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Maximum Water Harvest from Soil by Means of Solar Radiation: A Theoretical and Parametric Study

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Abstract

The need for potable water is becoming growing drastically and different methods of freshwater production are explored theoretically and experimentally. Meanwhile, water harvesting from soil is a method through which soil water is attempted to be extracted as much as possible in form of vapor and condensed on the inner surface of a plastic cover and collected in a container. In the present study, the maximum amount of harvested water from soil is theoretically calculated and a parametric study is conducted to find the effects of contributing parameters on the highest level of harvested water from soil. Soil of interest is located under a plastic cover which absorbs solar rays and get heated. Therefore, its water turns into vapor and the condensate is collected afterwards. In fact, such a small harvesting water structure resembles a solar greenhouse. So, the governing equations seem roughly the same. Based on the results of the theoretical and parametric study, increases in difference between temperatures of trapped air under the plastic cover and soil surface brought about lower levels of harvested water as a 10 ℃ increase led to a 13% decrease in harvested water. In contrast, solar radiation intensity, area of soil under the plastic cover and soil absorptivity were all directly proportional to the quantity of harvested water. Moreover, it was concluded that solar radiation intensity acts as a marginally (around 5%) more significant parameter in comparison to area of soil in the amount of harvested water.

Keywords: Soil conduction, Soil convection, Soil water, Solar energy.

1. Introduction

Water scarcity is a serious crisis across the world while it is more highlighted by the fast-growing rate of population (de Souza Moreira et al., 2021; Roggenburg, 2021). It is reported that the world population will reach between 9.4 and 10.2 billion by 2050 (Boretti and Rosa, 2019) which shows a 22 to 34% increase. Therefore, only two remedies remain: controlling the current rate of population growth or exploring new ways to fulfill the growing needs to potable water. Definitely, following both remedies is ideal, but it looks the second solution is more possible and favored. Therefore, to address this issue, different ways are suggested including various desalination technologies like commercially used Reverse Osmosis (RO), Thermal technologies (Multi-Effect Desalination (MED), Mechanical Vapor Compression (MVC), Multi-stage flash distillation (MSF)) (Paixão et al., 2023; Lawal et al., 2023; Sharaf et al., 2011; Hossseinipour et al., 2023), wastewater treatment (Rashid et al., 2021 and Xu et al., 2023; He et al., 2023), water harvesting techniques (Tashtoush and Alshoubaki, 2023; Tadros et al., 2021), etc. Water harvesting techniques also include a wide range of sources namely rainwater (Boers and Ben-Asher, 1982), rooftop (Anchan and Prasad, 2021), atmosphere (Kandeal et al., 2022) etc. Therefore, it seems human beings have already tried and still working to find new sources of water to tackle the existing problem of water shortage esp. in water-stressed countries or the imminent one in countries which will face the water scarcity sooner or later .

From the commercial point of view, some of these aforementioned methods have been widely used while others are still at the research stage and the researchers are hopeful to find solutions to make them more cost effective and generally accepted. But, freshwater production methods are mostly energy intensive (Ehteram et al., 2021 and Nassrullah et al., 2020) and meeting their energy requirements is also a great deal of concern. Nowadays, most of the required energy is supplied by fossil fuels which have led to global warming and the consequent problems. Hence, use of renewable energies have gained a lot of attention as they are abundant and environmentally-friendly sources of energy (Alawad et al., 2023 and Chen et al., 2021). Renewable energy-based systems of freshwater production are also of different independent types such as solar stills with different configurations (Hedayatizadeh and Sarhaddi, 2021; Saxena et al., 2022) or as an integration (solar, wind etc.) into an existing desalination technology (Annamalai and Kannappan, 2023; Kaheal et al., 2023; Rostami et al., 2023) while both of these categories are still under development. The major drawback of the solar stills is their low productivity and it has led to a broad range of experimental and theoretical studies to help increase the productivity. But, some design modifications have emerged promising and have resulted in higher levels of freshwater production. The main strengths of solar stills are their simple design, low maintenance cost, fully solar-energy dependent, warmly welcome by poor communities due to their low investment costs etc. However, the other desalination systems which partially use harnessed solar or other types of renewables to meet their energy needs, are mostly welcome by desalination industries and require high investments. Moreover, in these systems, part of required energy is fed by renewables and they are mostly used by fossil fuel-based energy backup systems.

