Experimental investigation on a modified design of hemispherical solar distiller with v-corrugated iron trays and wick materials for improving freshwater production

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Abstract
The low energy efficiency of the solar distillers is one of the key barriers to their effective usage in the desalination domain. Hence, this work introduces an experimental investigation to enhance the freshwater productivity of the hemispherical solar distiller with different trays’ configurations and utilizing wick materials. This was achieved by utilizing iron trays and wicks in the circular basin of hemispherical solar still in order to increase the vaporization surface area for better heat transfer of saline water. The performance of the hemispherical solar distiller was investigated with flat and v-corrugated iron trays configurations. Three distillers were designed and examined, namely, conventional hemispherical solar distiller, hemispherical solar distillery with flat iron trays, and hemispherical solar distiller with v-corrugated iron trays. Moreover, the combined effects of using wick materials with flat and v-corrugated iron trays in the basin of hemispherical distiller have been also investigated. Experiments were carried out at the desert climate conditions of El-Oued (33°27′N, 7°11′E), Algeria. The results showed that the productivity improvement is 42.85% and 14.30% over the conventional hemispherical distiller for v-corrugated and flat trays hemispherical solar still (HSD), respectively. While the inclusion of wick materials with v-corrugated iron trays further increases the productivity by about 83.12% over the reference distiller. Moreover, the energy efficiency of the flat trays HSD, v-corrugated trays HSD, HSD flat trays and wicks, and HSD v-corrugated trays and wicks is 38.72%, 48.28%, 52.16%, and 61.67%, respectively. Additionally, the cost of freshwater production of HSD v-corrugated trays and wicks was 41.72% lower than that of a traditional hemispherical distiller.

Keywords Hemispherical solar distiller · Flat trays absorber · V-corrugated trays absorber · Wick materials · Freshwater productivity enhancement · Cost analysis

Introduction
At present, increasing demand for drinking water is regarded as one of the main problems facing developing countries. The World Health Organization (WHO) has referred to that more than 2.10 billion people currently have no access to a safe source of potable water, and nearly 40% of the world’s people face squeaky freshwater deficiency (Aboelmaaref et al. 2020). Besides, millions of humans annually perish from diseases associated with defective water supply. The increased level of potable water shortage is robustly related to the industrial revolution, population outgrowth,
and increased pollution worldwide (Katekar and Deshmukh 2020). Currently, various common distillation technologies are obtainable to tackle the growing water demand including humidification dehumidification (Abdullah et al. 2018), reverse osmosis (Chang et al. 2020), thermal vapor compression (Zayed et al. 2021), multi-effect evaporation (Darwish et al. 2006), multi-stage flash (Lv et al. 2019), and solar distillation (Ahmed et al. 2019). Among these technologies, solar distillation is one of the most promising alternatives for supplying safe water with low energy and freshwater costs (Zayed et al. 2019). Solar distiller (SD) is one of the simplest and most cheap techniques for obtaining freshwater from saline/brackish water (Attia et al. 2021a). However, the low total freshwater production is represented as the essential drawback of any solar distiller system (Diab et al. 2021).

**Literature survey**

Recently, many previous studies dealt with different types of designs and improvements that were made on solar distillers, which aim to increase evaporation rates and increase operating periods, and then improve the performance of solar distillers such as the use of nanofluids (Benoudina et al. 2021), the cooling of distiller glass cover (Morad et al. 2015), the use of mirrors and reflectors (Attia et al. 2021b), sensible storage materials (Dumka et al. 2019), phase change materials (Zayed et al. 2020), the insertion of fins (Attia et al. 2021c), nano-black coatings (Panchal et al. 2021), rotating discs (Essa et al. 2020), rotating wick (Haddad et al. 2017), saline water preheating using solar water heaters (Patel et al. 2020; Modi et al. 2020; Mehdiabadi et al. 2020), and so on.

