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Field solution to produce irrigation-drinking water by condensation irrigation system from seawater

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ABSTRACT

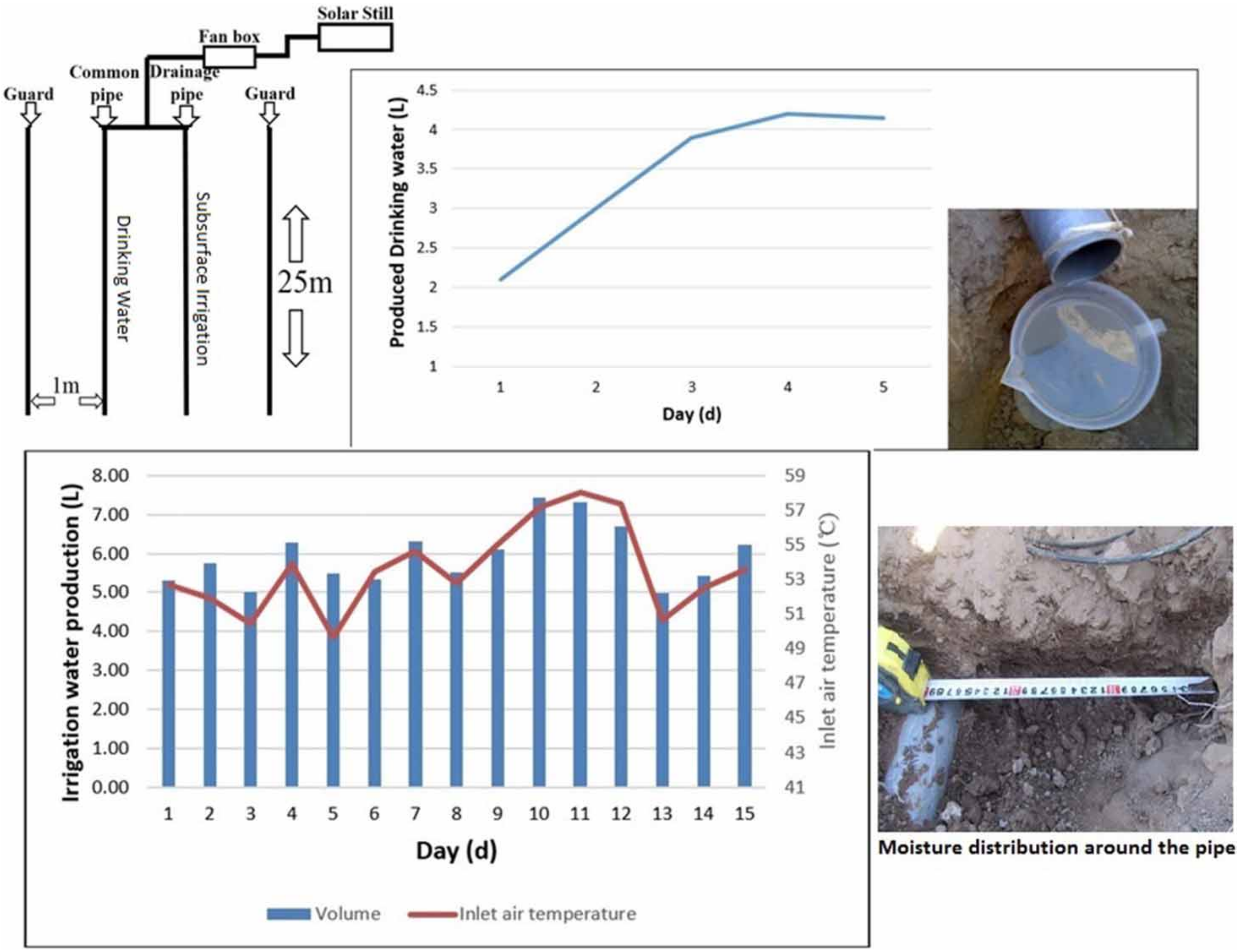
Condensation irrigation (CI) combines desalination with subsurface irrigation. Here, solar stills are used to heat and humidity air, which is condensed in underground drainage pipes to irrigate the soil, directly in the root zone. This article describes and evaluates a CI field test at Shahid Chamran University of Ahvaz in Iran. The objective was to gain a deeper understanding of the CI system in the production of drinking and irrigation water and to do a detailed assessment of heat and moisture transfer in the soil. Perforated and unperforated PVC pipes were used in two separate experiments while airflow properties, soil temperature and humidity, and ambient air temperature were monitored. The system produced 6 kg of irrigation water during 8 hours in the 25 m long pipe. When using an unperforated pipe, 4 kg of freshwater was collected at the pipe ending after 8 hours of operation. The preliminary economic analysis of irrigation system indicates a payback time of less than six years.

Key words: condensation, desalination, drinking water, field test, irrigation

HIGHLIGHTS

- Innovation in solar desalination of seawaters by Condensation Irrigation system in the field.
- Combines desalination and producing drinking-irrigation water in one system.
- Compared to other similar methods, in this system, heat exchanger is the earth.
- Economical method, long life, low maintenance cost, suitable for remote areas.
- Freshwater production efficiency in irrigation is higher than drinking water.

GRAPHICAL ABSTRACT



1. INTRODUCTION

Since water is vital to all living creatures and the lifeblood of agriculture and industry, water scarcity is one of the largest issues in the arid and warm parts of the world (Anderson *et al.* 2013; Neves-Kunrath *et al.* 2020). Also in semi-arid areas, with increasing population and depleting fresh water supplies, this issue is worsening (Kuylenstierna *et al.* 2009). Besides, urbanization has polluted groundwater aquifers and many rivers that carry water to remote areas and the ever growing world population is leading to further water shortages (Monjezi *et al.* 2020; Fattahi Nafchi *et al.* 2021). Hence, we have to find new water resources.

A possible alternative to solve the water problem is desalination of sea or brackish water. However, this means dependence on an expensive resource (Garcia-Rodriguez *et al.* 2002; Kalogirou 2005; Lindblom 2012; Grubert *et al.* 2014). Therefore, cheap and permanent energy will be required. A sustainable desalination system must therefore be based on renewable energy (Garcia-Rodriguez 2002; Raluy *et al.* 2005; Grubert *et al.* 2014).