Meanwhile, another sources of water is soil containing low to high levels of water content. This source of water is more favored especially in arid regions where water shortage is more severe and finding a water supply has a great significance. To this end, a structure can be built to enhance soil water evaporation through absorption of solar energy by soil surface and trap the evaporated water afterwards through condensation on the inner surface of a plastic film (Li and Zhang, 2022; Li et al., 2020). In fact, a mini greenhouse is built with the aim of collecting condensate. Similar to a solar still, this configuration is fully solar dependent and cheap. Moreover, it does not require skillful operators and it can be setup easily and everywhere. So, a freshwater production system can be built with the previous strengths to meet the urgency needs of people to water. But, analogues to solar still, they have low productivity and it can only produce water when there is sun in the sky. Anyway, as a technique of water harvesting, the given system is interesting to be studied and explored.

To the best knowledge of the author, the heat transfer process of such a water harvesting technique is not explored and more importantly it is presented in a simple form here. The point with the current set of equations presented here is introduction of a good rule of thumb for calculation of amount of harvested water. Therefore, this combination of equations help find the maximum harvested water under a specific meteorological condition. Besides, a set of parametric studies have also been conducted to explore the effects of different contributing parameters including solar radiation intensity, absorptivity of soil surface, difference between temperatures of soil surface and air trapped under the plastic cover. In the present study, it is assumed that whole solar radiation incident on the bare surface of soil under the plastic cover is absorbed and devoted to soil water evaporation. Therefore, the present study sets a maximum threshold to the harvested water from soil.

2. Materials and Methods

2.1. Water Harvesting System Description

The schematic of the given water harvesting system is shown in Figure (1) taken from Ref. (Li and Zhang, 2022). As seen, solar rays strike the plastic surface which has covered the specified area of the soil surface. This plastic cover acts as a condensing surface and is shaped like an inverted cone. The soil water is evaporated from its surface and reaches the condensing plastic cover. As a result of heat exchange, the evaporated water turns into droplets which are transported along the inner surface of the plastic cover and eventually drop into the container located at the center. In the following sections, it is attempted to model the heat transfer process through the soil and the corresponding process i.e. evaporation of soil water.

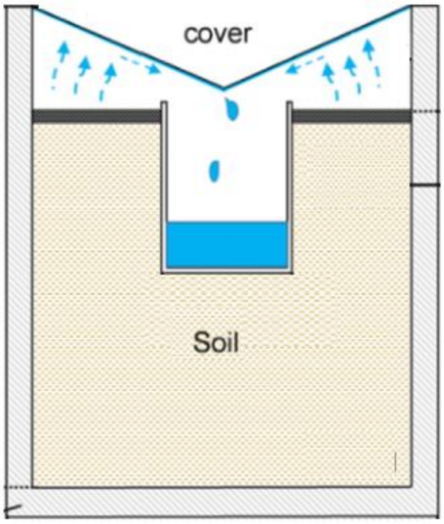

Fig. 1. The schematic of the given water harvesting system is shown in Figure (1) taken from Ref. (Li and Zhang, 2022)

2.2. Modeling

The major source of energy which leads to water evaporation from the surface of the bare soil is radiation received from the sun. This radiation is partly transferred through the condensing plastic surface and absorbed by the soil surface, partly reflected and partly absorbed by the plastic cover itself. Part of the incident radiation on soil surface which passes through the plastic cover, is absorbed by the soil surface which acts as the driving force for the evaporation of water.

2.2.1. Thermal Modeling

2.2.1.1. Solar Radiation Absorbed by the Soil

As mentioned earlier, a portion of the incident solar radiation on the plastic cover is transferred and absorbed by the soil surface as followings:

$$I_s = I.\tau_p.\alpha_s \tag{1}$$

where I is the total radiation on the plastic cover, τ_p is the transmissivity of plastic cover and α_s is the absorptivity of bare soil surface.

This amount of incident energy absorbed by the bare soil surface is mostly transferred to the soil which activates the evaporation process and partly transferred to the air, trapped in the enclosure by the convection process:

$$I_s = q_{cond} + q_{conv} \tag{2}$$

where q_{cond} represents the conductive heat transfer to the sublayers of soil and q_{conv} is the convective heat transfer from soil surface to the air in enclosure.

2.2.1.2. Convective Heat Transfer Between Soil and Air

Convective heat transfer between soil and air enclosed by the plastic cover is given by (Mahdavi et al., 2019):

$$q_{conv} = h_c\left(T_a - T_s\right) \tag{3}$$

where h_c is the convective heat transfer coefficient, T_a is the temperature of enclosed air and T_s is the temperature of soil surface under the plastic cover.

