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RESEARCH ARTICLE

Phosphate bags as energy storage materials for enhancement of solar still performance

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Abstract

In this experimental work, the effect of cotton bags filled with phosphate on solar distillery performance has been investigated. In this study, 25 phosphate bags are evenly distributed (5 × 5) with a length equal to 50 cm in a wooden box called the modified solar still (MSS). This system was compared with the conventional solar still (CSS) in the same climatic conditions. Phosphate bags are placed vertically to increase the energy storage capacity, and the water's surface area since the capillaries inside the phosphate bags play an important role in increasing the energy storage capacity. Experiments were conducted at El Oued University in Algeria during April and May 2020, with 1 cm and 2 cm of saltwater depth. The cumulative yield of 5.27 and 4.87 kg was produced from the MSS at 1 cm and 2 cm of saltwater, respectively, while the cumulative yield of the CSS was 3.8 kg. The MSS's overall efficiency at 1 cm and 2 cm of saltwater was enhanced by 28 and 22.5%, respectively compared with the CSS. The presence of calcium and copper in phosphate stores the heat energy during morning and afternoon, and stored heat energy was released during evening. Finally, it can be concluded that increasing phosphate bags significantly enhances the productivity in solar distillation, increasing efficiency and productivity.

Keywords Single slope · Phosphate granules · Filled cotton bags · Distilled water · Productivity · Solar still

Highlights

- Three solar stills (conventional solar still and modified solar stills with phosphate bags) were fabricated.
- Research was performed at Renewable Energy Laboratory in El Oued University, Algeria.
- Sustainable distilled water production from the modified solar still is higher than the conventional solar still.
- The yield and thermal efficiency of the conventional solar still was 3.8 kg and 31%, repectively.
- The yield and thermal efficiency of the modified solar still was 5.27 and 43%, repectively.
- The thermal efficiency of the modified solar still was improved by 28% higher as compared with the conventional solar still.

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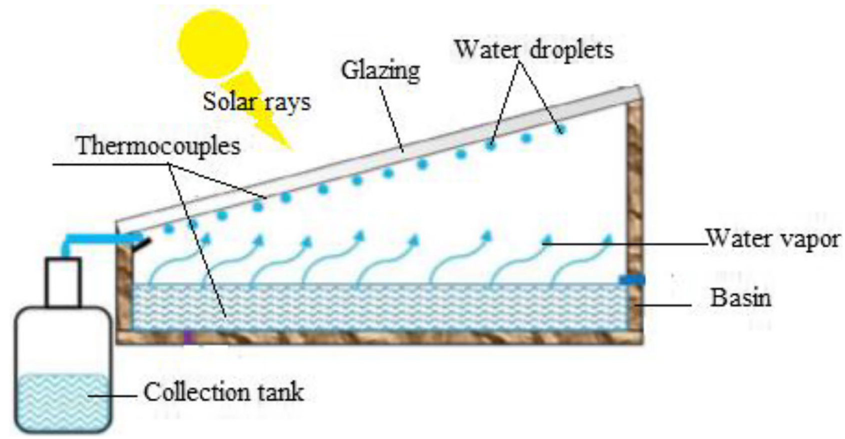

Fig. 1 Schematic representation of the CSS

Introduction

Among the problems that the world suffers from today are the great demographic growth and shortage of drinking water, as the sources of pure drinking water recently entered the era of scarcity. (Omara et al. 2011; Kabeel et al. 2018; Chamkha et al. 2020) Solar distillation is one of the simple devices that provide fresh water for drinking from salty water, and it is inexpensive. It only uses solar energy, and it is an environmentally friendly device (Manokar et al. 2014; Khechekhouche et al. 2020; Taamneh et al. 2020; Vaithilingam et al. 2020; Essa et al. 2020a; Attia et al. 2020a; Kumar et al. 2020). Scientists and researchers are constantly exploring various ways to improve the performance of solar stills, such as increasing distillate output, increasing surface area, and searching for new energy storage materials (Khechekhouche et al. 2020; Elango et al. 2015). Many researchers (Kabeel et al. 2020a; Manokar et al. 2018, 2018a; Sakthivel and Shanmugasundaram 2008) worked on sensible energy storage materials and phase change materials to enhance the yield of distillate from the still. Shanmugan et al. (2020) studied the impact of coating the basin liner by TiO_2 nanoparticles mixed with Cr_2O_3 on solar still. The researchers found that the coating of basin liner by TiO_2 nanoparticles mixed with Cr_2O_3 gave yield of 5.39 and 7.89 kg/m^2/day, and the daily efficiency of the system was 57.16 and 36.69% during the winter and summer, respectively. Abdullah et al. (2020) studied the impact of reflectors, nano-CuO in paint the solar still. Compared with the CSS, daily productivity was improved by 12% when using reflectors, nano-CuO in the paint. Abdullaha et al. (2020) experimentally investigated trays solar still productivity in different water depths (0.5, 1.0, 1.5, and 2.0 cm) by adding internal and external mirrors. They concluded

