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Energy, exergy, and economic analysis of indirect solar dryer integrated phase change material cans

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ABSTRACT

The efficiency of solar dryers fluctuates as the solar radiation declines, influencing the removed water content from products. Therefore, continuous heat delivery with a stable temperature range for a longer time using energy storage materials is an efficient way to enhance the drying process from energy and exergy prospects. To this aim, a solar dryer integrated with phase change material (PCM) was designed and examined in harsh weather conditions. The solar dryer performance with 1 and 2 kg of PCM (equipped in 6 and 12 cans, respectively) was analyzed against an identical reference dryer assessing numerous energy, exergy, and economic parameters. Research outcomes revealed that PCM cans have sustained the drying process, stabilized drying temperature and functioned as an extra heat source during the daytime. Furthermore, the modified solar dryer achieved an average moisture content removal of 86.5 % and 89.7 % by employing 6 and 12 PCM cans, compared to 82.5 % in the reference dryer. Energy analysis displayed that the useful heat gain was maximized by up to 3.9 % and 9.5 % integrating 6 and 12 PCM cans, respectively. Moreover, the thermal efficiency achieved by the modified dryers was about 2.5 % and 6.8 %, respectively. Exergy analysis indicated remarkable exergy gain, exergy efficiency, and sustainability index for the solar dryer modified with 12 PCM cans, achieving a maximum of 593 W, 20 %, and 46 %. Economic analysis exhibited that the solar dryer energy payback period with 6 and 12 PCM cans was shorter than that of the reference dryer by 33.7 % and 35.1 %, respectively.

1. Introduction

The drying process of fruits and vegetables has increasing demand, although traditional drying processes have energy consumption and economic concerns [1]. However, sustainable and eco-friendly dryers have been developed lately utilizing abundant solar energy and other renewable sources [2]. Solar dryers are characterized by a decent potential to lower energy consumption and CO_2 emissions, boosting sustainable energy efforts in the future society [3]. Employing solar dryers is a crucial solar energy technique to prevent agricultural fruit and vegetable inflation, which accounts for 30 %-40 % of total post-harvesting losses [4]. Economically, solar dryers can minimize drying process charges by up to 50 % and reduce the economic return by about 30 % [5]. Therefore, solar dryers could be among the technologically advanced solar systems in developing countries characterized by long sunshine hours and high solar radiation rates, like Iraq [6].

Solar dryers, of various design aspects and types, have reported remarkable technical and environmental advancements. However, it has been reported that the solar dryer combined with thermal energy storage mediums, especially phase change materials (PCMs) [7–10], showed an efficient drying process with the highest product moisture content removal, especially when combined with forced convective systems [11,12]. In addition, researchers have reported that indirect, forced convection dryers had a better drying speed and product quality than

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other direct solar dryers [13]. Besides, a better performance could be achieved when the solar collector has double or triple-pass recirculation [14,15].