To improve the productivity of solar distillers, the previous designs that were created dealt with several modifications on the basin of solar distillers such as the use of V-corrugated basin, doping of fins, basin coatings, and wick materials, for raises the evaporation rates within the single slope solar distillers. In this research perspective, Hansen et al. (2015) investigated the influences of different wicks such as pulpwood paper, polystyrene sponge, and coral fabric wicks on the thermal performance of solar distillers with various basin configurations. It was unveiled that the coral fabric wick with a stepped absorber basin had the best freshwater productivity. Agrawal et al. (2018) studied the impact of jute cloth on the water distillate of the single-slope solar distillery. It was obtained an increase in the freshwater output of 62% compared to traditional distiller. Kabeel et al. (2018) analyzed the effect of jute cloth doped with sand sensible heat storage on the productivity of single slope solar distillers. It was observed that the usage of jute cloth mixed with sand thermal storage improved the productivity by 18.0% compared to reference distiller at 20 cm saline water depth. Sahoo and Subudhi (2019) analyzed the effect of jute cloth and internal reflectors on the single slope solar distiller performance. It was revealed that the accumulative yield was increased by 72.10% compared to the conventional distiller. The effects of basin materials (steel, copper, and aluminum), as well as their metal chips, and bandage on the total water output of wick type single slope solar distillers were experimentally investigated by Sharshir et al. (2020a). It was refereed that the solar distillers with copper absorber integrated with wick-copper rings exhibited the maximal productivity improvement (62.30%) compared to all the other arrangements. In another effort, Sharshir et al. (2020b) studied the applicability of stepped double slope solar distiller with carbon black nanomaterial and linen wicks. This combination resulted in an improvement in overall productivity and daily efficiency by 80.5 and 110.5%, respectively, over traditional solar distiller. Omara et al. (2016) studied the performance of corrugated solar distillers with wicks and internal reflectors. Results indicated that the efficiencies of the modified corrugated solar distiller and conventional solar distiller were approximately 59% and 33%, respectively. El-Sebaii and Shalaby (2014) numerically studied the performance of V-corrugated basin solar distiller. The numerical results showed that the corrugated basin improved the productivity by 24.0% compared to the flat basin solar distiller. Shalaby et al. (2016) researched experimentally the impact of corrugated basin with wicks and phase change material (PCM) on the energetic performance of the single slope solar distillers. It was deduced that the modified solar distillers with wicks and PCM improved the productivity by 12.0% when compared to classical solar distiller. Kabeel et al. (2021) mathematically and experimentally studied the effect of using V-corrugated absorber and wick materials on the tubular solar still performance. The results show that the average daily efficiency and accumulated yield for the tubular still were improved by 47.0% and 44.8% compared to the conventional distiller. Elshamy and El-Said (2018) analytically analyzed the effects of the geometry of the absorber basin on the productivity of tubular solar distiller. They inferred that the utilization of a semi-circular corrugated basin ameliorated the distilled output by 26.5% compared to the other studied basin geometries. Kabeel et al. (2016) carried out experiments on the impact of tilt angles of glass cover surface on the productivity of square pyramid solar distillery. Three similar pyramid solar distillers with several cover angles of, i.e., 50.0°, 40.0°, and 30.5°, were examined. It was obtained that distilled yields of 2.94, 3.50, and 4.30 were attained at tilt cover angles of, i.e., 50.0°, 40.0°, and 30.5°, respectively. In a later effort, a pyramid SD with TiO₂ nano/black paint was designed and fabricated by...
Kabeel et al. (2019). They showed that the usage of TiO$_2$ nano mixed with black paint limitedly enhanced the overall productivity of the pyramid solar distiller by 6.10%, respectively, compared to the uncoated distiller at 1.0-cm water depth.

Recently, one of the used tools for augmenting productivity and decreasing the losses of the solar distillers is a promising design, which is defined as a trays solar distiller. The thermo-economic performance of trays solar distiller was theoretically and experimentally proposed by Abdullah et al. (2020a). The design of trays solar distiller was made via modifying the traditional SSSD by inserting internal metal trays at the interior sides of the distiller as well as utilizing exterior and interior mirrors at the bottom and top. The results indicated that the proposed trays solar distiller achieved a 95.0% increment in the distilled yield over the conventional solar distiller. In a consecutive effort (Abdullah et al. 2020b), they experimentally studied the effect of coating the trays solar distiller surfaces with the black paint mixed CuO nanopowder. Moreover, paraffin wax doped with nano CuO was added below the distiller basin as a TES material. It was shown the freshwater distillate was increased by 108% compared to the conventional solar distiller.

The hemispherical solar distiller is characterized by having a surface area larger than single slope solar distillers. Subsequently, the hemispherical cover is comprehensively subjected to the surroundings, reducing its temperature and improving condensation. In an earlier study established by our research team (Attia et al. 2021a), the performance of a hemispherical solar distiller was experimentally studied and compared to that of a traditional single slope solar distillers. The classical hemispherical solar distiller obtained an enhancement in the freshwater yield and daily thermal efficiency by 48.0% and 49.6%, respectively, over the single slope solar distillers. In another study (Attia et al. 2021b), the influence of interior reflectors on the freshwater production of hemispherical solar distiller was comparatively studied. It was reported that the water yield and daily efficiency of the hemispherical solar distiller with interior reflectors were ameliorated by 62.6% and 57.2% compared with the conventional hemispherical solar distiller. Later, the performance of hemispherical solar distillers under different configurations of iron-fins was experimentally studied (Attia et al. 2021c). The effect of pin fins spacing (5.0 and 7.0 cm) and fins length (1.0, 2.0, and 3.0 cm) was studied. It was found that the utilization of fins improved freshwater productivity up to 56.70% with the optimal configuration of hemispherical solar distiller with 7.0 cm fins spacing and 2.0 cm fins length.