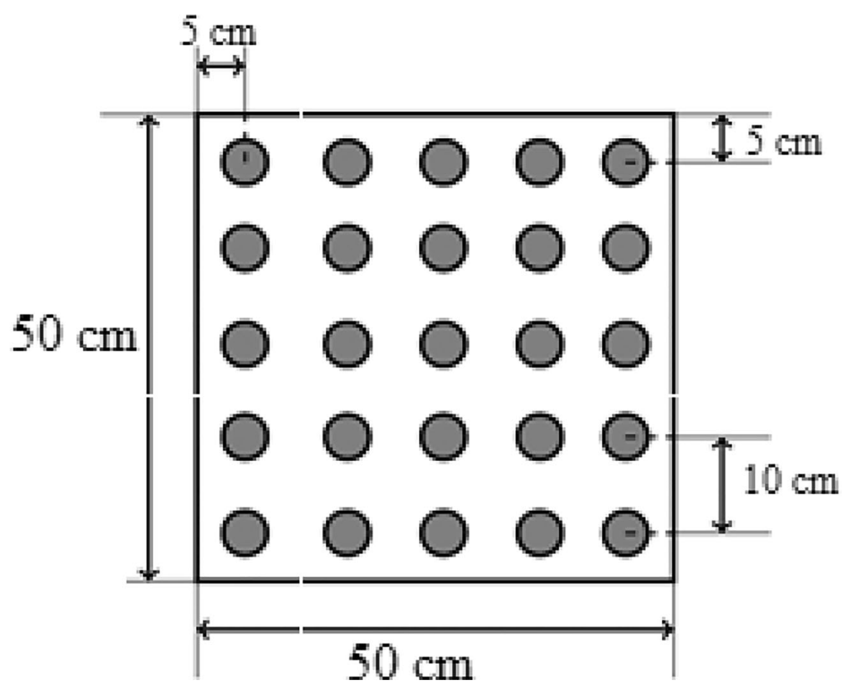

Fig. 2 Arrangement of phosphate bags in basin water box

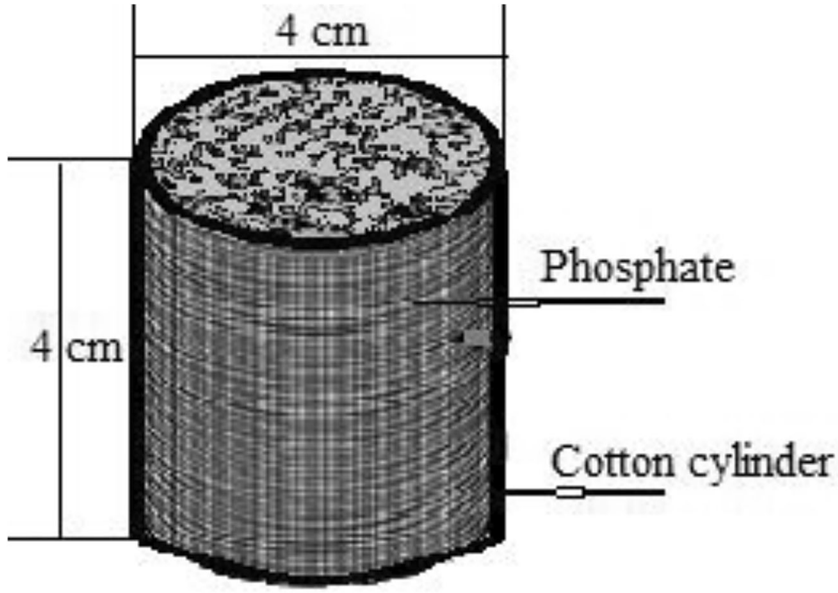

Fig. 3 Schematic of a phosphate bag

that average daily productivity was improved by 58% when using internal mirrors at 1 cm basin water. The daily productivity was improved by 84% when using external bottom and top mirrors, respectively, 1 cm basin water, compared with conventional solar still productivity. Thalib et al. (2020) conducted the impacts of materials (PCM and nano-PCM) on tubular solar still performances. The researchers found that the maximum daily yield is 4.3, 6.0, and 7.9 l/m^2, and the energy efficiency was 31, 46, and 59%, the exergy efficiency was 1.67, 2.20, and 3.75% when conventional tubular solar still, still with PCM, and still with nano-PCM, respectively. Abdullah et al. (2019) studied the effect of a rotating drum inside the solar still at different rotational speeds 0.02 to 4.0 rpm to investigate still performance. The solar water heater is also integrated into the distillation drum, an external condenser is integrated, and nano-CuO is added to the performance of the distillation drum. They concluded that the maximum productivity when using the rotary drum at a speed of 0.1 rpm and using the external condenser, heater, and nano-CuO was 9.220 l/m^2 compared with that of the CSS, which was 2.050 l/m^2, and it was enhanced by 350%. Essa et al. (2020b) developed a new prediction model of active solar still integrated with a condenser for improving the performance of the traditional artificial neural networks using Harris Hawks. They concluded that the productivity was increased by 53.21% with a fan speed of 1350 rpm on the active distiller integrated with the condenser. The model of Harris Hawks artificial neural network gave the best accuracy in predicting the solar still productivity. Sakthivel and Shanmugasundaram (2008) studied the impact of black granite gravel as thermal energy storage material inside a solar still with different depths.