Some research efforts were testified in the literature to advance the performance of solar dryers integrating PCMs, fins, baffles, nanofluids, waste energy sources and other methods [16–19]. For instance, Yüksel et al. [20] experimentally developed a photovoltaic/thermal system with a V-grooved double-pass solar dryer incorporated with a paraffin-based thermal energy storage unit to dry golden apple slices. The outcomes indicated that the drying process was finished early in the dryer equipped with paraffin where the solar collector thermal efficiency in the reference and PCM-integrated dryer was about 41 %-77 % and 55 %-78 %, respectively. Besides, the dryer chamber exergy efficiency was 65.69 % for the reference dryer and 66.23 % for the dryer integrated with the PCM thermal energy unit. Mirzaee et al. [21] explored the influence of repositioning the PCM inside the dryer cabinet on the drying of tomato slices. Their study assessed the dryer's thermal efficiency and specific energy consumption when positioning the PCM in the upper, lower and middle trays of the dryer. Study outcomes showed that integrating the PCM in the lower tray has shortened the drying time more than the other positions. In this regard, the dryer's specific energy consumption was decreased by up to 14.87 MJ/kg and the overall dryer thermal efficiency was improved by up to 38.92 %. Verma et al. [22] fabricated a tent house solar dryer consisted a 1.12 m^2 solar flat plate collector with two trays (0.57×1.11 m^2)-based drying chamber to dry potato sliced with 2.5 and 5.0 mm thickness. The experimental results were compared to a conventional natural convection dryer, where the drying took 6 h longer than the modified dryer. Besides, the moisture ratio for 2.5 and 5.0 mm slices was respectively between 0.475–0.001 and 0.650–0.003, and the dryer efficiency reached a maximum of about 27 % and 22 % at these thicknesses, respectively. Ahmed et al. [23] developed a solar dryer by combining a solar air heater with a greenhouse dryer, in which the dryer bed was integrated with paraffin wax-enhanced black painted gravel as a thermal storage medium to dry Tomato flakes. Study findings revealed that the drying efficiency of the developed dryer was about 50.18 %, against 30.02 % for the natural sun drying daily. Besides, the study stated that an effective moisture diffusivity of about 0.8666×10^{-10} m^2/s and 11.650×10^{-10} m^2/s were attained for the natural sun and developed dryers, respectively. Avargani et al. [24] explored the solar dryer performance consisting of a V-corrugated absorber plate-integrated FPSC and a drying chamber with 4-perforated trays. A validated numerical model was proposed considering the effect of airflow rate, moisture movement and instantaneous heat. Study outcomes showed that the average outlet air temperature of the dryer decreased from 62.9 to 46.6 °C when increasing the inlet airflow from 100 to 400 m^3/h, while the moisture ratio increased by about 116.95 %, 118.77 %, and 126.70 % for potato, apple, and carrot, respectively. Moreover, the results displayed that the highest moisture ratio reduction achieved for the apple slice drying process was 9.3 %. Susana et al. [25] developed and examined a small-scale rotary dryer for cherry coffee drying of a 62 % moisture content, comparing the sun drying and thermal energy obtained from burning rice husk at 10 kg, 15 kg, and 20 kg. Findings showed that the moisture content was 13.14 % and the average temperature was 29.44 °C for sun dryer, while the dryer-based thermal burning showed 10.71 %, 10.45 %, and 11.13 % moisture content at 10 kg, 15 kg, and 20 kg, respectively. Correspondingly, the drying time needed to complete drying process was 1440, 1680, and 1920 min, respectively, in which the fastest drying rate achieved at 10 kg and highest drying efficiency at 20 kg.

Madhankumar et al. [26] investigated the energy performance and viability of a solar dryer consisting of a blower integrated with three corrugated absorbing plate solar collectors (with PCM, without PCM and with PCM-enhanced fins) to dry bitter gourd slices. The numerical study considered the drying time, thermal efficiency, energy consumption, and moisture removal rate as effective variables. The findings showed the dryer integrated with PCM and fins accomplished the best energy performance compared with the other arrangements in which its average efficiency was 19.6 %, compared with 18.9 % and 17.3 % for the one integrated with and without PCM, respectively. Nevertheless, the dryer with PCM and fins indicated a 3.1 % higher capital cost than the arrangement without fins. Gunawan et al. [27] improved a solar air heater using paraffin wax, soy wax, and palm wax as thermal energy storage materials for potential drying applications. The PCMs were encapsulated with milk cans and the solar heaters were tested for three days with various solar radiations. The study reported maximum energy efficiency for paraffin wax with 30 %, 23.28 %, and 33.67 %, on the first, second and third day, while the maximum exergy efficiency was attained for palm wax with 20.27 %, 18.86 %, and 28.96 %, respectively. This improvement was attributed to the effect of air velocity which had the main role in improving the PCM performance in the solar dryer [28]. Sharma et al. [29] assessed a solar dryer used to dry tomato flakes considering thermal, environmental, economical, and quality aspects. The findings reported superior thermal performance for the modified dryer over the open sun dryer and the quality of dried tomato flakes. In addition, it was indicated that the moisture content of dried product reached 9 % in 10 h, while the energy payback period, and annual total CO_2 minimization, were 4.21 years, and 12.28 tones, respectively. The study concluded that the initial capital cost for the modified dryer (~US$245) could be paid back within 6 months of operation, representing a cost-effective system compared with solar dryers reported in the literature. Akhijahani et al. [30] analyzed a solar dryer-assisted parabolic trough collector to dry Rhubarb slices (5 mm thickness) employing Al_2O_3/water nanofluid with 3.75 % concentration and PCM with an adjustable air flow stream. The study investigated several parameters, including specific energy consumption, exergy efficiency, overall drying efficiency and collector efficiency under various scenarios. Findings indicated that increasing the air circulation speed has positively decreased the drying time. In the best scenario when the dryer integrated with nanofluid and PCM, the overall drying efficiency, and exergy efficiency were augmented by up to 8.21 % and 61.3 %, while specific energy consumption was reduced by a minimum of 1.91 %. Tuncer et al. [31] designed and examined a drying system comprised of a photovoltaic/thermal-air collector and drying chamber, which was compared with the same dryer with three numerous collector configurations (grooved absorber, spherical turbulators, and collector-integrated baffles). Results showed that all modified collectors indicated higher outlet air temperature than the reference collector by no less than 15.77 %. Study outcomes revealed that the average thermal efficiency of modified dryers ranged between 61.32 % and 77.49 %, while the overall exergy efficiency was between 10.65 % and 11.17 %, compared with the reference one. Moreover, the study reported that the drying chamber average sustainability index was between 3.74 and 5.82, and the dryer payback period was between 2.98 and 3.51 years. Jahromi et al. [32] assessed a solar dryer integrated parabolic dish solar collector to dry a Teucrium polium plant under the effect of Al_2O_3 nanofluid and PCM. The modified dryer was evaluated considering several energy and exergy parameters under two air flow rates (0.025 and 0.04 kg/s), with and without PCM. Results indicated that coupling PCM with the nanofluid presence has increased the dryer thermal efficiency and decreased the drying time keeping a good quality of the dried product. In the best case, the modified solar dryer has achieved thermal efficiency by up to 62.7 % at 0.04 kg/s airflow rate. However, study findings revealed that the peak overall dryer efficiency of about 41 % was achieved using PCM at 0.025 kg/s mass flow rate. El-Sebaey et al. [33] fabricated and compared chimney-type and fan-type solar dryers, comprising collector and drying chambers to dry banana pieces under Shebin El-Kom, Egypt weather conditions. Results showed that the chimney-type solar dryer indicated a lower moisture content of about 10.59 % compared with an open sun dryer, showing 81 % enhancement in the drying process. Furthermore, the chimney-type solar dryer performed better than the fan-type, in which the average collector thermal efficiency achieved for the chimney-type solar dryer was 34.14 %, while that of the fan-type dryer was 29.54 %, indicating a better thermal efficiency for the chimney-type dryer. Accordingly, the average thermal efficiency attained for the chimney-type solar dryer was 14.45 % against 12.76 % achieved for the fan-type solar dryer.