**Objectives of the current study**

The present work aims to achieve the highest accumulative productivity of the hemispherical solar distillers. Through previous studies, it was found that the use of the corrugated absorber surface with wick materials which was carried out on the traditional single slope solar distillers has a very effective effect in increasing the evaporation rates and thus improving the distillate productivity, whereas hemispherical solar distillers are characterized by having a hemispherical cover with a large surface area that is comprehensively exposed to the surroundings, which reduces its temperature and thus improves condensation rates. So, incorporating the iron v-corrugated absorber with wicks in the circular basin of the hemispherical solar distiller represents a good choice to increase the evaporation rates within the hemispherical solar distillers. Hence, increasing evaporation rates inside hemispherical solar distillers, which are characterized by having a large condensation surface area that has lower temperatures, is a good option to achieve maximum production rates for distillate water.

To demonstrate the effect of using the v-corrugated surface with a wick on the performance of hemispherical solar distillers, three hemispherical solar distillers were designed and tested under the same climatic conditions; the first is the conventional hemispherical solar distiller (CHSD) representing the reference distiller without any modifications, while the modifications addressed in this study were added to the second and third distillers. The experimentations were carried out in two scenarios; in the first scenario, a flat iron tray was placed in the basin of the second distiller (hemispherical solar distiller with flat iron trays (HSD-FIT)), and a v-corrugated iron tray was placed in the basin of the third distiller (hemispherical solar distillery with V-corrugated iron trays (HSD-VIT)) in order to show the effect of using the metal tray on the performance of the hemispherical solar distillers. In the second scenario, the double wick layers were added to the flat iron tray of the second distiller (hemispherical solar distiller with flat iron trays and wick materials (HSD-FIT&WM)), as well as the addition of the double wick layers to the v-corrugated iron tray of the third distiller (hemispherical solar distiller with v-corrugated iron trays and wick materials (HSD-VIR&WM)).

**Experimental methodology**

This experimental work targets to achieve the highest performance in hemispherical solar distillers. The experimental apparatus is clearly schematized in Fig. 1a and photographically displayed in Fig. 1b and Fig. 1c. The whole experimental apparatus is mainly composed of a feed saline water tank, wooden groove supporting base, and three hemispherical solar distillers. The three solar hemispherical distillers are conventional hemispherical solar distillers (CHSD), hemispherical solar distillery with v-corrugated iron trays (HSD-VIT), and hemispherical
solar distiller with flat iron trays (HSD-FIT). All three stills have a projected area of 0.11 m². The three hemispherical stills are carried on a wooden groove base of 2.50 cm deep and 38.0 cm diameter. The CHSD has a traditional circular solar basin fabricated from wood with 38.0 cm diameter, 2.50 cm thickness, and 4.0 cm depth edge. The bottom and interior sidewalls of the basin are painted with mat black rubber silicone to maximize the absorptivity of incident solar energy, while the exterior sidewalls are properly insulated with a polyester wrap of thickness 4.0 cm to minimize the heat losses to the surrounding. Moreover, the basin is covered by a hemispherical glass cap as a condensing surface with a 0.30-cm thickness and a diameter of 40.0 cm.

On the second hand, the modified HSD-FIT is also technically designed with the same dimensions as CHSD with adding new flat iron trays on the bottom of the solar still instead of the conventional basin to increase the evaporation...
area of the hemispherical solar distiller in order to maximize the heating of the water in the basin. The flat iron trays are designed with a circular area of 0.10 m², 3.0 cm height edge, and 0.30 cm thick. The iron metal plate is considered in fabricating the flat trays due to its excellent thermal storage performance. Table 1 presents the thermo-physical properties of the iron trays. Thirdly, the HSD-VIT has also the same dimensions as CHSD; besides, we used circular v-corrugated iron trays on the bottom of the basin of the still to further maximize the vaporization surface area for better evaporation. For the design of the v-corrugated bends, all the angles of v-corrugated bends are considered at 60° as the harvested energy incident on the v-corrugated absorber is maximized and thermo-hydraulic losses are minimized when the v-corrugated absorber is designed with 60° as a corrugation angle (Hedayatizadeh et al. 2012). Moreover, the spacing between any two tops is set at 4.40 cm, whereas the base of the corrugated basin has 7.0 bottoms and 7.0 tops of corrugated shape. In addition, a circular channel is installed at the down end of the glass cover for each distiller to collect the condensed water vapor and thereafter a water bottle for collecting the distillate water yield.

