increases, and according to Equation (1), the amount of water collected also increases. (2) It causes the fog droplets to collide with the collecting plate, and as a result, with the condensation of the droplets, water collection is done according to the main collection mechanism (inertia mechanism).

Although the design and construction of LFC type collectors is easier and less expensive than multi-faceted collectors, but in order to maximize the efficiency of water extraction, this type of collector must be placed perpendicular to the wind direction. After installing the collector perpendicular to the wind direction, the relative stability of the wind direction is important in increasing the water extraction efficiency, and its violation will introduce uncertainties in the results. The predominant wind direction of the studied area is from the east side, which can carry the moisture from the Caspian Sea to the studied plain (Figure 2).

Air quality and particles that get stuck on the collecting net affect the quality of the collected water. Fog is known as a solvent for bicarbonates, calcium, sodium chloride, heavy metals, nitrates, organic carbon and other ions. Depending on the concentration of dissolved chemical species in the air, the quality of collected water may be affected.

3.7. Economic aspects of implementing fog harvesting projects

The implementation of fog water harvesting projects in a region can be aimed at providing drinking water or agricultural uses. But the most important thing is to consider the potential of that area in supplying the required amount of water. Of course, it should be noted that the fog water collected cannot meet all the needs of a populous society or the entire needs of the agricultural sector.

The fog collector system has been of interest especially in poor communities due to its simplicity in design, construction and operation, as well as no need for energy, with a relatively low cost. Investigations carried out in the studied area showed that all the necessary equipment such as collecting metal structure, polyethylene pipe and polypropylene mesh can be easily obtained from urban stores in this area. According to the estimates, the cost of building an LFC collector is around 50 million Rials (approximate 100 US $).

The data on the average water collected in different parts of the world (Table 1) show that the amount of extracted water varies in different regions. This is despite the fact that none of these projects were in the same conditions, such as the height of the collector installation, the type and dimensions of the collector, the measurement period, and the weather conditions. The

Table 5 | Conservative and non-conservative crop inputs used in AquaCrop for winter wheat

Conservative parameters	
Description	Value
Crop growth and development	
Base temperature (°C)	0
Upper temperature (°C)	26
Initial canopy cover, CC_0 (%)	8
Maximum canopy cover, CC_x (%)	96
Canopy growth coefficient, CGC (%)	3
Canopy decline coefficient (CDC) at senescence (%)	7
Water stresses	
Upper threshold of leaf growth	0.2
Lower threshold of leaf growth	0.65
Curve shape of leaf growth stress coefficient	5
Upper threshold of stomatal conductance	0.65
Curve shape of stomatal stress coefficient	2.5
Upper threshold of senescence stress	0.7
Curve shape of senescence stress coefficient	2.5
Biomass production and yield formation	
Harvest index (%)	36
Water productivity normal. For ET_0 and CO_2 (gr/m^2)	15
Non-conservative parameters	
Management dependent	
Sowing rate (kg seed/ha)	250
1,000 seed mass (gr)	35
Germination rate (%)	75
Cover per seeding (cm^2/plant)	1.5
Plant density (plant/m^2)	535.7
Phenology	
Sowing (date)	23 Oct.
Time from sowing to emergence (date, day)	5 Nov., 13
Time to reach max canopy cover (date, day)	21 Apr., 180
Time from sowing to maximum root depth (date, day)	22 Mar., 150
Time to start senescence (date, day)	25 Jun., 245
Time from sowing to reach maturity (date, day)	22 Jul., 273
Time to reach flowering (date, day)	16 May, 205
Duration of flowering stage (date, day)	15 Jun., 30
Soil dependent	
Minimum effective root depth (m)	0.3
Maximum effective root depth (m)	1.5
Sampling depth (m)	0.5, 1, 1.5
Soil texture	Loamy-sand

Table 6 | Yield and yield component of wheat in two supplementary irrigation scenarios