The domain of solar dryers achieved notable advancements in literature studies adopting innovative techniques in the field of food drying and preservation by using various techniques to improve solar dryer systems. Although different designs, techniques, and modifications of solar dryers were explored to increase their performance, a comprehensive analysis of this promising technology is still disregarded. Most of the previous studies were limited to thermo-energetic advances, lacking exergy and economic analysis. Besides, utilizing recycled materials in this domain is overseen, especially since such a concept is in line with recent trends towards sustainability. Therefore, the current study affords a comprehensive analysis including an energetic, exergetic, and economic overview of solar dryers, utilizing widely-available waste materials (paraffin wax), equipped into recycled cans as storage units. To this aim, two indirect fan-type solar dryers were designed, fabricated, and examined under harsh weather conditions to dry melon slices, utilizing PCM thermal energy storage units. The results attained are believed to deliver a full analysis of solar dryers, contributing remarkably to the field of food preservation using renewable energy and encouraging the path towards recyclability, sustainability, and economic effectiveness.

2. Materials and methods

2.1. Solar dryer design and fabrication

In the current experiment, two indirect, fan-type solar dryers are designed, manufactured and tested under harsh weather conditions in Basra City, Southern Iraq. Solar dryers were made from locally low-cost wooden blocks and painted black to harvest as much heat as possible. One solar dryer is assigned as a reference, while the other dryer is improved using PCM-encapsulated cans with different quantities. Each solar dryer was composed of two parts, an air solar collector to maximize flow air temperature and a drying chamber where dried produce was placed. The solar collector is designed with dimensions of 1000 cm length, 500 cm width, and 100 cm thickness. The bottom side of the collector was made of aluminium layers, coated with black, to harness solar radiation, and then supported with thermal wool insulation and wood to minimize heat dissipation. Besides, eight wooden obstacles were fixed inside the solar air collector with equal distances along the collector length to obstruct the airflow passage on the winding path and increase the air heating process. A glass cover was placed on the top of wooden obstacles to ensure one-way movement of airflow with accumulated heat increment during the process. The outdoor air was supplied through a port made in the beneath right-front edge of the collector and provided with fan works with an AC power supply to keep a uniform airflow rate in the solar dryer. Furthermore, the outlet port was positioned at the end edge of the solar collector and connected to the drying