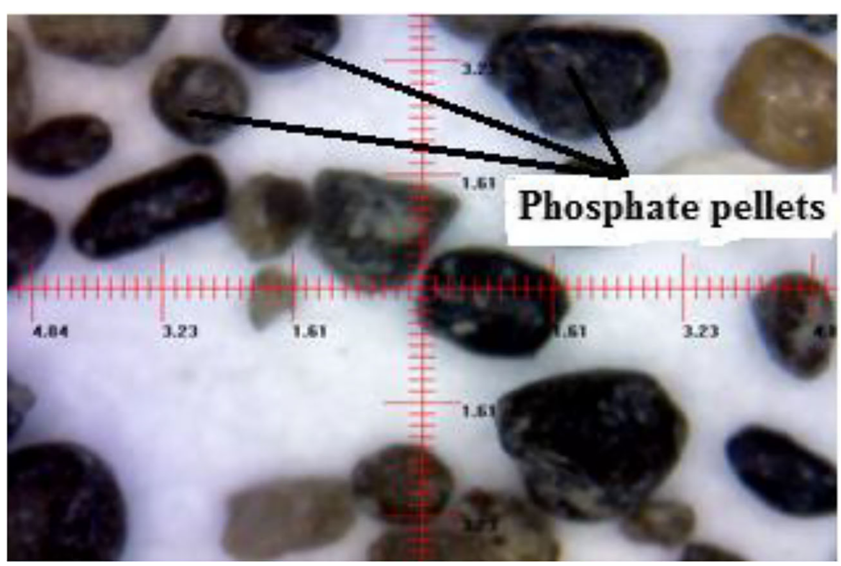

Fig. 4 Micrograph of phosphate granules

The researchers found that the black granite gravel productive presents a 17% increment in yield and obtains 3.9 kg/m^2 per day. El-Sebaii et al. (2015) conducted experiments on solar still using fins. They found that the solar's daily yield and efficiency still increased because of increases in fin height and decreased with increasing the fin thickness. They concluded that an increased number of fins led to decreases in productivity due to the fins' higher shaded area. El-Sebaii et al. (2000) studied the impacts of different plates as suspended absorber material like aluminum, copper, stainless steel, and mica in the CSS. They concluded that when using metallic plates (aluminum, copper, stainless steel), the daily productivity still was higher by 15–20% compared with the CSS. Rabhi et al. (2017) studied the performance of CSS and CSS with simple pin fins. The authors observed an increase of 14.53% in productivity when using simple pin fins. Naim and El Kawi (2003) studied the effect of different sizes of charcoal particles on still productivity and thermal performance. The results confirmed that the productivity of solar stills with charcoal particles was improved. Besides, coarse particles gave better results. Ayuthaya et al. (2013) studied the productivity and thermal performance of an ethanol solar still basin with fins. The results showed that adding fins to the basin decreases the preheating time. This fact is due to the effective absorption rate of the basin plate. They concluded that incorporating the fins into the basin increases the solar still productivity compared with the CSS. Okeke et al. (1990) conducted experimental investigations to measure the solar still productivity by adding coal and charcoal particle as thermal energy storage materials. They concluded that average daily productivity equal to 1.12 kg/m^2 and efficiency is 16.5%. Shalaby et al. (2016) studied the CSS's thermal performance with the v-corrugated absorber by adding the PCM. The results revealed that the PCM improves the output by 12%. Mona et al. (2002) conducted the impacts of mixed materials (paraffin, paraffin oil, and aluminum turnings) on solar performance still. The researchers found that the maximum daily productivity is 4.54 l/m^{2,} and efficiency was 36.2%. Kabeel et al. (2017) studied the pyramid's thermal performance still with the v-corrugated absorber by adding PCM. The experimental results showed that the use of PCM improved daily production by 87.4% compared with CSS. Kabeel et al. (2020) added cement-coated red bricks in the CSS to increase distilled water production. They also measured the daily accumulation by considering the water depth effect.

Table 2 Physical properties of phosphate (Jasinski 2012; Syers et al. 1986)

Melting point	1670 °C
Appearance	Spherical granules
Color	Dark gray
Thermal conductivity	0.236 W/(m K)
Specific heat capacity	0.77 J/g K
Dimensions	1.5–2 mm
Whereabouts	Most of the world's nations

The experimental results showed that the daily accumulation was 3.2, 2.8, 2.7, and 2.6 kg for water mass of 20, 30, 40, and 50 kg, respectively. While the results of the daily accumulation of the improved distilleries were the red brick covered with cement was 6.3, 6, 5.8, and 5.6 kg, respectively. They concluded that the cement-coated red bricks with cement coated are a material storing heat energy at a low cost. Balachandran et al. (2019) researched micro-coated and nano-Fe_2O_3 particles as thermal energy storage materials on CSS productivity. They found that the average daily yield is equal to 3.23 kg/m^2 for using micro absorbent layer solar still and 4.39 kg/m^2 for using nano absorbent layer solar still. Madhu et al. 2018a) reported that the productivity of the solar still using energy storage material was 3.3 and without energy storage material were 1.89 kg/m^2. They also concluded that the system's exergy efficiency improves by 30% than the CSS without any heat storage materials. Madhu et al. (2018b) studied the impacts of the rubber mat and polyester mat as sensible heat energy storage naterials (SHESMs) on the performance of inclined solar still (ISS) with baffles. The researchers found that ISS with SHESM improves the yield by 57.1 and 59.5% with the polyester mat and rubber mat, respectively. Khechekhouche et al. (2019) conducted performance studies on the sand bed to improve a CSS. The authors observed a decrease by 1.46 times in productivity when using sand bed compared with the CSS.

From literature, it has been renowned that several researchers have used sand as sensible energy storage materials to increase the productivity of solar still. In the present experimental work, phosphates were used as novel SHESM in the CSS. The presence of phosphates improves the surface area and reasonable heat storage capacity. The porous nature of phosphate bags increases capillaries and provides better use

Table 1 Phosphate rock materials (Jasinski 2012; Syers et al. 1986)

	Element (g/kg)										Element (mg/kg)						
	Ca	P	Mg	K	Na	Fe	Al	S	F	CO_3	Mn	Co	Cu	Zn	Cd	As	U
Phosphate rock	353	134	2.5	1.8	12	1.8	2.4	8	41	71	7	3	15	393	38	4	88

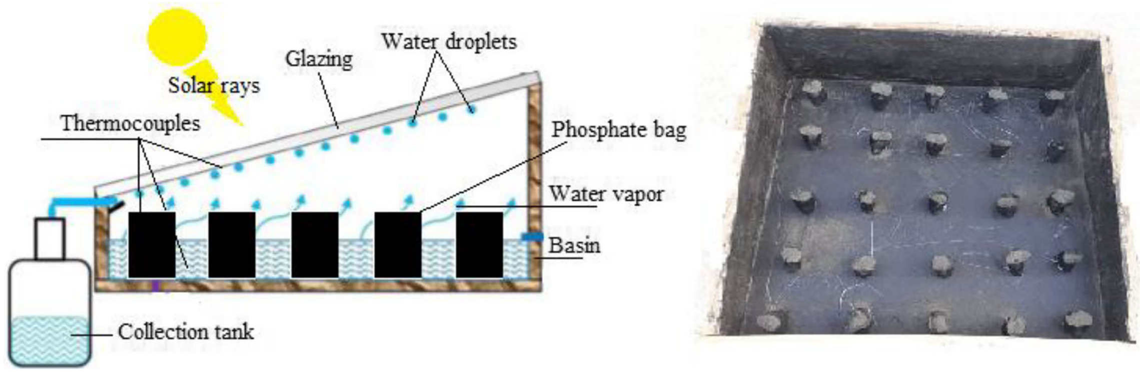

Fig. 5 Schematic representation and photo of the MSS

of stored energy to enlarge the surface area since the phosphates are good material for storing heat energy. This novel experimental study was developed at El Oued-Algeria University during April and May 2020. Twenty-five cotton bags filled with phosphate were placed vertically in a solar distillery regularly (5 × 5) in a 50-cm-long wooden box called the MSS. This system was compared with the conventional solar still (CSS), with 1 cm and 2 cm of saltwater depth, during day and night, in the same climatic conditions.