Solar desalination imitates nature's hydrological cycle: solar thermal energy is used to evaporate saline water, usually seawater, and as the vapor condenses, it is collected as freshwater (Lindblom 2012).

One of the systems suggested for solar desalination and drinking water production is condensation irrigation, in which the ground acts as a condenser of humid air (Lindblom 2006, 2012; Yousefi *et al.* 2012; Yousefi & Boroomand-Nasab 2015).

The suggested Condensation Irrigation (CI) system uses solar heat to evaporate saline or otherwise contaminated water, in solar stills. Ambient air is humidified by the warm water inside the still and thereafter led into an underground pipe system where it is cooled by losing its heat to the surrounding soil and the vapor condenses as freshwater on the inner pipe walls

(Lindblom 2012), see Figure 1. The water leaves the pipe through perforations of the drainage pipe and thus irrigates the surrounding soil. Since the subsurface irrigation system delivers water directly into the root zone, interception and evaporation losses will be eliminated (Appels & Karimi 2021). If an unperforated pipe is used, the condensed water is trapped and collected at the end of pipe (Lindblom 2006, 2012; Yousefi 2012).

There is a limited amount of scientific literature in this field since the first CI study was made in 1986 at Luleå University of Technology, Sweden, in a series of Master's theses (Widegren 1986; Göhlman 1987; Gustafsson & Lindblom 2001). Widegren studied the CI system theoretically and concluded that irrigation of a one-hectare land area would be possible by using a fan power of 3–10 kW. The CI technology was also used in the construction of a climate system for a large cucumber greenhouse to control and reduce the difference in air temperature between day and night. This greenhouse, which was located at the Arctic Circle in Sweden, was successfully in operation for 20 years. During the day, moist air was directed into the drainage pipes and warmed the soil, making it possible to prolong the growing season (Nordell 1987). Göhlman (1987) studied the difference in heat transfer between un-perforated (for drinking water production) and perforated pipes (for irrigation) and the results showed the heat transfer from the pipe into the surrounding ground was 50% higher in the perforated pipes.

Ruess & Hausherr (1989) describe a CI-like system where seawater was evaporated in plastic tubes and then condensed in buried pipes and energy consumption was 14 kWh per cubic meter. Gustafsson & Lindblom (2001) investigated the CI system theoretically and experimentally in their MSc thesis. They showed that it was technically and economically feasible to use warm humid air for subsurface irrigation. These studies inspired the National Research Institute for Agricultural Engineering in Tunisia to build a solar heated pilot CI plant and their system supplied more than half of the plants' water needs (Chaibi 2013). Lindblom (2012) developed a Matlab model (CI2D) in which the complex heat and mass transfer of the CI system was simulated. In addition, Okati *et al.* (2016) presented a thermodynamic model by numerical and theoretical study and showed by design of experiments the most important parameters. Poblete & Painemal (2018) and Kamali *et al.* (2020) condensed vapor from solar dryers and greenhouses by using a heat exchanger and used the condensed water for irrigation. In a similar system, Mircea *et al.* (2019) pumped cold water into copper and polyethylene pipes that were placed on a soil surface. This way, air moisture condensed on the outer surface of the pipes and then the water entered the soil drop by drop. Recently, Arabnejad *et al.* (2021), made a CI laboratory model ($1\times2\times0.3$ m) in a greenhouse for basil cultivation. He showed that the condensation irrigation system had the ability to supply the water demand of the basil and that the soil temperature increase due to condensation did not limit the plant growth.

Taking off from previous theoretical studies, the objectives of this study were to build and operate a field test of CI system to get a better understanding of its potential production capacity for irrigation and drinking water in the south of Iran. Another innovation was the simultaneous study of subsurface irrigation and drinking water production in this CI system. In addition, this field study was also conducted to determine the performance of the system in the field compared to theoretical and greenhouse studies. Furthermore, a brief economic analysis was performed to determine the payback time of the investment by using tariffs and prices in Iran. Based on the initial results of this field test, Yousefi *et al.* (2012) and Yousefi & Boroomand-Nasab (2015) found that the production of drinking water or distilled water is feasible by using this method. Yousefi *et al.* (2017) also showed that in the subsurface irrigation sector, the irrigation rate is 1.5 mm/day in the root development area and Yousefi *et al.* (2022) designed and built a laboratory model that showed that the change in flow temperature has the greatest impact on production efficiency. Yousefi & Boroomand-Nasab (2016) published a series of instructions and guidelines for the construction of a condensation irrigation system, in which limitations and problems that existed in the construction of this system and measurements are detailed.

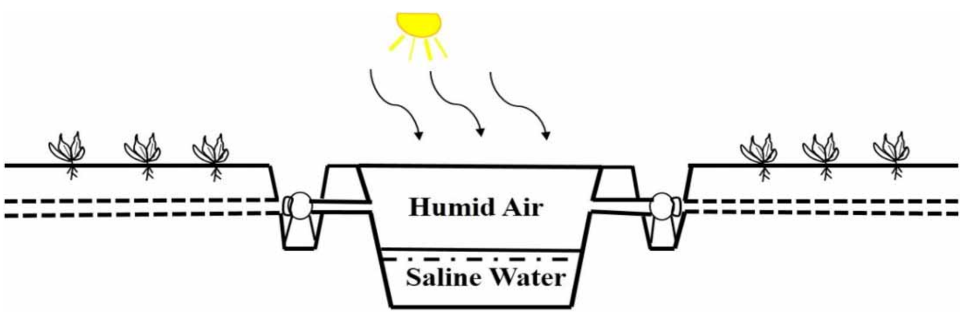


Figure 1 | Schematic diagram of condensation irrigation system (Lindblom 2012).

2. MATERIALS AND METHODS

This condensation irrigation research started by selecting a suitable plot of land for the field test. Then a number of soil parameters were measured before the pipe system and the solar still were installed. During the operation of the system the required parameters were measured at specific times each day and later used in the analysis of the operation. Finally, the economic analysis was carried out. These steps are described in detail below.