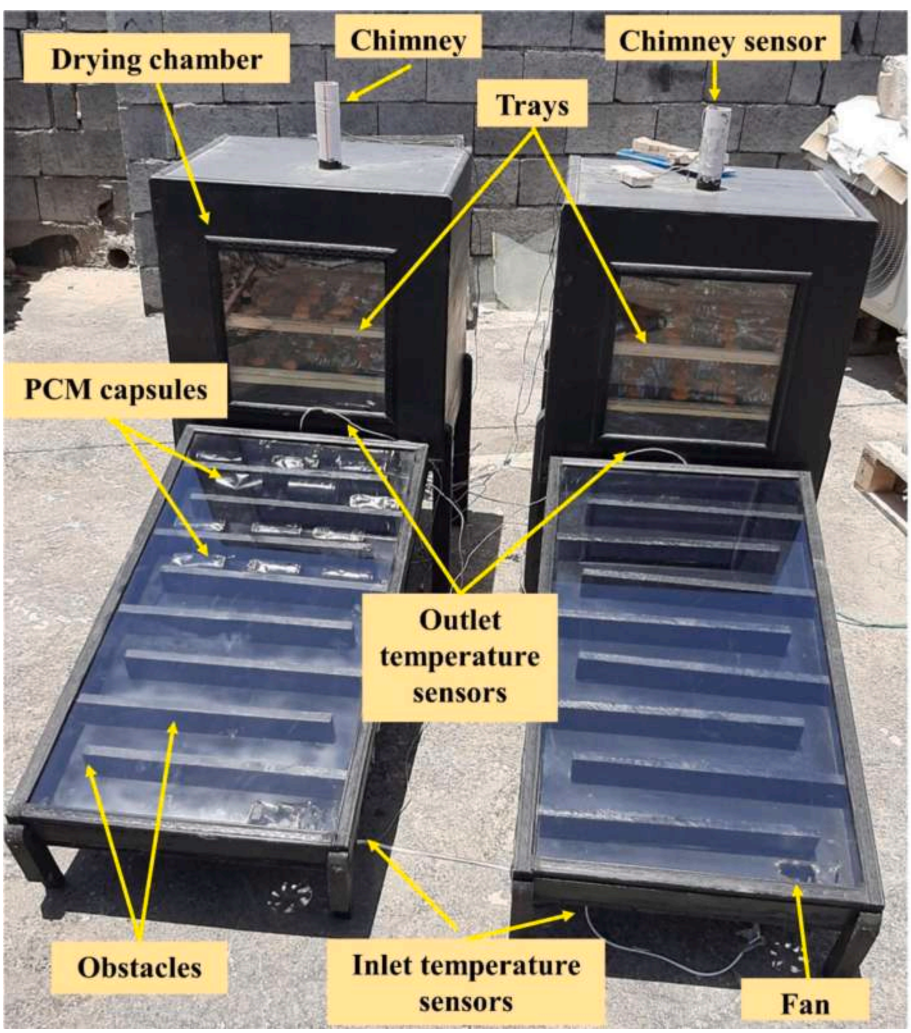

Fig. 1. Experimental solar dryers.

chamber by a small plastic hose fastened tightly.

The solar dryer chamber is designed with dimensions 600 mm length, 600 mm width, and 700 mm height. The drying chamber is delivered with two trays made of stainless-steel perforated plate surrounded by a wooden frame, placed at equal distances inside the chamber. The inside walls of the chamber are covered with thermal wool insulation and the top surface of the dryer chambers is provided by a chimney made of plastic for proper ventilation. The experiments were conducted on sunny days in July, in which both solar dryers were oriented towards the south to harvest as much solar radiation as possible during the experiment period. All parts of solar dryers are shown in Fig. 1.

2.2. Preparation of PCM cans

A popular Iraqi paraffin wax, having a 40 °C–44 °C transition temperature was employed as a PCM thanks to its suitable working temperature range for the application. Table 1 displays the thermophysical characteristics of used paraffin. The PCM with ~ 1 and 2 kg was weighed and poured into 6 and 12 cans, respectively. Waste soft drinks cans (recycled aluminium cans) with a total capacity of 185 ml were used as PCM cans in which ~ 165–170 g of PCM was poured into each can. These thin cans have high thermal conductivity to improve the charging/discharging of PCM, which is further improved by coating with black. Fig. 2 shows the preparation steps to fabricate PCM cans. PCM cans were distributed on the upper part of the air solar collector, placing 3 cans in a line (see Fig. 1), to charge heat from the hottest airflow stream, and discharge it with minimal losses to the drying chamber during the discharging phase.