	Scenario I (dry condition)		**Scenario II (normal condition)**	
Parameter	**Rainfed**	**Supplementary irrigation**	**Rainfed**	**Supplementary irrigation**
Biomass (ton/ha)	7.8	10.4	11.3	12.7
Dry yield (ton/ha)	1.8	3.5	3.9	4.5
Rainfall (mm)	221.6	221.6	246	246
Irrigation (mm)	0	60	0	30
WP (kg/m^3)	0.66	1.04	1.36	1.44
Harvest index (%)	23.6	33.8	35.2	36.2

average amount of water collected mentioned in this research (3.6 L/m^2/day) is only related to the period with agricultural activities. Despite the mentioned conditions, in case of using LFC with dimensions of 40 m^2 and supplementary irrigation of 60 mm, 35 LFC devices will be needed for 1 ha of wheat field. This number of collectors is acceptable compared to the projects implemented in Chile (with 50 LFC devices) to meet the water needs of a small village.

It goes without saying that if the project is implemented on the ridge, the efficiency of water collection can increase up to 19 times (Ritter *et al.* 2008). Assuming a 5-fold increase in efficiency in high places, the number of LFCs required will also decrease to 8. Local observations showed that fog events occur at higher altitudes much more often than at lower altitudes. In addition, high wind speed and the absence of obstacles compared to low points are among the advantages of installing collectors on the ridge.

As a result, considering that agriculture is the main source of income for the people of this region, and considering the potential of this region for the implementation of water extraction projects from fog, investing in the implementation of such projects will minimize the damage caused by the decrease in rainfall and lack of irrigation water in the agricultural sector of the region. It should be mentioned that the income from the increase in the product can compensate the cost spent for the implementation of the project.

3.8. Comparing the results to the other studies

On average, the SFCs installed at the Abi-beyglu Area could collect fog water at 3.6 L/m^2/day, which is comparable to the results of similar studies around the world. According to Table 1, average water yield of the SFC has been 6 L/m^2/day, with a maximum level of 30 L/m^2/day in Oman (Schemenauer & Cereceda 1994b) and a minimum level of 0.16 L/m^2/day in Chile (Carvajal *et al.* 2022). It is obvious that the amount of extracted water was different from one place to another. Quantities of extracted water in Chile (Schemenauer & Cereceda 1994b; Carvajal *et al.* 2022), South Africa (Olivier 2002; Olivier & De Rautenbach 2002), Namibia (Shanyengana *et al.* 2002), United States (Ruiz 2005), Colombia (Molina & Escobar 2008; Escobar *et al.* 2010), Saudi Arabia (Al-Hassan 2009; Gandhidasan & Abualhamayel 2012) and Ecuador (Carrera-Villacrés *et al.* 2017) were reported less than the average, all of which used the SFC type collector. On the other hand, the water extraction values in Peru (Schemenauer & Cereceda 1994b), Oman (Schemenauer & Cereceda 1995), Nepal (Mac Quarrie *et al.* 2001), Spain (Marzol 2008), and Morocco (Marzol & Sánchez 2008) with the same collectors have been obtained higher than the average. There are many reasons that cause differences in the amount of extraction water, including the type and height of the collector installation and meteorological factors such as wind speed and direction.

The fact that average water yield in the study area was below the global average could be attributed to suboptimal location of the fog collectors, which were slightly deviated from the highlands over which the fog front blows into the Ardabil Plain. The collectors were installed at an elevation of 1,340 m, while the mentioned highlands are estimated to be as high as 1,700 m. Accordingly, should the collectors be installed at higher elevations, one may expect higher water yields. Another point to note is the fog time. According to historical data, the study area is foggy for an annual average of 145 days (*i.e.*, more than one-third of a year). Therefore, the relatively long fog time in the study area highlights its large potentials for fog water collection.