Experimental setup

The developed experimental setup aims to study the effect of the phosphate bags in the solar still. Two identical CSS were fabricated by the wood with 5 cm thick, as presented in Fig. 1. The basin area is equal to 0.25 m^2, and the two sides are equal to 0.14 m and 0.06 m, respectively. Transparent glass with a 3 mm of thick has been used to cover the solar still with an angle of 10°. For the higher absorption of solar energy, the solar stills were coated using black paint.

Twenty-five cotton bags were fabricated as 4 cm in height and 4 cm in diameter. These bags are filled with phosphates (mass = 25 g/bag) to increase solar radiation absorption. The still containing phosphate bags are considered as a MSS. As presented in Fig. 2, 25 phosphate bags were evenly placed (5 × 5). In case (i), MSS-1 cm of saltwater in the basin is maintained, which contains 2.5 kg of saltwater. In the case (ii), MSS-2 cm of saltwater in the basin is maintained, containing 5 kg of saltwater. The schematic of a phosphate bag is presented in Fig. 3.

Phosphates are easily available low-cost energy storage materials in southeastern Algeria and other countries like the USA, China, India, Egypt, Russia, and Morocco. The phosphates are stones and ground in private factories to become granules, grey in color. Algeria possesses the second

Fig. 6 Photograph of the experimental setup

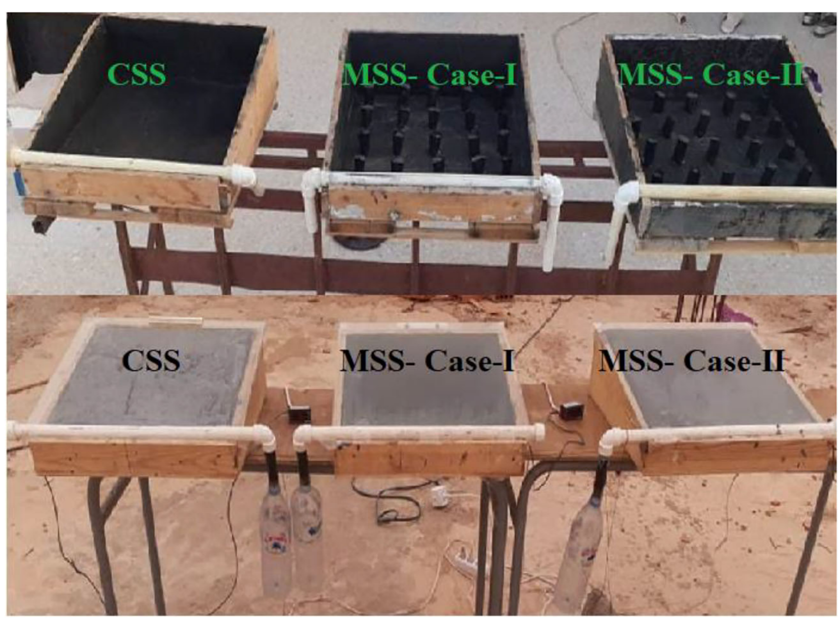

Table 3 Uncertainties of measuring devices

Instrument	Model	Accuracy	Range	Standard uncertainty
Solar power meter (W/m^2)	TES 132 Solar Power Meter (data logging)	± 1	0–1999	5.77
Thermocouple (°C)	Copper constantan K-type	± 0.1	− 50 to 150	0.06
Graduated cylinder (ml)	-	± 2	0–250	0.6

phosphate mine globally and is widely available as a raw material to be taken free of charge. In Fig. 4, a micrograph image is taken for the phosphate granules. The image shows that all phosphate granules have the same dimensions and are approximately equal to 1.5 mm. The properties of phosphate are listed in Tables 1 and 2.

Three thermocouples have been placed in the CSS and MSS to measure the inner glass temperatures, the outer glass, and the basin water temperature. Figure 5 represents the schematic and photo of the MSS. Figure 6 shows the full test setup. The experiments were conducted in April and May 2020 at the University of El Oued, Algeria (06° 47′ east and latitude 33° 30′ north). Two different water basins, for 1 cm and 2 cm of saltwater, were tested. The trial duration is 16 h.

Table 3 illustrates error analyses. The calibrated copper constantan type (K-type) thermocouples (± 0.1 °C), the range is − 50 to 100 °C were used to measure all temperatures inside and outside the solar still. Data logging solar power meter (DLSPM) with a range of 0–1999 W/m^2 and accuracy of ± 1 W/m^2 was used to measure the total insolation. A regulated flask of 250 ml capacity with an accuracy of ± 2 ml was used to measure hourly productivity.

Results and discussions

Symmetrical distribution of environmental parameters and temperature of solar still

Figures 7, 8, 9, and 10 present the symmetrical distribution of $I(t)$ and T_a, $T_{s.w}$, $T_{c.c}$, and difference between $T_{s.w}$ and $T_{c.c}$ of CSS, and MSS-1 cm of water and MSS-2 cm of water. From graph 7, it is identified that $I(t)$ increases during the morning and peaked at 12 p.m. (1030 W/m^2). Also, T_a increased linearly and reached its peak at 1 p.m. (39 °C). The symmetrical distribution of T_a, $T_{s.w}$, and $T_{c.c}$ have the arc parallel to $I(t)$ since it is the core source for T_a, $T_{s.w}$, and $T_{c.c}$. The maximum daily mean of $I(t)$ and T_a is 725 W/m^2 and 27.4 °C, respectively. From graph 8, it is seen that maximum $T_{s.w}$ of the CSS is 69 °C at 1 p.m., for the MSS-1 cm of water is 71 °C at 3 pm. and for the MSS-2 cm of water is 70 °C at 4 p.m.. The average daily $T_{s.w}$ of the CSS is 49.13 °C, for the MSS-1 cm of water is 52.56 °C and for the MSS-2 cm of water is 51.1 °C. $T_{s.w}$ of the CSS was improved by placing phosphate bags in the basin. The maximum $T_{s.w}$ of the MSS-1 cm of water is 2 °C above in comparison with the CSS, and the MSS-2 cm of water is 1 °C above in comparison with the CSS. Rising of the water mass