2.3. Drying product

In this research, melon fruit was selected as a drying product to examine the solar dryer since it is among the top ten fruits consumed in Iraq [35]. The melon is characterized by a high moisture content thanks to its fibres filled with water, making it a suitable product to test the ability of solar dryers to reduce the moisture content and produce locally demanded dried melon [36]. The melon was cut into slices of 4–6 mm thickness and then weighed to 850 g before being distributed on each tray of solar dryer chambers, as shown in Fig. 3.

2.4. Measurement instruments and tools

The experiments in this research were conducted for two days, from 7:00 to 00:00, in which the variation in temperature, humidity, wind speed, and solar radiation were measured on-site. Solar dryers were provided with thermal sensors distributed in the inlet and outlet of dryer collectors, chambers, chimneys, and ambient temperature to track the temperature variation. These sensors were connected to the data logger (Mega 2560) and set to measure temperature every 10 min. Two humidity sensors were positioned in each drying chamber to amount the humidity generated from the drying product every 30 min, and the measured data was collected from a small digital screen. The airflow inside the solar dryer's collector is inducted by a fan placed at the inlet port and the airflow rate was fixed at 3.2 m/s throughout the experiment time. The outdoor wind speed was recorded using an anemometer with a 30-minute time-step, while the solar radiation was measured from 7:00 to 18:00 using a solar power meter every 30 min, too. Finally, a thermal imaging camera was employed to graphically observe the temperature variation of the dryer collector and chamber in the reference and modified dryers at different times, namely at 7:00, 9:00, 12:00, 15:00, 18:00 and 21:00. Table 2 details the specifications of instruments used in the research.

Table 1
Thermal and physical characteristics of PCM [34].

Characteristics	Units	Values
Thermal conductivity	(W/m.K)	0.21
Specific heat	(kJ/kg.K)	2.1
Heat of fusion	(kJ/kg)	190
Density	(kg/m^3)	830 for liquid 930 for solid

2.5. Evaluation aspects of solar dryers

The reference and modified solar dryers were evaluated considering energy, exergy, environmental, and economic aspects, as follows:

2.5.1. Moisture content

The solar dryer performance was tested with 1700 g (850 g on each tray) of fresh melon slices, presenting remarkable water content to be removed from the product. The rate of moisture removed from the dried product is affected by the input heat energy to the solar dryer (specifically the drying chamber). The amount of moisture removed from the melon slices could be quantified as the difference between the initial weight of melon slices before drying (W_1), and the product's final weight after drying (W_2), according to Eq. (1) [37].

$$\text{Moisture content } = \frac{W_1 - W_2}{W_1} \times 100 \quad (1)$$

2.5.2. Energy analysis

The energy efficiency of the solar dryer could be estimated by considering the useful heat energy (Q_u) gained by the solar dryer and the input heat energy (Q_i). The useful heat energy was determined concerning several parameters, such as the temperature difference at the inlet (T_i) and outlet (T_o), airflow density (ρ), average airflow velocity (V), airflow-specific heat (c_p), solar collector cross-sectional area ($A_{collector}$), as presented in Eqs. (2) and (3) [38]. On the other side, the input heat energy to the solar dryer (Q_i) depends on the absorbed solar radiation by the dryer during the day (S) and the surface area of the solar collector exposed to falling solar radiation (A_c), according to Eq. (4) [38].

$$Q_u = \dot{m}c_p(T_o - T_i) \quad (2)$$

$$\dot{m} = \rho V A_{collector} \quad (3)$$

$$Q_i = S\,A_c \quad (4)$$

The solar collector efficiency ($\eta_{th,c}$) signifies the thermal efficiency obtained during the day hours considering the amount of input heat energy to the solar collector and useful heat energy gain, determined by Eq. (5) [39].

$$\eta_{th,c} = \frac{\dot{m}c_p(T_o - T_i)}{SAc} \quad (5)$$

After sunset when the solar radiation becomes zero, PCM cans start delivering the input energy to the dryer until the heat-discharging phase ends (the PCM temperature is equal to the ambient temperature). In that way, the input energy during the night could be specified concerning the PCM mass, PCM-specific heat, initial PCM temperature placed in the collector, and the final PCM temperature at the collector exit. Therefore, the solar dryer collector thermal efficiency during the night is calculated using Eq. (6) [40].

$$\eta_{\text{th,c}} = \frac{\dot{m}c_p(T_o - T_i)}{\dot{m}_{,PCM}c_{p,PCM}\left(T_{PCM,i} - T_{PCM,f}\right)} \quad (6)$$