For the given situation, the convective heat transfer coefficient is calculated based on an empirical formula (Deng et al., 2023):

$$h_c = 1.52\left(\Delta T\right)^{1/3} \tag{4}$$

where ΔT is the temperature difference between soil and air inside the enclosure.

2.2.1.3. Soil Moisture Evaporation

To find the amount of harvested water, it is required to calculate the thermal energy consumed for evaporation and also take the latent heat of vaporization of water into account. The latent heat of vaporization of water, denoted by L_e, is 2.45×10^6 J kg^{-1} which is often taken as a constant over the range of variation of temperatures happened in nature (Boast and Simmons, 2005).

As mentioned above, heat conduction through the soil is mostly responsible for the evaporation of soil water. Hence, knowing the amount of heat conducted through the soil (q_{cond}), neglecting the soil heat losses, the area of soil under the plastic cover (A) and taking the latent heat of vaporization of water into account, the maximum amount of evaporated and consequently condensed vapor can be found as follows:

$$m_v = q_{cond} \times A / L_e \tag{5}$$

2.3. Methodology

To theoretically study the given water harvesting procedure, it is required to have meteorological data available. To this end, Metronome 7.3 Software was used. It is a software based on reliable data sources and complicated calculation tools which provides access to different meteorological data. These data are core to any solar-based study as it includes information about ambient temperature, solar radiation intensity, sun duration etc. for a typical area and a specified time period. It is also worth mentioning that this software also takes its input information from available weather stations. So, it is highly reliable and applicable to the present research. Therefore, to use Metronome 7.3 Software, two things were required to be initially specified: 1) location and 2) date of concern. Therefore, Birjand city (32.8733° N, 59.2163° E), South Khorasan, Iran, and its hottest month (July), based on weather station reports, were chosen. The reason for choosing the given month was to see the maximum level of heat input into the soil and its effect on the quantity of distillate. Therefore, Figures (2-4) were generated by the given software. It should be mentioned that the time period for the collected data was between 2020-2023. Therefore, the data are used as inputs to MATLAB Software code which includes Equations (1-5). Finally, the amount of harvested water under different patterns of independent variables are studied (namely the parametric study). To do a parametric study i.e. study the effect of only an independent parameter variation on the variation of a dependent parameter (harvested water), it was needed to choose constant values for other independent parameters. Therefore, the trend of variation of the dependent parameter would be plotted against the variation of the given independent one only. To this end, the constant values are also reported to see under what condition, the present trend is achieved. It should also be mentioned that neither any experimental tests have been conducted nor an experimental test in literature has been found to help validate the theoretical study. It is only worth mentioning that it is only tried to use well-known and widely-used governing equations to be able to depend on the results of the present study.