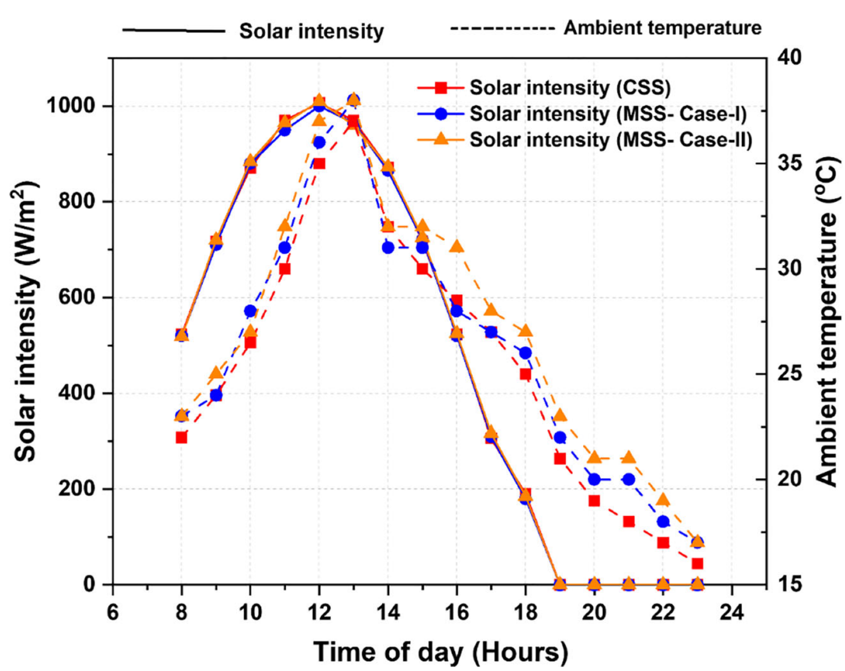

Fig. 7 Symmetrical distribution of $I(t)$ and T_a

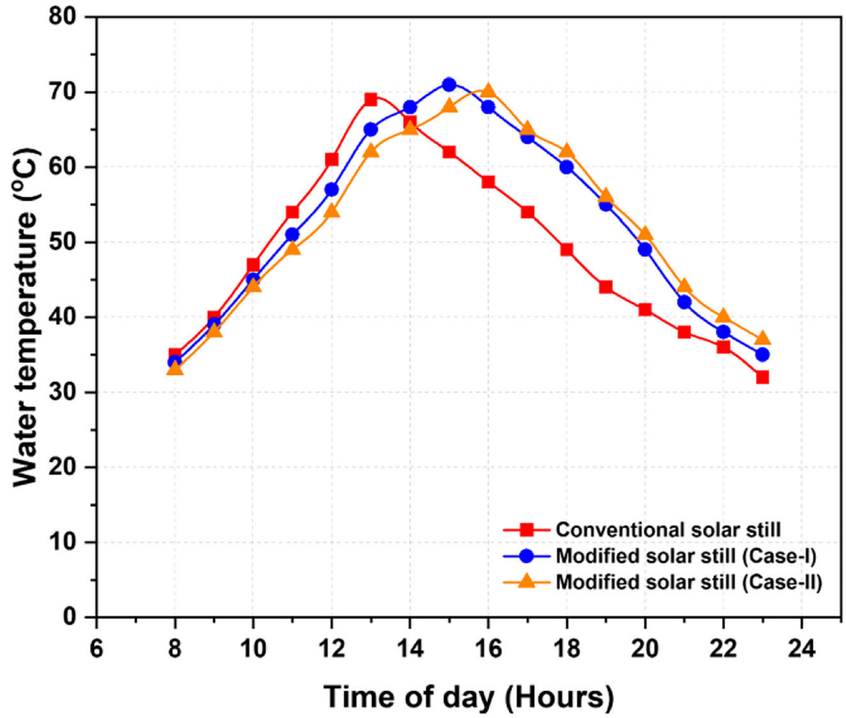

Fig. 8 Symmetrical distribution of $T_{s.w}$

from 1 to 2 cm of water reduces the $T_{s.w}$. The maximum $T_{s.w}$ of the MSS-2 cm of water is 1 °C less as compared with the MSS-1 cm of water. The presence of phosphate bags augments the $T_{s.w}$ since it enlarges the surface area of the basin. The highest $T_{c.c}$ of 50, 51, and 52 °C was measured at the CSS, MSS-1 cm of water, and MSS-2 cm of water, respectively. The daily mean $T_{c.c}$ of MSS-1 cm of water and MSS-2 cm of water is higher as compared with the CSS. The MSS-1 cm of water augments the average daily $T_{s.w}$ by about 6.54% as compared with the CSS. Simultaneously, the MSS-2 cm of water augments the average daily $T_{s.w}$ by about 3.68% compared with the CSS. The increase of the water mass from 1 to 2 cm reduces the average daily $T_{s.w}$ by about 2.97%. An increasing water mass reduces the maximum and average daily