4. CONCLUSION

In order to evaluate the potential of fog water collection in Abi-beyglu, northwestern Iran, a project was implemented where three fog water collectors were installed, and measurements were performed during April–December 2021. Accordingly, the volume of water collected in bilayer Raschel-mesh collectors was measured at different days. The results were then compared to similar projects and their correlations with meteorological parameters were assessed. Based on the results of this research, average fog water collection yield during the fog time (3.6 L/m^2/day) was acceptable in comparison to similar projects in other countries. The relatively high number of foggy days in the study area (*i.e.*, more one-third of a year) and distribution of the foggy days in different seasons provide the required basis for increased collection of fog water, which can be considered as an alternative water resource to supply local demand for drinking water and complementary irrigation of rainfed crops. Investigation of the contribution of collected water to supply water demand for wheat farming in the region showed that the collected fog water represents a proper resource for supplying a part of the water demand for dry-farming in the study area. This can be done through one or two complementary irrigations in sensitive growth stage(s) (*e.g.*, flowering stage). Application of the proposed strategy on dry-farming of wheat in the study area brought about increased crop yield and water productivity.

ACKNOWLEDGEMENTS

This research was supported by the Vice-Chancellor's Office for Research of University of Mohaghegh Ardabili, contract number 99-d-9-19958.The authors also acknowledge Ardabil Regional Water Company for making available the meteorological data set used in this study.

DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

CONFLICT OF INTEREST

The authors declare there is no conflict.

REFERENCES

Abdul-Wahab, S. A., Al-Hinai, H., Al-Najar, K. A. & Al-Kalbani, M. S. 2007 Feasibility of fog water collection: a case study from Oman. *Journal of Water Supply: Research and Technology – AQUA* **56** (4), 275–280. https://doi.org/10.2166/aqua.2007.045.

Algarni, S. 2018 Assessment of fog collection as a sustainable water resource in the southwest of the Kingdom of Saudi Arabia. *Water Environment Journal* **32** (2), 301–309. https://doi.org/10.1111/wej.12330.

Al-hassan, G. A. 2009 Fog water collection evaluation in Asir region–Saudi Arabia. *Water Resources Management* **23** (13), 2805–2813. https://doi.org/10.1007/s11269-009-9410-9.

Allen, R. G., Pereira, L. S., Raes, D. & Smith, M. 1998 *Crop Evapotranspiration, Guidelines for Computing Crop Water Requirements*. FAO Irrigation and Drainage Paper, No. 56, Rome, Italy.

Al-Mandhari, A. 2019 Achieving' health for all by all' in the eastern Mediterranean region. *Eastern Mediterranean Health Journal* **25** (9), 595–596. https://doi.org/10.26719/2019.25.9.595.

Bruijnzeel, L. A., Eugster, W. & Burkard, R. 2005 Fog as a hydrologic input. In: *Encyclopedia of Hydrological Sciences*. pp. 559–582. https://doi.org/10.1002/0470848944.hsa041.

Carrera-Villacrés, D. V., Robalino, I. C., Rodriguez, F. F., Sandoval, W. R., Hidalgo, D. L. & Toulkeridis, T. 2017 An innovative fog catcher system applied in the Andean communities of Ecuador. *Transaction ASABE* **60** (6), 1917–1923. http://doi.org/10.13031/trans.12368.

Carrera-Villacrès, D. C., Carrera Villacrés, J. L., Braun, T., Zhao, Z., Gómez, J. & Carabalí, J. Q. 2020 Fog harvesting and IoT based environment monitoring system at the llalo Volcano in Ecuador. *International Journal on Advanced Science Engineering and Information Technology* **10** (1), 407–412. https://doi.org/10.18517/ijaseit.10.1.10775.

Carvajal, D., Mora-Carreño, M., Sandoval, C. & Espinoza, S. 2022 Assessing fog water collection in the coastal mountain range of Antofagasta, Chile. *Journal of Arid Environments* **198**, 104679. https://doi.org/10.1016/j.jaridenv.2021.104679.

Cereceda, P., Schemenauer, R. S. & Suit, M. 1992 An alternative water supply for Chilean coastal desert villages. *International Journal of Water Resources Development* **8** (1), 53–59. https://doi.org/10.1080/07900629208722533.