Experiments have been carried out on the proposed three hemispherical distillers under the same hot outdoors conditions of El-Oued (33°27′N, 7°11′E), Algeria in two consecutive days in October 2021 from 8:00 a.m. to 6:00 p.m. To fulfill the best amending that reaches the maximum freshwater productivity, the experiments were carried out in two experimental manners. In the first manner, the thermal performance of the three distillers (CHSD, HSD-FIT, and HSD-VIT) has been tested and compared without using wick materials. In the second manner, the influences of flat and v-corrugated iron trays with wick materials on hemispherical still performances were investigated. Hence, in the 2nd testing manner, a double wick layer was added in the basin of HSD-FIT and HSD-VIT as seen in Fig. 2, to maximize the vaporization rate in order to attain the maximal conceivable usage of the large condensing surface area and to further ameliorate the total distilled yield and daily efficiency of the distiller, where the 2nd distiller became a hemispherical solar distiller with flat iron trays and wick materials (HSD-FIT&WM), and a 3rd became a hemispherical solar distiller with v-corrugated iron trays and wick materials (HSD-VIR&WM).

**Table 1.** Thermophysical characteristics of iron metal trays.

| Properties            | Value          |
|-----------------------|----------------|
| Thermal conductivity  | 80.50 W/m. K   |
| Melting temperature   | 1538 °C        |
| Boiling temperature   | 2861 °C        |
| Density               | 7870 kg/m³     |

For each testing scenario, the temperatures and freshwater productivities of the modified hemispherical distillers have been measured and compared with that of the CHSD. During the experimentations, the amount of saline water in the basin of all tested distillers was set at 1.50 cm depth. K-type thermocouples (±0.10 °C accuracy) have been attached at suitable positions in the three solar stills to measure the absorber basin, saline water, and glass cover temperatures as well as the ambient temperature which was also monitored. Moreover, a data logging solarimeter (±10.0 W/m² accuracy) has been also utilized to record the total solar radiation. Furthermore, a graduated cylinder (accuracy ± 1.0 ml) was also used to measure the volume of hourly distillate. All measurements have proceeded on an hourly essential. The measuring accuracy, creative range, and uncertainty for the measuring instrumentations are summarized in Table 2. Based on the uncertainty, accuracy, and range of the measuring devices depicted in Table 2, the relative errors in the overall freshwater production and daily energetic efficiency are computed using the analysis described by Holman (2012), which are predestined to be 3.97% and 2.28%, respectively.

**Results and discussion**

The current investigation aims to augment the distilled water production of the hemispherical solar distiller by implementing flat and v-corrugated iron trays absorber basins. To fulfill the optimal modification that reaches the maximum freshwater productivity, the experiments were carried out under the outdoors desert conditions of El-Oued (33°27′N, 7°11′E), Algeria on two typically consecutive days in October 2021 based on two experimental manners. In a 1st manner, the effects of using flat and v-corrugated iron trays absorber basins on the performance of hemispherical distillers were studied. Wherefore, three solar distillers were fabricated and examined, namely, conventional hemispherical solar distiller (CHSD), hemispherical solar distillery with V-corrugated iron trays (HSD-VIT), and hemispherical solar distiller with flat iron trays (HSD-FIT). In a 2nd manner, the impacts of utilizing flat and v-corrugated iron trays with wick materials on hemispherical still performances were investigated. Hence, a double wick layer was also utilized to measure the volume of hourly distillate. All measurements have proceeded on an hourly essential. The measuring accuracy, creative range, and uncertainty for the measuring instrumentations are summarized in Table 2. Based on the uncertainty, accuracy, and range of the measuring devices depicted in Table 2, the relative errors in the overall freshwater production and daily energetic efficiency are computed using the analysis described by Holman (2012), which are predestined to be 3.97% and 2.28%, respectively.
time for two of the typical test days for the two experimental sceneries of the proposed hemispherical distillers in October 2021 (07-10-2021 and 08-10-2021) from 8:00 a.m. to 6:00 p.m. It can be observed in Fig. 3 that the trends of solar irradiance within the two experimented days are the same which increments gradually to the maximum value in midday’s and slightly reduce till afternoon time. It is recorded that the average and maximum solar intensity values are found to be 619.3 and 1006.0 W/m², respectively, while the averagely and maximal ambient temperatures are recorded to be 38.2 and 44.0 °C, respectively.