2.5.3. Exergy analysis

According to the second law of thermodynamics, exergy is a metric to measure the actual work of a thermal system and evaluates its

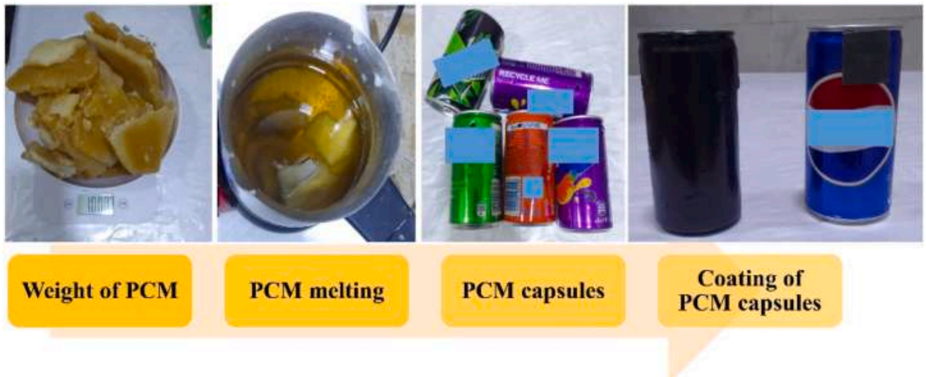

Fig. 2. Fabricating of PCM cans.

Fig. 3. Melon slices weighed and distributed on trays of the solar dryer's chamber.

Table 2
Instrument specifications as reported in the manufacturer datasheets.

	Temperature sensors	Humidity sensors	Anemometer	Solar power meter	Thermal imaging camera
Model	K-type (2 m length)	AM2305	MT-4615	SM206	WB-80VOLTCRAFT®
Range	− 200 °C to 1350 °C	0–100 % RH at −40–80 °C	1.40 ~ 108.00 km/h	0.1–399.9 W/m^2	−20–600 °C
Accuracy	0.25 °C	± 2 % RH at ± 0.3 °C	0.80 ~ 30.00 m/s	± 10 W/m^2	± 2 % ± 2 °C (tested @25 °C)
Photo of instrument/tool					

effectiveness by considering the energy quality. The exergy gain of the solar dryer could be evaluated by considering the exergy efficiency (η_{Ex}) based on the ratio of the inlet exergy (Ex_{out}) and outlet exergy (Ex_{in}), as presented in Eqs. (7–10) [41,42].

$$Ex_{out} = \dot{m}\left[C_p(T_o - T_i) - T_a\left(C_v \ln\left(\frac{T_o}{T_i}\right) - R\ln\left(\frac{\rho_o}{\rho_i}\right)\right)\right] \tag{7}$$

$$Ex_{in} = \left[1 + \frac{1}{3}\left(\left(\frac{T_a}{T_s}\right)^4 - \frac{4}{3}\left(\frac{T_a}{T_s}\right)\right)\right]SA_c \tag{8}$$

$$\eta_{Ex} = 1 - \frac{Ex_{in} - Ex_{out}}{Ex_{in}} \tag{9}$$

$$E_{X_{loss}} = Ex_{in} - Ex_{out} \tag{10}$$

The sustainability index (SI) is another metric that could be used to evaluate the solar system's effectiveness towards sustainability. Accordingly, the higher SI for a solar system indicates a better contribution towards sustainability [43]. Mathematically, this index could be calculated using Eq. (11) [44]. The exergy efficiency that appeared in Eq. (11) could be calculated in terms of the so-called waste exergy ratio (WER) and the improvement potential (IP). The WER signifies the exergy losses of the solar dryer to the inlet exergy, as indicated in Eq. (12) [44], while the IP refers to the improvement in the solar dryer system's performance to effectively help reduce negative environmental impacts. The IP could be mathematically estimated using Eq. (13) [44].

$$SI = \frac{1}{1-\eta_{ex}} \tag{11}$$

$$WER = \frac{E_{x_{loss}}}{E_{x_{in}}} \tag{12}$$

$$IP = (1-\eta_{ex}) \times E_{x_{loss}} \tag{13}$$

2.5.4. Economic assessment

Economic analysis is a vital concern to specify the feasibility of using solar dryers and motivates the manufacture of more efficient solar dryers with affordable processes. Despite the limited scale of the solar dryers manufactured in this work, they may give an appropriate benchmark for the extrapolation of various-scale dryers. In this regard, the energy payback period (EPB) is a fair metric to specify the period that a solar dryer needs to meet its cost in terms of energy production. Accordingly, the solar dryer becomes more sustainable with a shorter EPB, which could be estimated by Eq. (14) [45].

$$EPB = \frac{Embodied\ energy}{Annual\ energy\ output} \tag{14}$$

The embodied energy of solar dryer components could be specified according to Table 3.