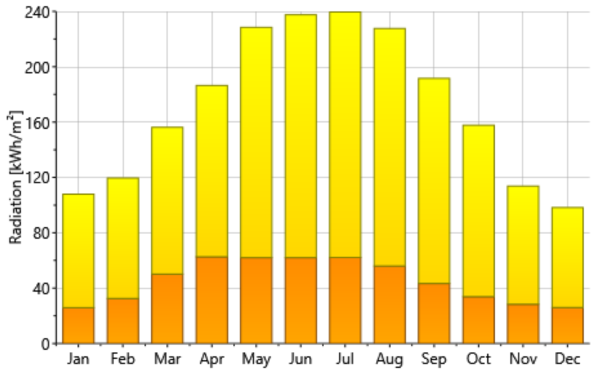

Fig. 2. Monthly average of solar radiation

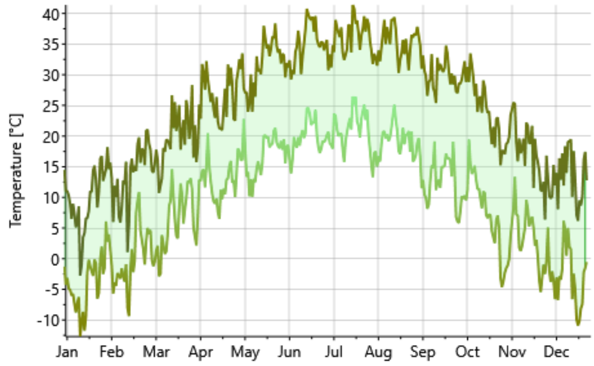

Fig. 3. Monthly average of ambient temperature

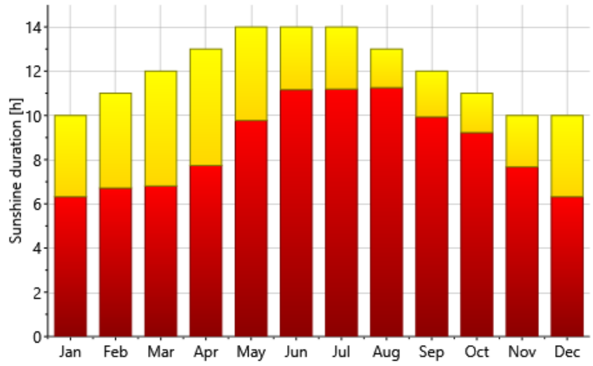

Fig. 4. Monthly average of sunshine duration

The maximum, minimum and standard deviation of the data used (taken from Metronome 7.3 Software) are summarized in Table 1.

Table 1. The maximum, minimum and standard deviation of the data used (month: July)

	Maximum value	Minimum value	Standard deviation
Solar radiation (kWh/m^2)	238.1	99.1	51.2
Ambient temperature (°C)	40	25.3	9.3
Sunshine duration (h)	11.5	6.9	1.83

3. Results and Discussion

3.1. Harvested Water with Different Air and Soil Temperature Differences

By a parametric study here, the variation of a single parameter namely difference between temperatures of air trapped under the plastic cover and soil is studied. As observed in Figure (5), by the increase in temperature difference between trapped air and soil surface from 1 to 10 °C, the harvested water decreases from 46.2 to 40.5 mg.

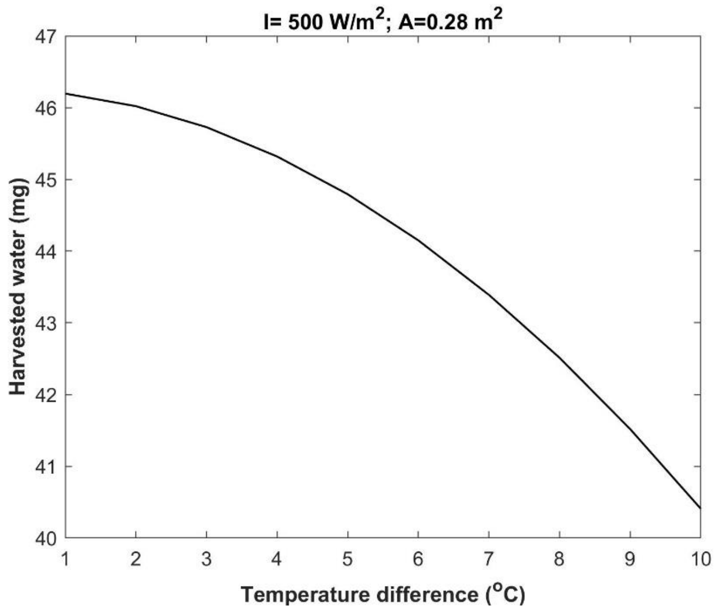

Fig. 5. Variations of harvested water with temperature difference

It depicts that through the given temperature difference increase, less absorbed energy is transferred to the subsoil layers by conduction and as a result less heat is devoted to evaporation of soil content. In fact, the temperature difference acts as the driving force for the convective heat transfer, here. So, for the given case, it seems that the temperature difference between soil surface and air is much higher than soil surface and sublayers. Therefore, the convective form of heat transfer overcomes the conduction and it causes more absorbed energy to be used for convection rather than conduction and the consequent process of evaporation is also affected. Therefore, to gain higher harvested water, it is required to decrease this difference to the lowest possible level. For this case of parametric study, the area of soil under plastic cover was assumed 0.28 m^2 and the solar radiation was also taken as 500 W/m^2 and the absorptivity of soil surface was considered 0.7. It is also worth mentioning that the relation between harvested water and given temperature difference is parabolic-shaped.

3.2. Harvested Water Due to Change in Solar Radiation

In Figure (6) trend of variations of harvested water as a result of change only in solar radiation is depicted. As seen, the amount of harvested water keeps an incresing trend parallel with an increase in solar radiation intensity. The reason is attributed to the fact that more energy is incident on bare soil surface and as a result more heating energy is transferred to the soil which leads to more water evaporation. Considering the fact that more solar energy may lead to higher temperature differences between air in enclosure and soil surface, an innovation is required to help heat sink to sublayers rather than accumulation of heat in the soil surface. Otherwise, this increase in solar radiation will lead to higher temperature differences, case of section 3.1, which can show countereffects.