The thermal performance of HSD-VIT and HSD-FIT have been examined with and without using wick materials (WM) and compared with CHSD. To illustrates the influences of utilizing flat and v-corrugated iron trays with wick materials on the evaporation rates within the hemispherical solar distillers. The measured values for basin water temperature of the different configurations of the studied distillers (HSD-VIR&WM, HSD-FIT&WM, HSD-VIT, HSD-FIT, and CHSD) at constant saline water level (1.50 cm) are presented in Fig. 4. The results of this figure indicated that HSD-VIR&WM has the maximal saline water temperatures, followed by HSD-FIT&WM, HSD-VIT, and HSD-FIT, respectively, whereas the CHSD has the minimal saline water temperatures. It is found that the improvement in the basin water temperatures for HSD-VIR&WM, HSD-FIT&WM, HSD-VIT, and HSD-FIT about 0–8 °C, 0–6 °C, 0–5 °C, and 0–2 °C greater than that for CHSD,
respectively. The significant increase in water basin temperature of the HSD-VIR&WM compared to the CHSD is due to the combined utilization of v-corrugated iron trays and wicks with the absorber basin, where the utilization of the v-corrugated iron trays increases the heat transfer area between the absorber and basin water. These remarkably maximized the vaporization surface area, and thus, the condensation and evaporation rates in HSD-VIR&WM were higher than that of CHSD, especially since the temperatures of glass cover were almost the same for the HSD-VIR&WM and the CHSD. It is found that the mean and maximum water temperatures of the HSD-VIR&WM are recorded to be 69.0 and 59.2 °C, respectively, whereas they are obtained to be 61.0 and 51.54 °C, respectively, for the CHSD.

Figure 5 illustrates the hourly fluctuation of the temperature of exterior and interior cover surfaces of the hemispherical still under the diverse modified cases (HSD-VIT&WM, HSD-FIT&WM, HSD-VIT, HSD-FIT, and CHSD). It is obvious that the temperatures of the inner surface of the glass cover surface are higher than that of the outer cover surface, as a result of the distilled content collected on the inner surface of the glass casing of the distiller. Also, as shown in Fig. 5, the HSD-VIR&WM indicated a higher glass temperature than CHSD by about 0–1.0 °C. The increment in the cover temperature of the HSD-VIR&WM is mainly due to the condensation and vaporization rates than CHSD as a result of the increased vaporization surface area that characterized the HSD-VIR&WM. The difference between
the interior surfaces temperatures of the glass of all studied solar stills was about 0.0–1.5 °C.

The diurnal changes in hourly freshwater productivity for all investigated cases of hemispherical distillers (HSD-VIT&WM, HSD-FIT&WM, HSD-VIT, HSD-FIT, and CHSD) at a saline water depth of 1.5 cm inside the distillers are displayed in Fig. 6. As shown in this figure, throughout the test period from 8:00 am to 6:00 pm, the HSD-VIT&WM achieved the highest distilled water productivities, followed by HSD-FIT&WM, HSD-VIT, and HSD-FIT, respectively, whereas the lowest distilled water productivities are obtained by the CHSD. The latter result is due to that the use of a v-corrugated iron tray basin in the HSD-VIR&WM remarkably increased the saline water temperature and thus augmented the rates of vapor generation and freshwater productivities as a result of the increased vaporization surface area that characterized the HSD-VIR&WM. Besides, the utilization of wick materials acts as a thermal moderator by further increasing the water heating in the v-corrugated iron tray basin by the heat energy transferred by radiation and convection from the pores of wick materials. Figure 5 indicates that the hourly output freshwater had low values in the morning at the outset of the solar distiller and progressively increases with time attaining maximal productivity midday, and afterward, it gradually decreases till late evening. The experimental findings unveiled that the hourly distillate was maximum at 02:00 pm, where it was recorded to be 1.0, 0.95, 0.85, 0.65, and 0.60 kg/m².h for HSD-VIT&WM, HSD-FIT&WM, HSD-VIT, HSD-FIT, and CHSD, respectively. These results of the hourly distillate
productivity indicated that the utilization of the modified hemispherical distiller with v-corrugated iron trays and wicks represents a good choice to achieve the highest accumulative productivity.

Figure 7 demonstrates the accumulative amounts of freshwater for the different configurations of the studied distillers (HSD-VIR&WM, HSD-FIT&WM, HSD-VIT, HSD-FIT, and CHSD). It is obvious from Fig. 7 that the utilization of the v-corrugated iron tray and wick materials achieved the highest accumulative productivity compared with other modifications of the hemispherical distiller and traditional hemispherical distiller, for the same above-previously mentioned reasons. The maximum accumulated water distillate was found to be 7.05 kg/m².d, for the HSD-VIT&WM, while the corresponding for the HSD-FIT&WM, HSD-VIT, HSD-FIT, and CHSD were about 5.95, 5.50, 4.40, and 3.85 kg/m².d, respectively. These results refer that the accumulative distillate productivity of the modified hemispherical distiller with v-corrugated iron trays and wicks is enhanced by 83.12 % more than that for CHSD. The improvement in the accumulative distillate productivity of the HSD-VIR&WM is mainly due to the higher condensation and vaporization rates than CHSD, as a result of the
increased vaporization surface area and the influence of wick materials that characterized the HSD-VIR&WM.