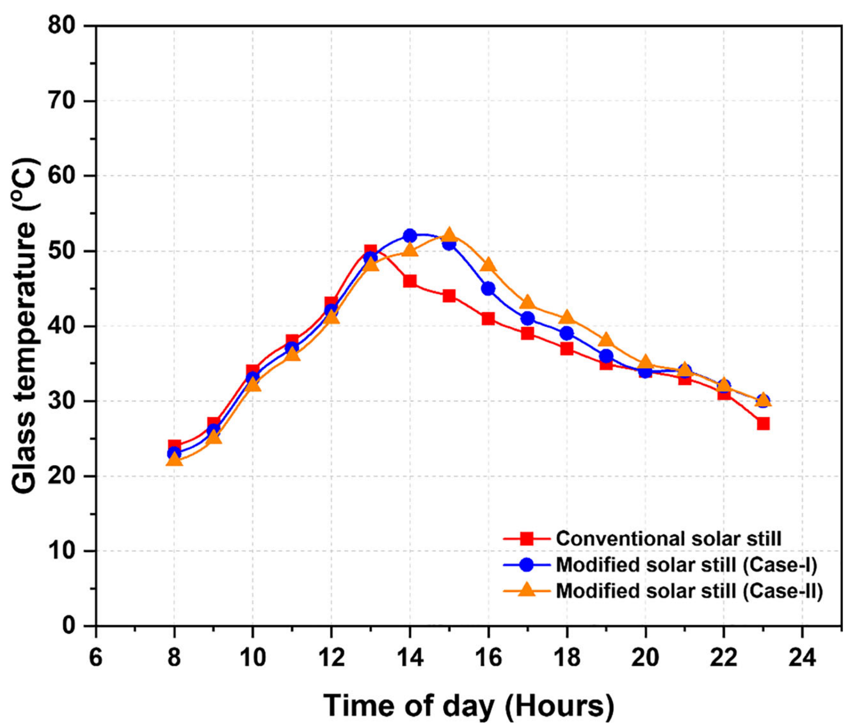

Fig. 9 Symmetrical distribution of $T_{c.c}$

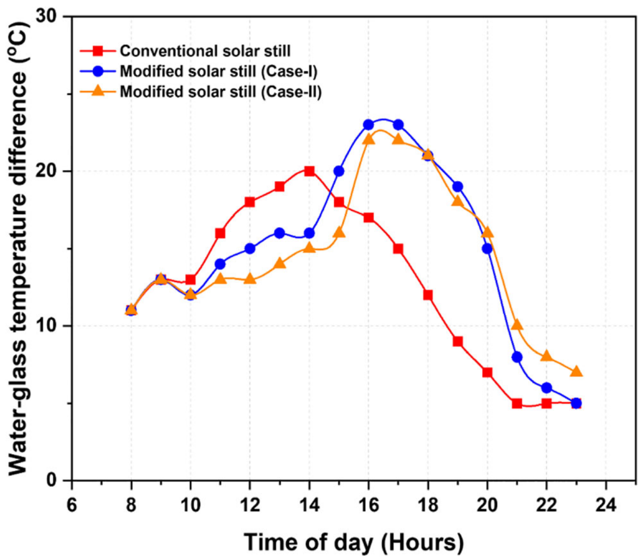

Fig. 10 Symmetrical distribution of the difference between $T_{s.w}$ and $T_{c.c}$

$T_{s.w}$. In the MSS-1 cm of water and 2 cm water, phosphate bags were placed in the CSS basin to enlarge the basin's surface area and improve the water temperature. The difference between $T_{s.w}$ and $T_{c.c}$ of the CSS is maximum during the morning time, whereas the difference between $T_{s.w}$ and $T_{c.c}$ of the MSS-1 cm of water and 2 cm water is maximum in the evening time (Fig. 10). The higher difference between $T_{s.w}$ and $T_{c.c}$ was obtained by using phosphates as energy storage materials. The phosphate bags present in the MSS were used to minimizes the heat losses to the ambiance by storing the heat energy, and this stored heat energy was used to increase the $T_{s.w}$ during the evening time. So, the phosphate bags' presence enhances the water temperature by giving the heat to the water when $I(t)$ is minimum.

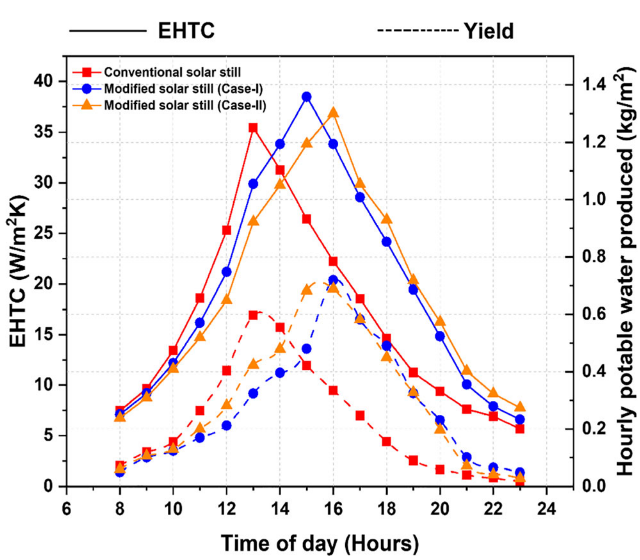

Fig. 11 Symmetrical distribution of EHTC and distilled water production during daytime

Symmetrical distribution of evaporative heat transfer coefficient and distilled water production

Figure 11 displays the symmetrical distribution of EHTC and distilled water production from the CSS, MSS-1 cm of water and MSS-2 cm of water. The EHTC is calculated using the empirical relation from Appendix 1. The highest calculated EHTC of 38, 40, and 39 W/m^2 was obtained from the CSS, MSS-1 cm of water, and MSS-2 cm of water, respectively. In the MSS, phosphate bags' presence minimizes the heat losses from the basin of the MSS to the atmosphere. So $T_{s.w}$ and EHTC of the MSS are above in comparison with the CSS.

The maximum and distilled water production during daytime from the CSS are 0.67 and 3.53 kg, from the MSS-1 cm of water is 0.8 and 4.52 kg, and from the MSS-2 cm of water is 0.81 and 3.99 kg, respectively. The distilled water production during the daytime from the CSS is minimal compared with the MSS-1 cm of water and MSS-2 cm of water. The distilled water production during daytime from the MSS-1 cm of water and MSS-2 cm of water is 0.99 and 0.46 kg higher than the distilled water production during daytime from the CSS. Simultaneously, MSS-1 cm of water (4.52 kg) has 0.53 kg higher distilled water production during the daytime compared with the MSS-1 cm of water (3.99 kg). The distilled water production during the daytime from the MSS-1 cm of water and MSS-2 cm of water is 21.9 and 11.5% higher than the distilled water production during the daytime from the CSS.

Similarly, the MSS-1 cm of water has 11.7% higher distilled water production during daytime as compared with the MSS-2 cm of water. The phosphate bags placed on the basin has a higher surface area, so it augments the $T_{s.w}$, EHTC, and productivity from the MSS as compared with the CSS. When using phosphate bags in the MSS-1 cm of water and MSS-2 cm of water, the productivity was increased by about 39 and 28% higher than the CSS.