As observed, harvested water is positively proportinal and linearly related to solar radiation and an increase from 200 to 700 W/m^2 in solar radiation resulted in an increase of harvested water from 17 to 62.5 mg. For this case of study, the other parameters were kept constant and had the previous values.

3.3. Harvested Water as a Result of Change in Area of Soil Under the Plastic Cover

As seen in Figure (7), the area of soil under plastic cover has a positive impact on the amount of harvested water. This result could be expected, but the main point which must be mentioned is that in comparison to Figure (6), the effect of solar radiation on harvested water is marginally more significant than area of soil and it justifies the more important role of solar radiation as it acts as the driving force of evaporation. Such an observation was under a constant solar radiation intensity of 500 W/m^2.

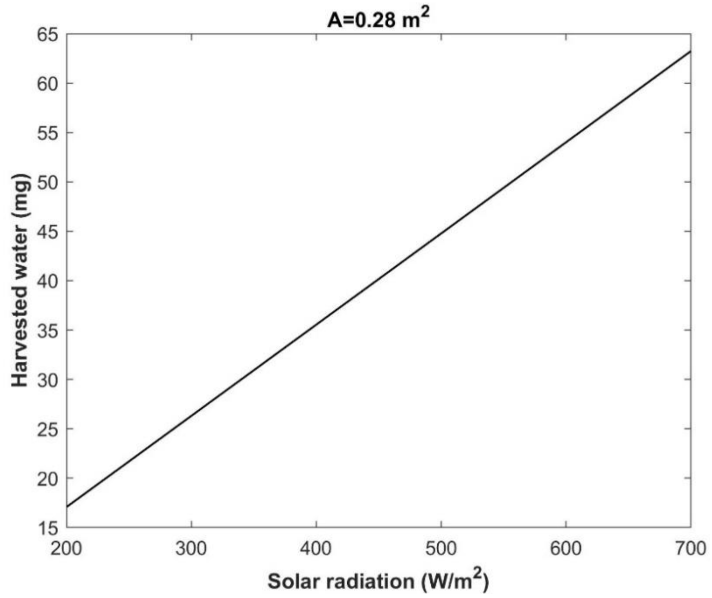

Fig. 6. Variations of harvested water with solar radiation

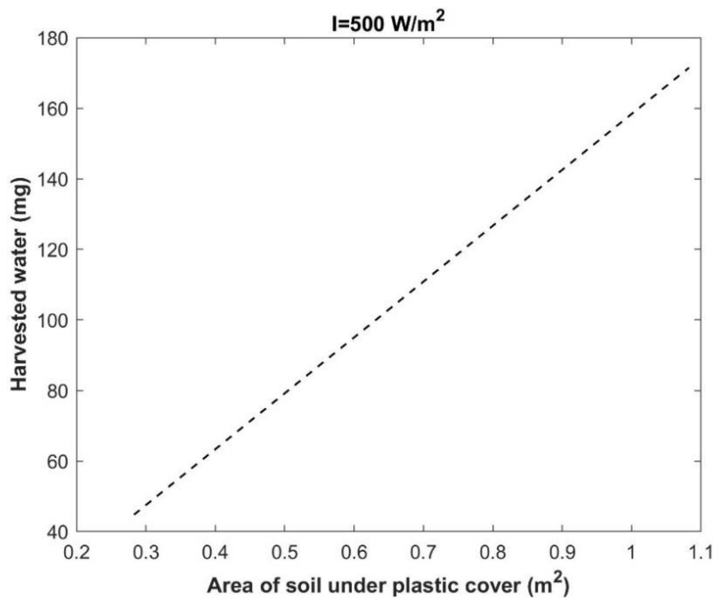

Fig. 7. Variations of harvested water with area of soil under plastic cover

The same as the case of solar radiation, area is also positively and linearly correlated to the quantity of harvested water. Moreover, it must be taken into account that this trend of variations was for the bare soil absorptivity of 0.7 and plastic cover transmissivity of 0.8. Undoubtedly, an increase in absorptivity of soil surface can strengthen the effect of soil area on harvested water. Hence, the effect of bare soil absorptivity is also brought into consideration in the following section (Section 3.4.).