The capital recovery factor (CRF) of the solar system is another essential economic aspect to show the annual payment contribution that could cover the capital cost of the solar dryer system. The CRF over the experiments was calculated for the solar dryer lifespan (n = number of operation years which is supposed to be from 5 to 10 years [49]), with interest rate (i = 12 %), according to Eq. (15) [50,51]. The annual payment contribution involved the price of each component of the solar dryer and implementation, as indicated in Table 4, considering the Iraqi dinar currency (IQD). The fixed annual cost (FAC) could be estimated considering the CRF and capital cost of the solar dryer system (IC) ($FAC = IC \times CRF$) [52], which is 358,500 ID (about 272 $).

The annual maintenance cost (AMC) is also considered in this work, which fluctuates according to the FAC multiplied by 15 %, electricity consumed by the collector fan (EC), and the CRF *(mathematically,* $AMC = 0.15 \times FAC + EC \times CRF$) [52,53]. Thereby, the annual cost (AC) could be determined using Eq. (17) [53], where the annual salvage value (ASV) is a substantial parameter to specify the annual cost considering the sinking fund factor (SFF) and salvage value (S) ($ASV = SFF \times S$). SSF represents the funds specified during the year with earning interest during the solar dryer's system lifespan (obtained from Eq. (16)), while S is proposed to equal 20 % of capital cost [53]. The cost of each 1 kg of hot air produced from the solar dryer (CPL) can be calculated by Eq. (18) [53], where M signifies the hot air mass delivered to the solar collector.

Table 3
Embodied energy of solar dryer system parts.

Material	Embodied energy coefficient (kWh/kg)	Quantity (kg)	Total energy (kWh)	Reference
Plywood	2.88	8.68	24.998	[46]
Aluminum sheet	55.28	1.86 × 2	205.641	[46]
Glass	7.2	4.87 × 2	70.128	[47]
Black paint	34.4	2	68.8	[47]
PCM	26.2	1	26.2	[46]
DC fan	3.31 (2 no.)	0.150	0.4965	[46]
Wooden plates	2.88	14.32	41.241	[46]
Glass	7.2	1.64 × 2	23.616	[47]
Black paint	34.4	1.5	51.6	[47]
Trays	8.89	1.05 × 2	9.334	[48]
Plastic pipe	19.44	0.223 × 2	9.059	[46]

Table 4
Cost of solar dryer components according to the local Iraqi market.

Component/Material	Cost (IQD)
Wooden plate	18,000
Aluminum sheet, No.2	20,000
Insulation	16,000
Glass	20,000
Black paint	6500
PCM for 6 and 12 cans	3000, 6000
Cans	2000
DC fan, No.2	6000
Silicon	3000
Wooden block board	70,000
Glass	10,000
Insulation	9000
Black paint	8000
Trays, No.4	12,000
Plastic pipe	5000
Manufacture of solar dryer systems	150,000

$$CRF = \frac{i(1+i)^n}{(1+i)^n - 1} \tag{15}$$

$$SFF = \frac{i}{(1+i)^{n-1}} \tag{16}$$

$$AC = FAC + AMC + ASV \tag{17}$$

$$CPL = \frac{AC}{M} \tag{18}$$

2.6. Uncertainty analysis

Determining the uncertainty of the measurements is critical to avoid errors and ensure the reliability of the values obtained during experiments. Various errors may occur systematically or randomly during measurements of inlet, outlet, drying chamber temperature, useful heat gain, and thermal efficiency, requiring some verification of measured values. The uncertainty analysis was conducted on the useful heat gain and thermal efficiency results obtained in the current study considering the uncertainty of instruments described in Table 2. Eqs. (19) and (20) [50,54] are used to determine the uncertainties, indicating that the uncertainty of useful heat gain and thermal efficiency was about ± 1.46 % and ± 1.67 %, respectively.