2.1. Description of the study area

The city of Ahvaz is an arid area located in the southwest of Iran (31°20′N, 48°40′E) and is the capital of Khuzestan province. According to the Köppen-Geiger climate classification, the climate of Ahvaz is hot arid desert (Kottek *et al.* 2006). The average annual temperature and precipitation for the period of ten recent years were 25.3 °C and 182 mm, respectively (Iran Meteorological Organization 2019). Recently, Ahvaz is considered as the hottest city (54.0 °C) on earth in modern measurements by the Weather Underground Organization in 2017 (The Washington Post 2017).

The study was conducted in 2012 in a 180 m^2 area at the research farm of Shahid Chamran University of Ahvaz (SCU). The area was separated from the rest of the farm by a rope, and a ditch was dug around it to prevent possible runoff.

The soil texture is fine loam, see Table 1. Since the percent of clay is only 22% no filter had to be used around the perforated pipe. However, to enhance the humid transport into the soil some gravel was packed around the pipe.

The porosity and density in Table 1 are for undisturbed soil. Since the installation of pipes and probes disturbed the soil, the porosity increased while the density decreased compared to given values.

2.2. Installation

In the first step to install the CI system, four parallel 25 m ditches were plowed to a depth of 0.4 m with 1 m spacing (Figure 2), which means that each m of pipe irrigates 1 m^2 of land.

In this system, two types of PVC pipes were used, unperforated pipes and drainage pipes, with the diameter of 63 mm and 25 meter in length. The 5 mm holes of the drainage pipe were drilled with a spacing of 21 mm.

The unperforated pipe and the drainage pipe were both placed in the two center trenches, which sloped slightly in the flow direction. After the installation, the trenches were refilled with soil. The side pipes (drainage or guard pipes) and the ditch around the test area were installed to reduce boundary effects as they controlled any surface or subsurface runoff. The system design is outlined in Figure 2. A plastic film was prepared as rain protection of the field test. It was used two months before the start of the test. However, it was never used during the test because no precipitation occurred during that period.

After installation of all pipes, a solar still and a fan with the power of 16 W and 65 m^3/h flow rate were installed. The tested pipe (only one at the time) was connected by thermally insulated pipes.

2.3. Operation of the system

The saline water of the still was warmed up close to 70 °C by solar heat and by an electrical heater to create stable conditions. Ambient air, driven by a fan creating a negative pressure, was flowing over its water surface (0.4 m^2) at which it was humidified.

2.3.1. Drinking water production

First, humid air was pumped into the unperforated pipe during 8 hours per day for 5 days, while humidity and airflow rate and temperature were measured at the inlet and outlet of the pipe. The humid air cooled along the pipe and the moisture

Table 1 | Undisturbed soil texture at the test site

	Particle classes (%)					
Depth (cm)	Sand	Silt	Clay	Texture	Porosity %	Bulk density (ρ_b) gr/cm³
0–28	44	34	22	Loam	39.5	1.59
28–49	44	34	22	Loam	38.4	1.62
49–83	39	37	24	Loam	42.75	1.50

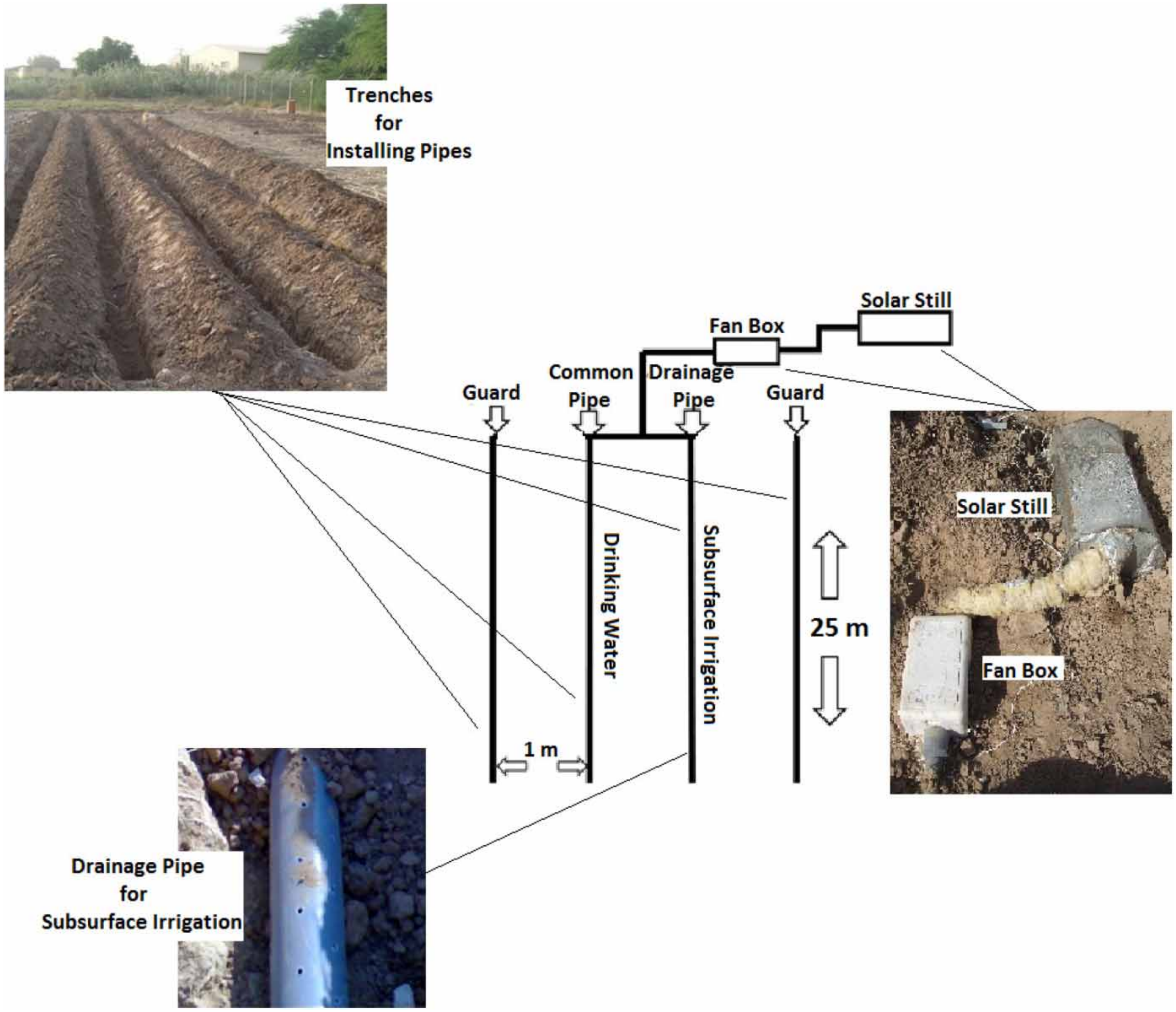


Figure 2 | Four 25 m trenches were dug to a depth of 0.4 m for the installation of pipes which were connected as shown in the main scheme. The guard pipes were used to control of subsurface currents.

condensed at the pipe wall. Due to the slope of the pipe, the water was collected at the end of the pipe. The mass of water was compared with the calculated amount of drinking water. After these measurements, the CI system was shut down until the soil temperature was back at its original state (temperature), before the next test started.