Dodson, L. L. & Bargach, J. 2015 Harvesting fresh water from fog in rural Morocco: research and impact Dar Si Hmad's Fogwater Project in Aït Baamrane. *Procedia Engineering* **107**, 186–193. https://doi.org/10.1016/j.proeng.2015.06.073.

Echeverria, P., Dominguez, C. H., Villacis, M. & Violette, S. 2020 Fog harvesting potential for domestic rural use and irrigation in San Cristobal Island, Galapagos, Ecuador. *Geographical Research Letters* **46** (2), 563–580. http://orcid.org/0000-0003-2971-7163.

Escobar, C. M., Lopez, A., Aristizabal, H. F. & Molina, J. M. 2010 Operational fog collection and its role in environmental education and social reintegration: A case study in Colombia. In *5th International Conference on Fog, Fog Collection and Dew*, Münster, Germany.

Estrela, M. J., Valiente, J. A., Corell, D., Fuentes, D. & Valdecantos, A. 2009 Prospective use of collected fog water in the restoration of degraded burned areas under dry Mediterranean conditions. *Agricultural and Forest Meteorology* **149** (11), 1896–1906.

Fessehaye, M., Abdul-Wahab, S. A., Savage, M. J., Kohler, T. & Tesfay, S. 2015 The potential for scaling up a fog collection system on the eastern escarpment of Eritrea. *Mountain Research and Development* **35** (4), 365–373.

Gandhidasan, P. & Abualhamayel, H. I. 2012 Exploring fog water harvesting potential and quality in the Asir Region, Kingdom of Saudi Arabia. *Pure and Applied Geophysics* **169** (5), 1019–1036.

Harb, O. M., Salem, M. S. H., Abdel Hay, G. H. & Makled, K. H. M. 2016 Fog water collection for agriculture use (Peanut irrigation) under semi-arid region conditions in North Coast of Egypt. *Advances in Crop Science and Technology* **4**, 219. https://doi.org/10.4172/2329-8863.1000219.

He, C., Liu, Z., Wu, J., Pan, X., Fang, Z., Li, J. & Bryan, B. A. 2021 Future global urban water scarcity and potential solutions. *Nature Communications* **12** (1), 1–11.

Holmes, R., de Dios Rivera, J. & de la Jara, E. 2015 Large fog collectors: new strategies for collection efficiency and structural response to wind pressure. *Atmospheric Research* **151**, 236–249.

Karkee, M. B. 2005 Harvesting of atmospheric water: a promising low-cost technology. In *Ninth International Water Technology Conference*. Vol. 1720.

Klemm O., Schemenauer, R. S., Lummerich, A., Cereceda, P., Marzol, V., Corell, D., van Heerden, J., Reinhard, D., Gherezghiher, T., Olivier, J., Osses, P., Sarsour, J., Frost, E., Estrela, M. J., Valiente, J. A. & Fessehaye, G. M. 2012 Fog as a fresh-water resource: overview and perspectives. *Ambio* **41** (3), 221–34. http://doi.org/10.1007/s13280-012-0247-8.

Mac Quarrie, K., Shrestha, Y., Schemenauer, R. S., Vitez, F., Kowalchuk, K. & Taylor, R. 2001 Results from a high elevation fog water supply project in Nepal. In *Proceedings of 2nd International Conference on Fog and Fog Collection*, Canada.

Marzol, M. V. 2008 Temporal characteristics and fog water collection during summer in Tenerife (Canary Islands, Spain). *Atmospheric Research* **87** (3–4), 352–361. http://dx.doi.org/10.1016/j.atmosres.2007.11.019.

Marzol, M. V. & Sánchez, J. 2008 Fog water harvesting in Ifni, Morocco. an assessment of potential and demand. *Die Erde* **139** (1–2), 97–119.

Molina, J. M. & Escobar, C. M. 2008 *Fog Collection Variability in the Andean Mountain Range of Southern Colombia*. *Doctoral Dissertation*, Colorado State University. Libraries. Available from: http://hdl.handle.net/10217/37880.