The performance of the five investigated hemispherical distillers has been compared and assessed in terms of the daily energy efficiency and total distillate production of the distiller. The daily efficiency of the still \( \eta \) is a vital parameter to figure out the actual improvement in the performance of the solar distiller from the perspective of the total energy received by the distiller. It accounts for the entirety of hourly yield \( \sum m_w \), latent heat of the vaporization \( h_l \), daily solar intensity \( \sum I(t) \), and surface area of the basin \( A_s \), as described in the following equation (Mevada et al. 2022):

\[
\eta = \frac{\sum h_l \times m_w}{\sum A_s \times I(t) \times 3600} 
\]

where the latent heat of distilled vapor \( h_l \) is computed in terms of saltwater basin temperature \( T_w \):

\[
h_l = 10^3 \times \left[ 2501.897 - (2.407 \times T_w) + (1.192 \times 10^{-3} \times T_w^2) - (1.596 \times 10^{-5} \times T_w^3) \right] 
\]

Figure 8 demonstrates a bar chart of the total cumulative yield and daily thermal efficiency along with their amelioration percentages for the four modified hemispherical distillers (HSD-VIT&WM, HSD-FIT&WM, HSD-VIT, and HSD-FIT) compared to the CHSD. It is reported that the HSD-VIT&WM, HSD-FIT&WM, HSD-VIT, and HSD-FIT obtained an enhancement in the total cumulative yield of 83.12% (7.05 kg/m².day), 54.55% (5.95 kg/m².day), 42.85% (5.50 kg/m².day), and 14.30% (4.40 kg/m².day), respectively, over the CHSD at a constant saltwater deepness of 1.5 cm over day cycle.

Moreover, the daily efficiency of CHSD, HSD-FIT, HSD-VIT, HSDFITWM, and HSDVITWM has been computed to be 33.94, 38.72, 48.28, 52.16, and 61.67%, respectively. It is obviously confirmed that employing flat iron trays and v-corrugated iron trays improves the daily efficiency of the hemispherical distiller by about 14.06 and 42.23 %, respectively, over that of CHSD. However, the addition of wick materials to the flat iron trays and v-corrugated iron trays further enhances the daily efficiency of the hemispherical distiller by about 53.66 and 81.68 %, respectively, over that of CHSD. Accordingly, the latter results inferred that the amalgamation between two those efficacious modifications (v-corrugated iron trays and wick materials) regards as the best choice among the different investigated modifications for augmenting the freshwater productivity and daily efficiency of the hemispherical solar distillers.

**Comparison with other published designs of solar distillers**

To demonstrate the importance of using the v-corrugated iron trays and wick materials to improve the performance of hemispherical solar distillers, a comparison between the results of recent modifications in the previous relevant studies and the present modifications suggested in the present study has been demonstrated in Table 3. The obtained enhancements in both daily efficiency and total water production exhibited a good performance compared to those revealed by other previous works.
Economic analysis

In this section, an economic analysis is conducted to assess the economic feasibility of the developed modifications applied for the proposed hemispherical distiller to determine and compare the cost per unit of distilled water produced by all studied distillers. The daily freshwater productivity for HSD-VIT&WM, HSD-FIT&WM, HSD-VIT, HSD-FIT, and CHSD were 7.05, 5.95, 5.50, 4.40, and 3.85 kg/m².d, respectively. The cost analysis is accomplished according to Eqs. (2–8) that were described by (Kateshia and Lakhera 2021; Abdelgaied et al. 2022).

The cost per freshwater liter (\(C_W\)) can be calculated as follows:

\[
C_W = \frac{TAC}{M_{w,annual}} = \frac{TAC}{M_{w,daily} \times N}
\]  

(2)

where \(TAC\) is the sum of total annual cost, \(M_{daily}\) is the daily accumulative yield, and \(N\) refers to the number of operating days of still over the year, which is assumed to be 270 days to attain reliable water cost results and consider the scarcity of solar energy through the seasons of the year (Attia et al. 2021d). \(TAC\) can be computed as follows:

\[
TAC = AFC + AMOC - ASV
\]  

(3)

where \(AFC\) is the yearly fixed cost that is described by Eq. (4), whereas \(AMOC\) is the annual maintenance and operating cost which is computed by Eq. (6) (Elashmawy 2020), while \(ASV\) depicts the yearly salvage value which is represented by Eq. (7):

\[
AFC = TCC \times CRF
\]  