2.3.2. Subsurface irrigation

Before the CI system was used for subsurface irrigation, the system was connected to the drainage pipe. Just as in the previous test, humid air was precipitating as fresh water on the inside of the drainage pipe. The condensed water, and part of humid air, percolated the surrounding soil through the holes in the pipe. Consequently, the surrounding land was warmed, aerated and irrigated. This test was conducted over 15 days, with irrigation occurring for 8 hours each day. The water production was calculated as the difference in water content of the air, between the inlet and outlet of the pipe.

2.4. Measurements

During operation a set of main parameters were measured at the inlet and outlet of the pipes. These hourly measurements included relative humidity, temperature and velocity of airflow. Meteorological data such as ambient air temperature and humidity were measured every day.

Dry and wet temperatures were used to determine temperature and relative humidity while a pitot tube was used to determine the airflow velocity.

Measurement probes for temperature and humidity were installed in the soil every 5 m along the pipes to enable monitoring of temperature and moisture variations. For the unperforated pipe, the soil moisture was not measured since no water could escape through the water tight pipe walls.

2.5. Production of condensed water

In the calculation of produced water, it was assumed that the humid air behaved as an ideal gas under normal pressure at the inlet and outlet of the pipe. Therefore, the amount of condensed water can be obtained using the measured data from field tests:

$$P_{v,sat} = \frac{e^{\left(77.345+0.0057\cdot(T+273.15)-\frac{7235}{T+273.15}\right)}}{(T+273.15)^{8.2}} \tag{1}$$

$P_{v,sat}$ [Pa], is the saturation pressure for water vapor and T [°C] is the temperature of the air and vapour (Gibson *et al.* 1995; Gustafsson & Lindblom. 2001). The relative humidity, φ [%RH], was calculated by using wet and dry temperatures to describe the amount of moisture in the air and able to obtain the vapour's partial pressure, P_v [Pa] (Pan & Sun 2006):

$$P_v = \varphi \cdot P_{v,sat} \tag{2}$$

and the partial pressure for the dry air, P_{da} [Pa], is the difference between the total pressure, P_{tot} [Pa] and the partial pressure of the vapour (Pan & Sun 2006):

$$P_{da} = P_{tot} - P_v = P_{tot} - P_{v,sat} \cdot \varphi \tag{3}$$

Now by knowing the cross sectional area, A [m^2], density of saturated air, $\rho\ \left[\frac{kg}{m^3}\right]$, and velocity, $v\ \left[\frac{m}{s}\right]$, the mass flow of saturated air, $\dot{m}_{a,tot}\ \left[\frac{kg}{s}\right]$, can be obtained (Lindblom 2006):

$$\dot{m}_{a,tot} = \rho \cdot A \cdot v \tag{4}$$

The mass of the condensate, m_v [kg], can be obtained from the Ideal Gas law (Gustafsson & Lindblom 2001; Lindblom 2006; Yousefi 2012):

$$m_v = \frac{P_v \cdot V}{R_v \cdot (T+273.15)} \tag{5}$$

in which R_v [J/kg,K] is the universal gas constant for water vapour. From Equation (5) it is possible to express the partial mass of vapor, m_v, relative to the partial mass of dry air, m_{da}, gives the weight of available water of the air (Gustafsson & Lindblom 2001; Yousefi 2012):

$$\frac{m_v}{m_{da}} = \frac{R_{da}}{R_v} \cdot \frac{P_{v,sat} \cdot \varphi}{P_{tot} - P_{v,sat} \cdot \varphi} = \frac{287}{462} \cdot \frac{P_{v,sat} \cdot \varphi}{P_{tot} - P_{v,sat} \cdot \varphi} \tag{6}$$

In other words, the ratio of m_v/m_{da} equals the absolute humidity, x [kg water/kg dry air], expressed as (Gustafsson & Lindblom. 2001; Lindblom 2006; Yousefi 2012):

$$x = 0.622\frac{p_{v,sat} \cdot \varphi}{(p_{tot} - p_{v,sat} \cdot \varphi)} \tag{7}$$

The difference in absolute humidity between inlet and outlet equals the mass of condensed water.

By knowing the mass flow (kg/s) and absolute humidity of the humid air, it is possible to determine the mass flow rate of dry air, $\dot{m}_{da}$ (kg/s) (Gustafsson & Lindblom. 2001; Lindblom 2006; Yousefi 2012):

$$\dot{m}_{da} = \frac{\dot{m}_a}{1+x} \tag{8}$$

where $\dot{m}_a$ is the mass flow of humid air [kg/s]. Then, the condensation rate, $\dot{m}_e$ [kg/s] is obtained by multiplying the mass flow of dry air by the difference in absolute humidity, between inlet and outlet (Lindblom & Nordell 2006):

$$\dot{m}_e = \dot{m}_{da} \cdot (x_{inlet} - x_{outlet}) \tag{9}$$

2.6. Preliminary economic analysis

The desirability of an investment is directly related to its payback period. Hence, shorter periods mean more attractive investments (Poblete & Painemal 2018):

$$\text{Payback period} = \frac{\text{Initial investment}}{\text{Net annual cash flow}} \tag{10}$$

The initial investment includes the total cost of construction and the net annual cash flow is the income from yield and freshwater production. However, the rate of payback period depends on several factors, all of which are related to where the project was built. Therefore, Iran was selected and it was assumed that no money was paid for the land and the seawater. In addition, it was assumed that the land would be used only once a year and that the dominant crop in the area, wheat, would be planted. The average growth period is 180 days and according to the annual precipitation, the net irrigation water requirement of wheat in Ahvaz area is 2250 m^3/ha (Moayeri 2018). Furthermore, part of this study showed this mentioned CI system was able to meet the average water requirement of 1.5 mm/d in the root zone (Yousefi *et al.* 2017). Thus, the yield is more than 5000 kg/ha or 0.5 kg/m^2. However, with the use of localized irrigation methods like CI system, the yield has increased to 0.8 kg/m^2 and more (Oron *et al.* 1986; Akhavan 2015; Andarzian 2019). Also, the Statistical Center of Iran was used for wheat purchase tariffs and electricity prices (2021), see Table 2. It should be noted that the total costs and tariffs for water and energy have been converted into dollars (Exchange Rate 2021).