3.4. The Effect of Absorptivity of Bare Soil Surface on Harvested Water

To see the effect of bare soil absorptivity on harvested water, the present parametric study is also conducted. As Figure (8) reveals, the absorptivity of bare soil surface is positively effective on harvested water while its effect is highly insignificant in comparison to solar radiation intensity and area of soil surface on the amount of harvested water. An increase in absorptivity from 0.4 to 0.9 lead to a 0.26% increase in harvested water which is so low and negligible. The current result is achieved while the intensity of solar radiation was taken as 500 W/m^2 and the allocated area under the cover was assume 0.28 m^2. Increasing the soil surface absorptivity can be achieved through blackening the surface or using materials with high absorptivity.

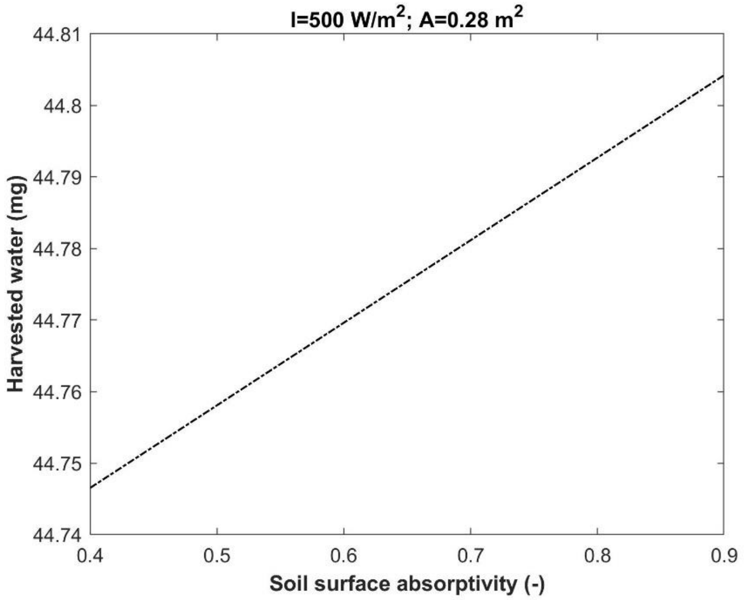

Fig. 8. Variations of harvested water with absorptivity of soil under plastic cover

The trends observed in Figures (6-8) are linear. The major reason behind these observations is the fact that the equation corresponding to the quantity of harvested water (Eq.5) is linearly related to the independent variables of solar intensity, area of absorbing soil surface and also the coefficient of absorptivity.

4. Conclusion

Harvesting water from soil can be an effective and practical way in case there is an urgent need for water. Based on a claim by some researchers (Li and Zhang, 2022), this method is applicable to even arid areas. It is less productive in these areas, though. It only requires a plastic cover which allows transmission of solar rays and acts as a condensing surface and it is a reason why this method is also trained to soldiers as a way of obtaining water in case of severe need to water. Therefore, this cover should be sealed completely around to prevent any vapor leakage. The present study included a parametric study to explore the effects of contributing parameters on harvested water such as solar radiation intensity, transmissivity of plastic cover, area of land under the cover and the difference between temperatures of soil surface and air in the enclosure. It should also be mentioned that the thermal modeling introduces a rough estimation of maximum amount of water that can be harvested from soil since all the absorbed energy by the soil surface is assumed to be consumed for soil water evaporation. Therefore, it can be considered an easy method which specifies the maximum level of condensate under different meteorological and design conditions. The results revealed that harvested water is directly proportional to solar radiation intensity, area of soil under the plastic cover and absorptive of soil surface and inversely proportional to the temperature differences between air inside the enclosure, air trapped by cover, and soil surface. The higher temperature difference means that higher portion of received solar radiation by the soil surface is transferred to the air by convection and less is remained to be transfer through conduction to the subsoil layers. Therefore, some techniques should be applied to intensify soil heat conductivity working as a sink. It is also worth mentioning that every factor affecting the absorption and release of moisture by soil can place a limit on the amount of harvested water. The more loosely moisture is attached to soil particles (depending on the soil texture), the higher the moisture content of soil (soil moisture) and the higher the temperature difference exists between the higher and the lower depths of soil profile (temperature), the higher quantity of water is expected to be harvested. It is also expected that such a phenomenon maybe affected by air relative humidity that can be explored in more detailed studies. Finally, from the economic point of view, this method is also viable since the required pieces of stuff for establishing such a setup are cheap and broadly available. But, the productivity of such a configuration, the same as the productivity of solar stills, is not comparable with other methods of fresh water production and only seems a way of coping with water scarcity in case of high urgent.

5. Disclosure Statement

No potential conflict of interest was reported by the authors.

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