(4)

where \(TCC\) is the total capital cost of the distiller system and \(CRF\) is the capital recovery factor that is represented by Eq. (5):

\[
CRF = \frac{K_d (1 + K_d)^i}{(1 + K_d)^i - 1}
\]  

(5)

where \(K_d\) is the yearly discount rate (12%) and \(i\) refers to the lifetime of the still (10 years).

\[
AMOC = 30\% \times TAC
\]  

(6)

\[
ASV = S \times SFF
\]  

(7)

The salvage value of the distiller (\(S\)) is considered 20% of the total capital cost (Attia et al. 2021d). While the sinking funding index (\(SFF\)) can be represented as

Table 3  Comparison between the results of the current work and previous relevant studies in performance improvement of solar distillers.

| Ref.          | Design of solar distiller               | Additives and modifications                       | Daily productivity (kg/m².d) | Daily eff. (%) | Productivity increase (%) |
|---------------|-----------------------------------------|--------------------------------------------------|-----------------------------|----------------|--------------------------|
| Kabeel et al. (2018) | Single slope solar distiller             | Jute cloth wicks mixed with sand                  | 5.90                        | 56.0           | 18.0                     |
| Sahoo and Subudhi (2019) | Single slope solar distiller             | Copper absorber with wicks and copper chips        | 6.30                        | 60.9           | 62.30                    |
| Sharshir et al. (2020b) | Stepped double slope distiller           | Carbon black nanoparticles and linen wicks        | 4.46                        | 60.2           | 80.5                     |
| Shalaby et al. (2016) | Single slope solar distiller             | V-corrugated basin and PCM                        | 3.76                        | 37.1           | 12.0                     |
| Kabeel et al. (2021) | Tubular solar still                      | V-corrugated basin and wicks                      | 4.15                        | 51.4           | 44.82                    |
| Elshamy and El-Said (2018) | Tubular solar still                      | Semicircular corrugated absorber                  | 3.40                        | 34.1           | 26.47                    |
| Kabeel et al. (2019) | Pyramid solar distiller                  | TiO₂ nano mixed with black paint                  | 6.60                        | -              | 6.10                     |
| Abdullah et al. (2020a) | Single slope solar distiller             | Flat steel trays at the basin sides               | 2.95                        | 41.0           | 45.0                     |
|                        |                                         | Flat trays with internal mirrors                   | 3.40                        | 42.0           | 57.0                     |
|                        |                                         | Flat trays with internal and bottom external mirrors | 4.05                        | 44.0           | 84.0                     |
|                        |                                         | Flat trays with internal and (bottom + top) external mirrors | 4.20                        | 50.0           | 95.0                     |
| Attia et al. (2021a) | Hemispherical solar distiller            | Hemispherical cover                                | 5.38                        | 38.6           | 48.0                     |
| Attia et al. (2021b) | Hemispherical solar distiller            | Reflective mirrors                                | 6.76                        | 59.7           | 62.6                     |
| Attia et al. (2021c) | Hemispherical solar distiller            | Iron pin fins                                     | 6.38                        | 61.0           | 56.7                     |
| This study             | Hemispherical solar distiller            | Basin with flat iron trays                        | 4.40                        | 38.72          | 14.30                    |
|                        |                                         | Basin with v-corrugated iron trays                | 5.50                        | 48.28          | 42.85                    |
|                        |                                         | Basin with flat trays and wicks                   | 5.95                        | 52.16          | 54.55                    |
|                        |                                         | Basin with corrugated iron trays and wicks        | 7.05                        | 61.67          | 83.12                    |
Table 4 demonstrates the findings of the cost analysis of the proposed hemispherical distillers. The economical findings revealed that the cost per liter of freshwater for the HSD-VIT&WM, HSD-FIT&WM, HSD-VIT, and HSD-FIT was lower than CHSD by 41.72% (0.0081 $/L), 33.81% (0.0092 $/L), 25.18% (0.0104 $/L), and 10.79% (0.0124 $/L), respectively.