3. RESULTS AND DISCUSSION

Both experiments were performed daily between 8.00 and 16.00. The average air temperature, velocity, and humidity of the inlet and outlet of two pipe sections for irrigation and drinking water are shown in Table 3. The drinking water and irrigation water are very different. It is seen that the temperature, humidity and velocity have decreased more at the outlet of the irrigation pipe. It is concluded that these differences are because of greater heat transfer and friction in the irrigation pipe and that part of the air leaves the pipe though the drainage holes.

3.1. Drinking water

In the drinking water system, with unperforated buried pipes, the condensation heat is transferred into the surrounding ground by heat conduction only.

Table 2 | Tariffs of electricity per KWh, wheat purchase and initial investment made in $

Parameters	2012	2013	2014	2015	2016	2017	2018	2019
Cost of electricity per 100 Kwh	0.57	0.55	0.26	0.29	0.35	0.32	0.32	0.32
Cost of wheat per kg	0.28	0.37	0.32	0.34	0.4	0.34	0.38	0.52
Cost of pipes, humidifier, fans and pumps	215							

Table 3 | Measured mean values at inlet and outlet of the pipe in CI system for drinking water (after 5 d) and subsurface irrigation (after 15 d)

Parameters	CI system	Inlet	Outlet
Temperature (°C)	Drinking	54	20
	Irrigation	54	16.3
Velocity (m/s)	Drinking	5.5	1
	Irrigation	5.5	0.1
Humidity (%)	Drinking	90	78
	Irrigation	90	68

The amount of produced fresh water in the pipe, shown in Figure 3, was collected at the outlet of the pipe. The least drinking water was produced during the first days and the greatest amount of drinking water was obtained during the fourth day. The reason is most likely that part of formed water was stuck in the pipe since the inner surface of the unperforated pipe was initially dry and some water formed a thin water film on the inner surface of the pipe. At first glance, this reason is strange but in 25 m of pipe it has a significant effect. Also, wetting continued on the second day since the drinking water production was less than other days. After 3 days, the water production stabilized and the amount of collected drinking water was approximately 4 kg/d and the salinity of the incoming water was zero. An additional reason for the difference in the collected and calculated water was possibly some leakage of humid air. Another result could be to increase the slope of the pipe for future work, so that water can be easily directed to the outlet.

Figure 3 shows that both the calculated and measured values increased after the first days of operation. The reason for this difference is that the calculations assume that no water remains in the pipe, and do not consider that a water film is initially formed on the pipe walls. The average drinking water production was 4 kg/d while the average evaporation in the still (i.e. the humidification of air) was almost 10 kg/d. This means that only 40% of the evaporated water was collected at the end of the pipe.

When the humid warm air was cooled and condensed it emits its heat to the pipe and then the surrounding soil. In this experiment, the pipe surface and soil temperature increased during the daily 8-hour testing and decreased during the night to almost the initial temperature.

As shown in Figure 4, the soil temperature above the pipe increased during the 5-day test period. The temperature difference between the humid air and soil was greatest at the beginning of the test and also at the starting point of the pipe. Therefore, more heat is released. This front, indicating a greater production of water, is moving with the flow along the pipe.

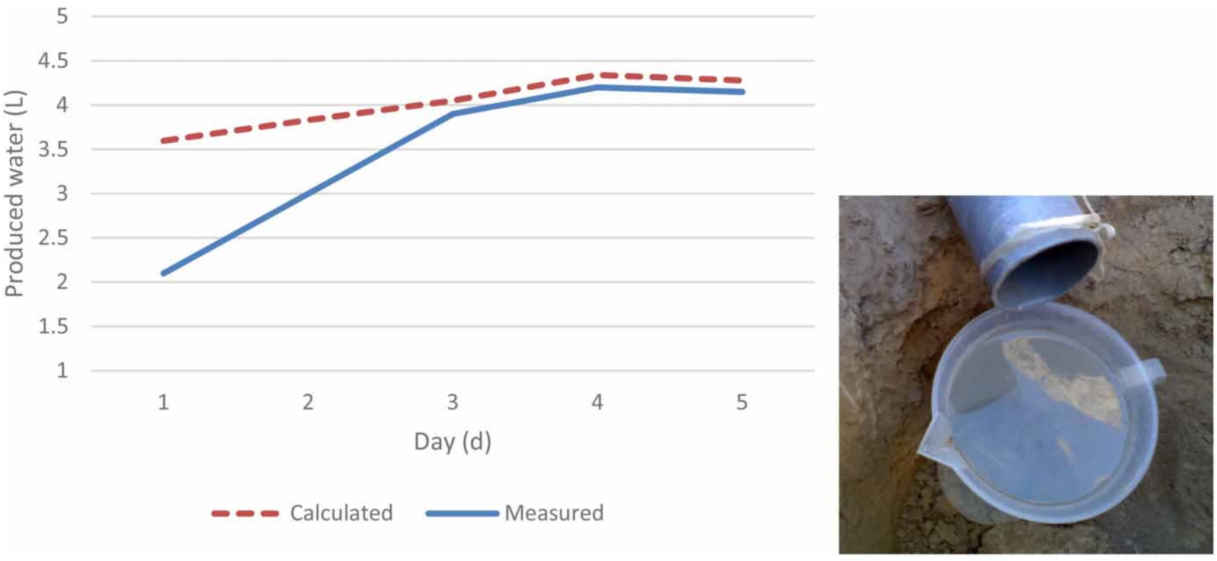


Figure 3 | Calculated and experimental volume of produced drinking water in the CI field test.