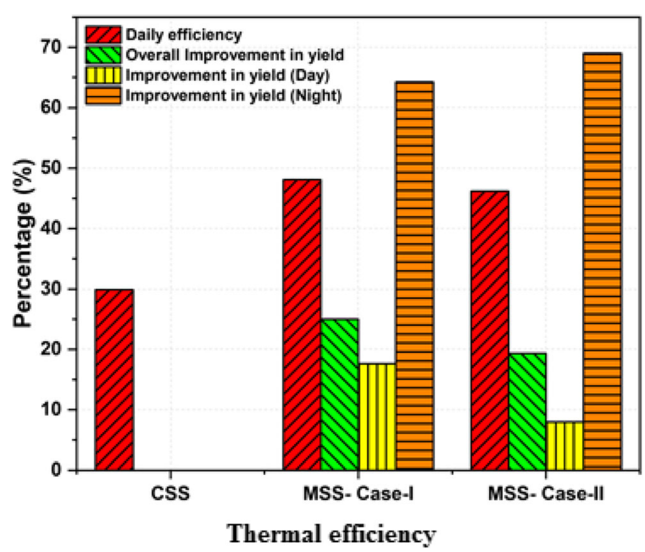

Fig. 12 Daily thermal efficiency and improvements in productivity

Table 4 Daily yield and efficiency

Date	Yield (kg/m^2)			Total radiation (W/m^2)	Daily efficiency (%)		
	CSS	MSS-1 cm of water	MSS-2 cm of water		CSS	MSS-1 cm of water	MSS-2 cm of water
26.4.2020	3.57	4.75	4.42	7665	29.15	38.87	36.13
28.4.2020	3.33	4.65	4.21	7620	27.38	36.27	34.63
02.5.2020	3.80	5.27	4.87	7683	30.99	42.97	39.75

The maximum and cumulative distilled water production after daytime from the CSS is 0.1 and 0. 27 kg, from the MSS-1 cm of water is 0.34 and 0.75 kg, and from the MSS-2 cm of water is 0.32 and 0.88 kg, respectively. After daytime, the distilled water production from the CSS is minimal compared with the MSS-1 cm of water and MSS-2 cm of water. After daytime from the MSS-1 cm of water and MSS-2 cm of water, the distilled water production is 0.48 and 0.61 kg higher than the distilled water production after daytime from the CSS. Simultaneously, MSS-2 cm of water (0.88 kg) has 0.13 kg higher distilled water production after daytime compared with the MSS-1 cm of water (0.75 kg). The phosphate bags inside the MSS stores the heat energy used to augment the distilled water production after the evening time. Whereas in the CSS, the amount of heat energy entering the basin continuously transfers the heat from the basin surface to the ambiance; hence the yield produced during the evening time from the MSS is always higher than the CSS.

Daily thermal efficiency and improvement in yield

Figure 12 displays the daily thermal efficiency for the CSS, MSS-1 cm of water, and MSS-2 cm of water and improvements in productivity for the MSS as compared with the CSS. The highest thermal efficiency of 50.25, 66, and 69% have been calculated for the CSS, MSS-1 cm of water, and MSS-2 cm of water, respectively. The daily average thermal efficiency for the CSS is 31%, for the MSS-1 cm of water is 43%, and for the MSS-2 cm of water is 40%. From the calculations, it is found that the thermal efficiency of the MSS-1 cm of water is 28% lesser in comparison with the CSS, and the thermal efficiency of the MSS-2 cm of water is 22.5% higher as compared with the CSS. The MSS's daily thermal efficiency-1 cm of water was improved up to 7% compared with the MSS-2 cm of water. The MSS's daily thermal efficiency-1 cm of water and MSS-2 cm of water was increased by about 28 and 22.5% higher than the efficiency of the CSS while Using phosphates bags as energy storage. Table 4 summarizes the daily output from the CSS, MSS-1 cm of water, and MSS-2 cm of water during the experimental days Table 5 shows the Cumulative distillate yield of CSS and MSS during daytime and after daytime for 1 cm and 2 cm of salt water.

Economic analysis

Daily cumulative yield

Table 4 shows the cumulative distillate yield of CSS and MSS during daytime and after daytime for 1 cm and 2 cm of saltwater. The cumulative distillate recorded resulting from the conventional solar still and improved solar still, of the day of the experiment on May 02, 2020, the trial duration is equal to 24 h.

Economic analysis

Table 6 shows the calculation of net profit after subtracting the physical cost and maintenance cost and specifies the recovery period for CSS, MSS-1 cm, and MSS-2 cm of salt-water.

Water quality analysis

Table 7 shows the water quality analysis before use (saltwater) and the resulting water (distilled water). The following chemical values (pH, EC, TDS, TH, Cl^-, $SO^{-2}{}_4$, and NO^{-3}) were obtained from the water quality analysis for saltwater and the resulting distilled water and tabulated in Table 7 and compared with WHO drinking water quality. The saline water and distilled water's pH and TDS values are found as 7.92, 3062, and 7.05, 21, respectively. Based on the results, the obtained distilled water is suitable for different industry applications. Also, it can be used for drinking.

Table 5 Cumulative distillate yield of CSS and MSS during daytime and after daytime for 1 cm and 2 cm of salt water

CSS		MSS-1 cm of water		MSS-2 cm of water	
Day (kg/m^2)	Nocturnal (kg/m^2)	Day (kg/m^2)	Nocturnal (kg/m^2)	Day (kg/m^2)	Nocturnal (kg/m^2)
3.53	0.27	4.52	0.75	3.99	0.88

Table 6 A comparison of CSS, MSS-1 cm of water, and MSS-2 cm of water (1$ = 112.78 DZD, 1€ = 136.03 DZD)

Description	CSS	MSS-1 cm of water	MSS-2 cm of water
Physical cost (DZD)	8000	8030	8030
Maintenance cost (DZD)	50	50	50
Total cost (DZD)	8050	8080	8080
The amount of water produced during the day, (kg/m^2/day)	3.8	5.3	4.9
Cost of 1 l of distilled water on the market (DZD)	60	60	60
Price of daily water production (DZD)	228	318	294
Recovery period (day)	35 days	25 days	28 days