### Conclusions

This study aims to enhance the energy and economic performance of hemispherical cover solar distillers using v-corrugated and flat iron tray materials. The iron trays were used on the bottom of the distiller basin in order to increase the vaporization surface area for better heat transfer of saline water. Three hemispherical distillers, namely, conventional hemispherical solar distiller (CHSD), hemispherical solar distillery with flat iron trays (HSD-FIT), and hemispherical solar distiller with v-corrugated iron trays (HSD-VIT), were tested and compared at the outdoors conditions of El-Oued (33°27′N, 7°11′E), Algeria. Moreover, the effects of using wick materials (WM) in the basin of HSD-FIT and HSD-VIT have been also investigated and compared to that of CHSD. The key conclusions were deduced as follows:

- The utilization of v-corrugated iron trays within the basin of hemispherical distiller remarkably increased the saline water temperature and thus augmented the rates of evaporation as a result of the larger vaporization area. Besides, the usage of wick materials acts as a thermal moderator by further increasing the water heating in the v-corrugated iron tray basin by the heat energy transferred by radiation and convection from the pores of wick materials.
- The HSD-VITWM achieved the maximal improvement from both freshwater production and thermo-economic performance among the different modifications applied to hemispherical distillers.
- The HSD-VITWM, HSD-FITWM, HSD-VIT, and HSD-FIT obtained an enhancement in the total cumulative yield of 83.12% (7.05 kg/m²·day), 54.55% (5.95 kg/m²·day), 42.85% (5.50 kg/m²·day), and 14.30% (4.40 kg/m²·day), respectively, over the CHSD.
- Utilizing flat and v-corrugated iron trays improved the daily efficiency of the hemispherical distiller by about 14.06% and 42.23%, respectively, over that of CHSD, while the addition of wick materials to the flat and v-corrugated iron trays further enhanced the daily efficiency of the hemispherical distiller by about 53.66% and 81.68%, respectively, over that of CHSD.
- Cost analysis indicated the economic feasibility of the different modulations applied to hemispherical stills as the cost per liter of freshwater for the HSD-VIT&WWM, HSD-FIT&WWM, HSD-VIT, and HSD-FIT was lower than CHSD by 41.72% (0.0081 $/L), 33.81% (0.0092 $/L), 25.18% (0.0104 $/L), and 10.79% (0.0124 $/L), respectively.
- It can be inferred that the inclusion of v-corrugated iron trays and wick materials in the basin of hemispherical solar distillers is a highly effective choice for augmenting the freshwater productivity and daily efficiency of the hemispherical solar distillers.

The proposed hemispherical solar distiller with v-corrugated iron trays and wick materials suggested in this study represented a highly effective choice for augmenting the freshwater productivity and daily efficiency of the hemispherical solar distillers in the sunrise periods. To extend the operating time after sunset, it may be recommended to add the energy storage materials with v-corrugated iron trays and wick materials to store a part of solar thermal energy in the period of higher solar intensity and recover it in the periods of low solar intensity and after sunset. This represents a good choice to take advantage of the additional decrease

### Table 4 Economic assessment for the proposed hemispherical distillers

| Financial parameter | CHSD  | HSD-FIT | HSD-VIT | HSD-FIT&WWM | HSD-VIT&WWM |
|---------------------|-------|---------|---------|-------------|-------------|
| Total capital cost of the still, TCC ($), | 66.16 | 67.63   | 70.55   | 67.63       | 70.55       |
| Annual fixed cost, AFC ($) | 11.71 | 11.97   | 12.486  | 11.97       | 12.486      |
| Annual maintenance and operating cost, AMOC, ($) | 3.513 | 3.591   | 3.746   | 3.591       | 3.746       |
| Salvage annual value, ASV ($) | 0.754 | 0.771   | 0.804   | 0.771       | 0.804       |
| Total annual cost, TAC ($) | 14.47 | 14.79   | 15.43   | 14.79       | 15.43       |
| Distillate productivity per year, (L/m²·year) | 1039.5 | 1188    | 1485    | 1606.5      | 1903.5      |
| Cost per liter of freshwater productivity, C_w ($/L) | 0.0139 | 0.0124  | 0.0104  | 0.0092      | 0.0081      |
in temperatures of hemispherical condensation cover after sunset for increasing the condensation rate and then improving the daily accumulative freshwater production.

These type of solar distillers falls under the category of low-capacity desalination plants, where the productivity of these types is limited and estimated at 7.05 liter/m² per day. This type of plant is suitable for remote and arid regions that suffer from a scarcity of pure drinking water and electric power. This type of solar desalination system is characterized by being simple, easy to maintain, does not require an electrical source, and operates on direct solar energy.

**Author contribution**
Mohammed El Hadi Attia: Experimental work, Writing - original draft preparation.
Mohamed Zayed: Formal analysis and investigation, writing—review and editing.
Mohamed Abdelgaied: Conceptualization, methodology—review and editing.
Swellam Sharshir: Conceptualization, writing—review and editing.
Abdelkader Abdalla: Writing, review revised version.
Abd Elnaby Kabeel: Conceptualization; writing, review and editing;

**Data availability**
Not applicable.

**Declarations**

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Not applicable.

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The authors declare no competing interests.

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