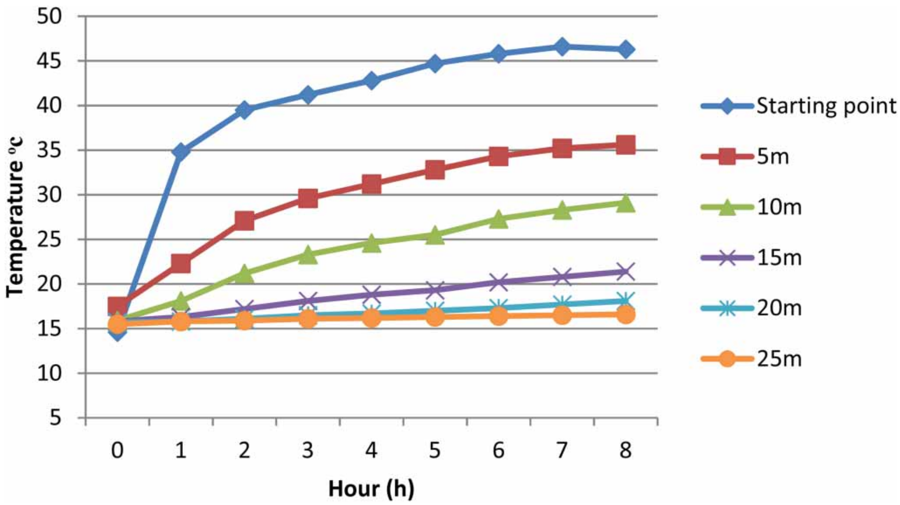


Figure 4 | Measured soil temperature 5 cm above pipe surface of the un-perforated pipe.

It is also concluded that the water production rate is decreasing along the pipe, see Figure 4, until steady state is reached.

By comparing the obtained results with the theoretical result of Lindblom & Nordell (2006) it was found that the amount of produced water is less than previous work. One reason was that the selected fan did not have enough power for its task, i.e. for the required airflow rate, and that the selected pipe diameter was much smaller than in their theoretical study.

3.2. Subsurface irrigation

In this kind of irrigation system the condensation heat is transferred into the surrounding ground not only by heat conduction but also by convective heat transfer. This heat is transferred by water and humid air transported through the drainage holes of the pipe. This way the soil is irrigated and the water is later absorbed by the plant roots.

According to Figure 5, during 15 days of the irrigation experiment, the amount of condensed water varied from 5 to 8 kg/d. This difference in water production was mainly due to the varying inlet airflow temperature, which is indicated by the zigzag red line, and the relationship between the amount of water production in the drainage pipe and inlet airflow temperature clearly shows if the inlet air temperature increases, water production also increases, and if it decreases, production decreases, too.

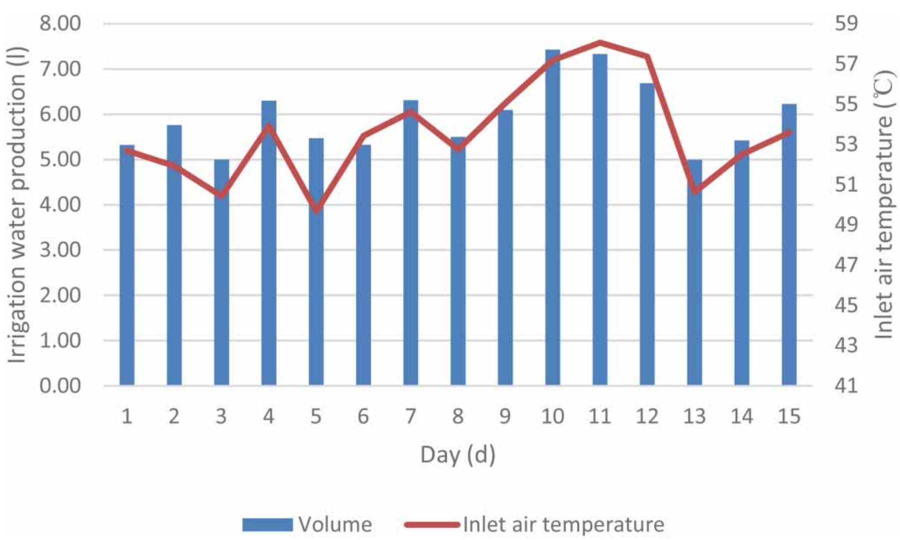


Figure 5 | Water production in the subsurface irrigation system and inlet airflow temperature.

Figure 5 shows that changing inlet air temperature which was affected by the ambient temperature variations (see Table 4), caused changing water production, for example on the 10th and 11th days, which were the hottest days, also the highest water production occurred.

The average production of subsurface irrigation water for these 15 days was 6 kg/d with an average irrigation rate of 1.5 mm/d (Yousefi *et al.* 2017). This was less than the result from the greenhouse study of Arabnejad *et al.* (2021), 2.08 mm/d. Of course, considering that these two experiments have been studied with different dimensions, equipment and designs and in two completely different environments, one in the greenhouse and the other in the field environment and real conditions, this comparison may not be correct. In this field study, since average water evaporated in the solar still was 10 kg/d, the average production of water by subsurface irrigation was 60% and the maximum daily production of water was 74% during the 10th day of operation.

As in previous theoretical studies (Lindblom 2006; Okati *et al.* 2016), it can be stated that a higher inlet air temperature produces more water. However, in Figure 5 it is observed that although the inlet temperature on the 10th day is lower than the 11th day, the amount of water production on the 10th day is higher than the 11th day.

Further studies showed (see Figure 6) that the separation of water production at different hours in these two days also has some fluctuations, but it can not be said with certainty why the total water production on the 10th day is higher.

By comparing the inlet airflow and soil temperature during the 10th and 11th day (Table 5), it was found that the soil temperature at 8.00 in the morning was about 1 °C lower during day 10. That should cause a higher water production compared to day 11, as shown in Figure 6. Therefore, despite the fact that the inlet temperature has the greatest impact on water production, other environmental factors should not be ignored. One of the advantages of field testing is that some results and limitations can be achieved during the experiment that are unlikely to be achieved in theoretical studies and in greenhouses.