Mousavi-baygi, M. 2008 The implementation of fog water collection systems in Northeast of Iran. *International Journal of Pure and Applied Physics* **4** (1), 13–21.

NASA 2016 "NASA finds drought in Eastern Mediterranean worst of past 900 years." https://www.nasa.gov/feature/goddard/2016/nasa-finds-drought-in-eastern-mediterranean-worst-ofpast-900-years.

Nelson, R. A. 2003 *Air Wells, Fog Fences & Dew Ponds. Methods for Recovery of Atmospheric Humidity*. Available from: http://www.rexresearch.com/airwells/airwells.htm.

Olivier, J. 2002 Fog-water harvesting along the West Coast of South Africa: a feasibility study. *Water* **28** (4), 349–360. https://doi.org/10.4314/wsa.v28i4.4908.

Olivier, J. & De Rautenbach, C. J. 2002 The implementation of fog water collection systems in South Africa. *Atmospheric Research* **64** (1–4), 227–238. https://doi.org/10.1016/S0169-8095(02)00094-7.

Regalado, C. M. & Ritter, A. 2016 The design of an optimal fog water collector: a theoretical analysis. *Atmospheric Research* **178**, 45–54. https://doi.org/10.1016/j.atmosres.2016.03.006.

Ritter, A., Regalado, C. M. & Aschan, G. 2008 Fog water collection in a subtropical elfin laurel forest of the Garajonay National Park (Canary Islands): a combined approach using artificial fog catchers and a physically based impaction model. *Journal of Hydrometeorology* **9** (5), 920–935. https://doi.org/10.1175/2008JHM992.1.

Ritter, A., Regalado, C. M. & Guerra, J. C. 2015 Quantification of fog water collection in three locations of Tenerife (Canary Islands). *Water* **7** (7), 3306–3319. https://doi.org/10.3390/w7073306.

Ruiz, G. 2005 *Characterization of fog Water Collection Potential at Fort Ord and Glen Deven Ranch Near Big Sur*. *Capstone Projects and Master's Theses*. Available from: https://digitalcommons.csumb.edu/caps_thes.

Schemenauer, R. S. & Cereceda, P. 1994a A proposed standard fog collector for use in high-elevation regions. *Journal of Applied Meteorology and Climatology* **33** (11), 1313–1322. https://doi.org/10.1175/1520-0450.

Schemenauer, R. S. & Cereceda, P. 1994b Fog collection's role in water planning for developing countries. *Natural Resources Forum* **18** (2), 91–100.

Schemenauer, R. S. & Cereceda, P. 1995 Reply. *Journal of Applied Meteorology (1988–2005)* **34** (9), 2111–2112. Available from: https://www.jstor.org/stable/26187432.

Schemenauer, R. S. & Joe, P. I. 1989 The collection efficiency of a massive fog collector. *Atmospheric Research* **24** (1–4), 53–69. https://doi.org/10.1016/0169-8095(89)90036-7.

Shanyengana, E. S., Henschel, J. R., Seely, M. K. & Sanderson, R. D. 2002 Exploring fog as a supplementary water source in Namibia. *Atmospheric Research* **64** (1–4), 251–259. https://doi.org/10.1016/S0169-8095(02)00096-0.

Steduto, P., Hsiao, T. C., Raes, D. & Fereres, E. 2009 Aquacrop – the FAO crop model to simulate yield response to water: I. Concepts and underlying principles. *Agronomy Journal* **101**, 426–437. https://doi.org/10.2134/1gronj2008.0139s.

Todorovic, M., Albrizio, R., Zivotic, L., Abi Saab, M., Stöckle, C. & Steduto, P. 2009 Assessment of AquaCrop, CropSyst, and WOFOST models in the simulation of sunflower growth under different water regimes. *Agronomy Journal* **101** (3), 509–521. https://doi.org/10.2134/AGRONJ2008.0166S.

WHO 1993 *Guideline for Drinking-Water Quality, Second ed. Recommendations*. World Health Organization, Geneva.

First received 13 April 2023; accepted in revised form 9 August 2023. Available online 22 August 2023