Table 7 Analysis of saline and distilled water

Chemical parameters	Distilled water	Saline water	WHO drinking water quality guidelines
pH	7.05	7.92	6.5–8.5
EC (σ) (μs/cm)	28	10185	800
TDS (mg/l)	21	3062	500–1000
TH ($CaCO_3$) (mg/l)	10	979	200
Cl^-(mg/l)	10	791	250
$SO^{-2}{}_4$ (mg/l)	8	842	250
$NO^-{}_3$ (mg/l)	2	39	40

Comparison of present research with other research using sensible storage materials

Table 8 shows a comparison of our results with the daily cumulative results of other research using sensible storage materials. From these results, it is clear that the solar still with phosphate bags present an increase in cumulative yield equal to 39% and 28% with 1 cm and 2 cm of saltwater, respectively. By referring to the anterior studies, it has been observed that increasing phosphate bags significantly enhances the productivity of solar still, increasing efficiency and productivity.

Table 8 A comparison of the daily productivity of our work and previously published work

References	Cases	Productivity (kg/m^2/day)	% Increase in cumulative yield
Present experimental work	CSS	3.8	-
	MSS-1 cm of water	5.3	39
	MSS-2 cm of water	4.9	28
Essa et al. (2020a)	CSS	3.6	-
	Still with coffee-based colloid	4.8	35.14
Panchal et al. (2020)	CSS	1.8	-
	Still with vertical fins	2.3	24.19
	Still with inclined fins	2.3	26.77
Attia et al. (2020)	CSS	3.7	-
	Still with aluminum balls	5.0	37
Sakthivel and Shanmugasundaram (2008)	CSS	3.3	-
	Still with gravel	4.0	20
Nafey et al. (2001)	CSS	3.9	-
	Still with black rubber	4.7	20
Dumka et al. (2019)	CSS	2.7	-
	Still with sand-filled cotton bags, 30 kg of basin water	3.4	28.56
Dumka et al. (2019)	CSS	2.3	-
	Still with sand-filled cotton bags, 40 kg of basin water	3.1	31

Therefore, phosphate bags are excellent energy storage materials.

Conclusions

The use of phosphate-filled cotton bags in the solar still was experimentally evaluated on 3 days. Experiments were carried out in both cases at 1 cm and 2 cm of basin water depth, during day and night. Based on the experimental results, we conclude the following:

i. Phosphate bags improved distillation efficiency.
ii. The distilled water production from the CSS during daytime and after daytime are found as 3.53 and 0.27 kg, respectively.
iii. The distilled water production from the MSS-1 cm of water during daytime and after daytime is 4.52 and 0.75 kg, respectively.
iv. The distilled water production from the MSS-2 cm of water during daytime and after daytime is 3.99 and 0.88 kg, respectively.
v. The CSS's overall productivity, MSS-1 cm of water, and MSS-2 cm of water is 3.8, 5.27, and 4.87 kg, respectively.
vi. Phosphate bags improve the distilled water production by 39% and 28% for MSS-1 cm of water and MSS-2 cm of water, respectively, compared with the CSS.
vii. The daily distilled water formed from the MSS-2 cm of water is 8.2% less than the MSS-1 cm of water.
viii. The presence of calcium and copper in phosphate stores the heat energy during the morning and afternoon, and stored heat energy was used during the evening.
ix. The use of phosphate bags improves the overall efficiencies by 28% for the basin containing 1 cm of saltwater and 22.5% for the basin containing 2 cm of saltwater.

Finally, it can be concluded that phosphate bags significantly enhance solar distillation and efficiency. Therefore, phosphate bags present excellent energy storage materials in the application of solar still desalination.

Authors' contribution Mohammed El Hadi Attia: investigation, project administration, and writing-introduction part. Zied Driss: project administration and writing-review & editing. Abd Elnaby Kabeel: formal analysis and project administration. Karthick Alagar: data curation and software. Muthu Manokar A: writing-results and discussion part, data curation, writing-review & editing. Ravishankar Sathyamurthy: writing-results and discussion part, data curation, software, and writing-review & editing.

Data availability All data are given in the manuscript.

Compliance with ethical standards

Competing interests The authors declare that that have no competing interests.

Ethics approval and consent to participate Not applicable

Consent for publication Not applicable

Nomenclature CSS, Conventional solar still; MSS-1, Modified solar still with 1 cm basin water; MSS-2, Modified solar still with 2 cm basin water; SHESM, Sensible heat energy storage materials; ISS, Inclined solar still; $I(t)$, Solar irradiation; Ta, Atmosphere temperature; $T_{s.w}$, Saline water temperature; $T_{c.c}$, Collector cover temperature

Appendix 1

The EHTC from saline water to glass cover is calculated by Tiwari and Lawrence (1991) and (Tiwari et al. 2009),

$$h_{e,w-g} = 16.273 \times 10^{-3} \times h_{c,w-g}\left[\frac{P_w - P_{gi}}{T_{b.w} - T_{gi}}\right]$$

Convective heat transfer coefficient from the saline water to the glass cover is calculated by Tiwari and Lawrence (1991) and Tiwari et al. (2009),

$$h_{c,w-g} = 0.884\left[\left(T_{b.w} - T_{gi}\right) + \frac{\left(P_w - P_{gi}\right)\left(T_{b.w} + 273\right)}{\left(268.9X10^{-3} - P_w\right)}\right]$$

Partial vapor pressure at the $T_{b.w}$ is calculated by Tiwari and Lawrence (1991) and Tiwari et al. (2009),

$$P_w = exp\left(25.317 - \left(\frac{5144}{273 + T_{b.w}}\right)\right)$$

Partial vapor pressure at the glass surface is calculated by Tiwari and Lawrence (1991) and Tiwari et al. (2009),

$$P_{gi} = exp\left(25.317 - \left(\frac{5144}{273 + T_{gi}}\right)\right)$$

The thermal efficiency of the CSS and MSS is estimated as Tiwari and Lawrence (1991) and Tiwari et al. (2009),

$$\frac{\eta_{passive} = \sum \dot{m}_{ew} L}{\sum I(t) A_s \times 3600 \times 100}$$

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