3.2.1. Soil temperature variation

The changes in soil temperature during this period were almost the same for 15 days, so that during 8 hours of condensation irrigation, the soil temperature increased, and in the following 16 hours soil temperature decreased almost back to the initial

Table 4 | Average ambient temperature during the experiment days

	Day														
Parameters	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**
Average ambient temperature (°C)	19	19.8	19.8	19.8	19.4	8.6	16.2	17.8	16.3	20.6	20.7	21.1	19.2	19.5	20

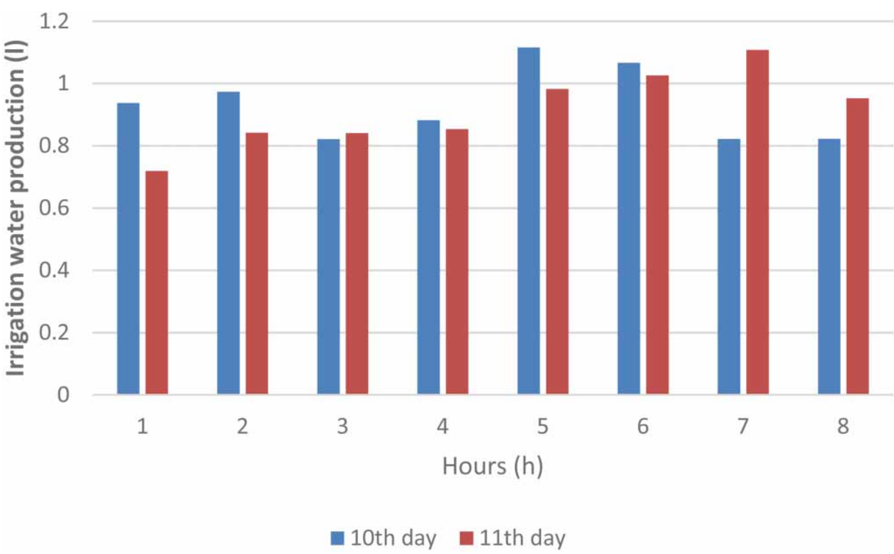


Figure 6 | Water production in the subsurface irrigation system in two days.

Table 5 | Meteorological parameters on the 10th and 11th days during the experiment

Day	Inlet air temperature (°C)	Inlet air relative humidity %	Ambient air temperature (°C)	Ambient air relative humidity %	Soil temperature (°C)
10th day	57.8	88.9	20.61	46.5	19.1
11th day	58.06	89.5	20.66	43.9	20.2

temperature. Figure 7 shows the soil temperature at 5 cm above the pipe at the inlet, middle and end of the pipe on the 10th day.

Figure 7 illustrates that the soil temperature rises along the pipe during subsurface irrigation, similar to the drinking water experiment (Figure 4). However, this increase in soil temperature is greater at the pipe inlet than further down the pipe. Therefore, as we move towards the end of the pipe, the amount of condensed water and irrigation water decreases. Comparing Figures 7 and 4 also raises the question of why the initial soil temperature is different at the pipe inlet than at the middle and end of the pipe. As can be seen in Figure 7, the initial soil temperature at the pipe inlet is higher than in the middle and end of the pipe. This indicates more moisture and water in the soil. Therefore, the higher soil moisture means that it takes longer for the system to lose heat due to the specific heat capacity of the water compared to the dry soil.

Figure 8 shows how the soil temperature increases during the 10th day of the condensation irrigation experiment at the pipe inlet at 5, 10 and 15 cm above the pipe. At 5 cm the temperature increases rapidly during the first 2 hours. Then, it reaches a near steady value after about 4 hours of the operation. Similarly, the soil temperature rises at 10 cm and a little later at 15 cm above the pipe with an almost constant slope. In the subsurface irrigation system, this increase in temperature is due to the heat released from the condensation as well as the infiltration of vapour through the pipe holes into the soil pores. Also, according to Figure 8 and Table 5, it is clear that on the 10th day, the average inlet temperature of humid air is 57.8 °C, but the soil temperature is constant at 5 cm after about 4 hours, although the soil temperature continues to increase at 10 and 15 cm after that. Since the maximum temperature of the soil (closest to the pipe in the radial and longitudinal direction) is not greater than 45 °C, roots will not grow into the pipes. It should be noted that the soil temperature in both systems of CI during the nightly cooling returns to the initial values and will not exceed this value. Also, compared to Figure 4, it is clear that due to the presence of moisture in the soil and more heat transfer in the subsurface irrigation system, the soil temperature around the pipe in the same conditions will always be lower than the temperature around the drinking water production system.

3.2.2. Soil moisture variation

Soil moisture measurements along and around the 25 m irrigation pipe were performed after 15 days of operation in the field. The average increasing moisture content of soil at 5 cm from the pipe was measured by TDR (Time-Domain Reflectometry).

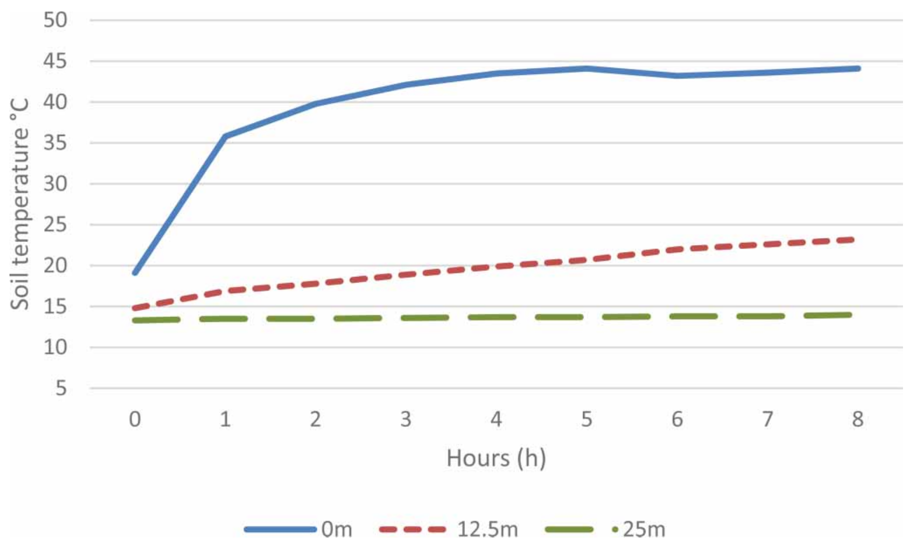


Figure 7 | Soil temperature at 5 cm above the pipe, at three different locations along the pipe on day 10 of the experiment.

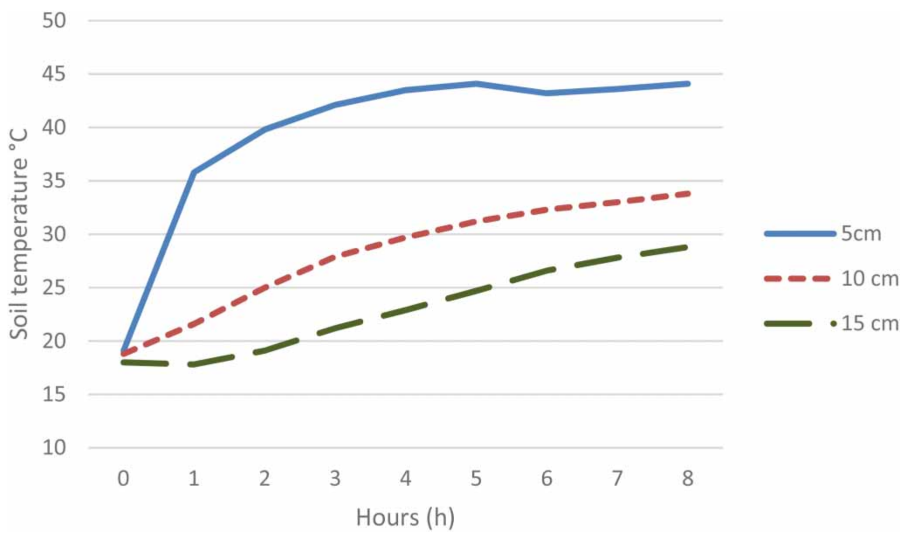


Figure 8 | Soil temperature at 5, 10 and, 15 cm above starting point of the pipe.

Figure 9 shows the increased soil moisture varies from 32% at the pipe inlet to the 6% at the end of pipe in the 15 days. It corresponds to 1.82 mm/day (Yousefi *et al*. 2017), not too far from 2.26 mm/day measured in a laboratory test with sandy soil (Lindblom 2012). It was found that the soil moisture content along the first 15 m of the pipe increased much more than along the remaining 10 meters. One conclusion of this observation is that two shorter pipes would have resulted in greater water production or a more powerful fan should have been used. This is in agreement with previous studies (Lindblom & Nordell 2007).

3.3. Preliminary economic analysis

Given that this study is part of a multi-year study, the data used in this section are fact-based and from relevant organizations. Therefore, the calculations that were based on wheat purchase tariffs, electricity prices and initial operating costs showed that the payback period for this method was six years. As mentioned before, if we assume that the land was planted twice a year, or that crops other than wheat were cultivated, the payback period would certainly be shorter. Nordell (1987) showed that this system has a useful life of more than 20 years, which is economically unique compared to other irrigation methods. Condensation irrigation systems are very efficient and effective in its optimal use of water and energy, especially in countries where energy and water tariffs are expensive. Furthermore, if we add the topic of selling salt or distilled water, this return period will be shorter. Besides, this system can act as a drainage system in critical situations when the ground is flooded and prevent damage to the crop, or it can help the ground to warm up earlier in the spring for growing plants. Economically this system can compete with any other type of irrigation method.

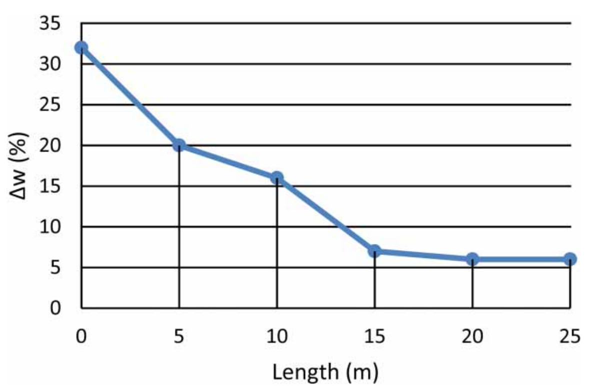


Figure 9 | Measured increased volumetric soil moisture (Δw) at 5 cm around the pipe after 15 days in field test by TDR.

4. CONCLUSION

Condensation irrigation (CI) for the production of drinking water and subsurface irrigation has the potential to become an important system for a sustainable future. So far, very few CI tests have been carried out but in the current study both applications, i.e. irrigation and drinking water, were investigated in an arid region of Iran. This field study showed that the inlet temperature has the greatest impact on production efficiency, but this study also revealed many facts that can only be understood in the natural conditions. Results of performed evaluation indicate that the fan power should have been greater, i.e. the humid flow rate was too small. Also, the duration of the test was not long enough for the system to reach steady state operation. Still, it can be concluded that the produced amount of water in the two tested applications was slightly lower but still in reasonable agreement with previous works. It also showed that the drinking water production was about 40% lower than the corresponding irrigation rate. Because the heat loss of humid air and its transfer to the soil around the pipe was better in the irrigation section, so more water was obtained from its condensation. However, the soil temperature increasing in subsurface irrigation was less compared to drinking water due to the higher specific heat of wet soil compared to dry soil. In addition, the analysis of the data of this field experiment proved that the soil temperature during this period of 8 hours a day would not reach critical conditions, i.e. the temperature around the pipe returned (almost) back to initial temperature during the night. The obtained results indicate that this method can be a supplementary system or even supply the whole water demand to hot-arid regions.

As a next step, the already installed test pipes should be used as they are in a new improved field test. Then, the heater, humidifier, and the fan could be replaced and designed for the tested pipe system. Also, the measurement system should be improved. More detailed system studies should also be made in the future development of the system. In the long term, this system should be solar driven, for heating the still and for the driving energy of the fans. However, if inexpensive energy. i.e. industrial waste energy is available such heat would be a great advantage for the desalination part of the system. Large-scale systems of this type will affect the area on which it is built. If it has any influence on its (dry) surrounding, it would be positive as it increases air humidity and cools the area.

DATA AVAILABILITY STATEMENT

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

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