$$UQ = \sqrt{\left(\frac{U_{\dot{m}}}{\dot{m}}\right)^2 + \left(\frac{U_{ch}}{T_{ch}}\right)^2 + \left(\frac{U_{T_{in}}}{T_{in}}\right)^2 + \left(\frac{U_{T_{out}}}{T_{out}}\right)^2} \tag{19}$$

$$\frac{U_\eta}{\eta} = \sqrt{\left(\frac{U_{\dot{m}}}{\dot{m}}\right)^2 + \left(\frac{U_{T_{in}}}{T_{in}}\right)^2 + \left(\frac{U_{T_{out}}}{T_{out}}\right)^2 + \left(\frac{U_S}{S}\right)^2} \tag{20}$$

3. Results and discussion

The experimentations were conducted under the weather conditions of Basrah City, Iraq (Fig. 4) during July 2024. The current study involved two cases to investigate the energy and exergy efficiency of the solar dryer in addition to the economic and environmental aspects. In the first case, the reference solar dryer was evaluated and assessed

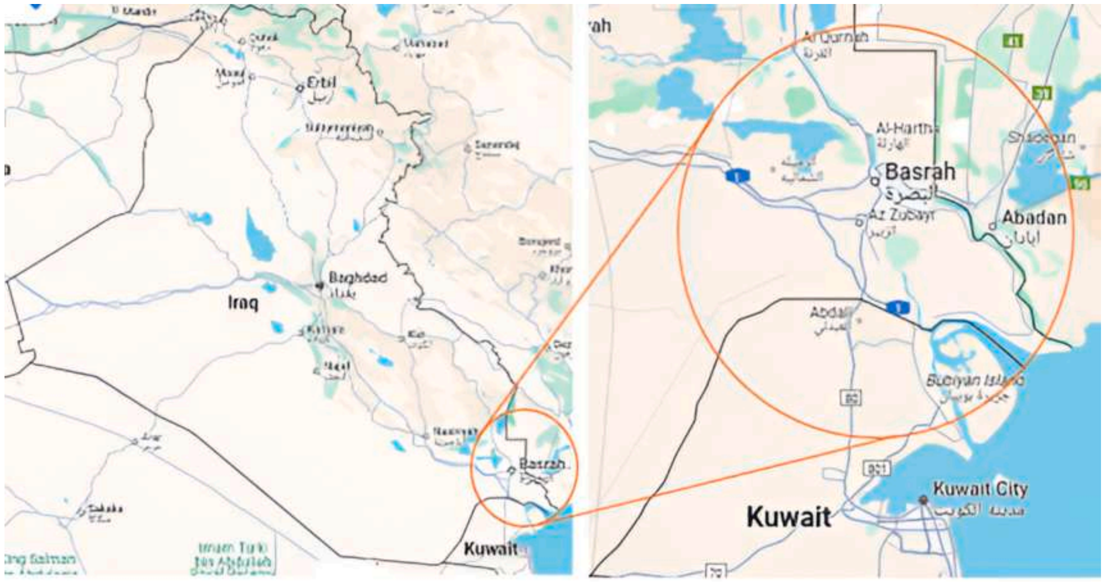

Fig. 4. Geographical map of study location.

against the modified solar dryer when 6 PCM cans were applied. Moreover, the second case investigated the dryer performance using 12 PCM cans, in which a double PCM quantity was integrated.

Fig. 5 shows the in-site variation of solar radiation, wind speed, and relative humidity, measured every 30 min. The weather conditions showed nearly similar variations measured throughout the experiment days, therefore, the average value during experimental days was considered in the figure. The solar radiation of experiment days was varied during the day until sunset, beginning to increase gradually from the early morning hours until noon, recording a maximum of 1164 W/m^2 at noon, and a minimum of 112 W/m^2 at 18:00. At the beginning (at 7:00), the average ambient temperature was 36.32 °C, which increased later at the midday recording a mark of 50.93 °C at 12:50 and slowly decreased to 39 °C at the end of day time around 18:00. The relative humidity rises in the figure in the early morning and midnight, where the maximum mark recorded was 38.7 % at 7:00 then significantly dropped with the temperature rising in the afternoon, then rising again at night. Besides, the average outdoor wind speed was fluctuating between 3.97 and 2.23 m/s during the experimental days.

3.1. Temperature variation analysis

The solar dryer's thermal performance is impacted by the temperature difference throughout the operation time. In this regard, the inlet temperature (T_i), outlet temperature (T_o), PCM temperature (T_{PCM}), and drying chamber temperature (T_{ch}) are the most influencing temperatures in the solar dryer performance. Fig. 6 shows the measured temperature variation of solar dryers in both cases during the day and night.

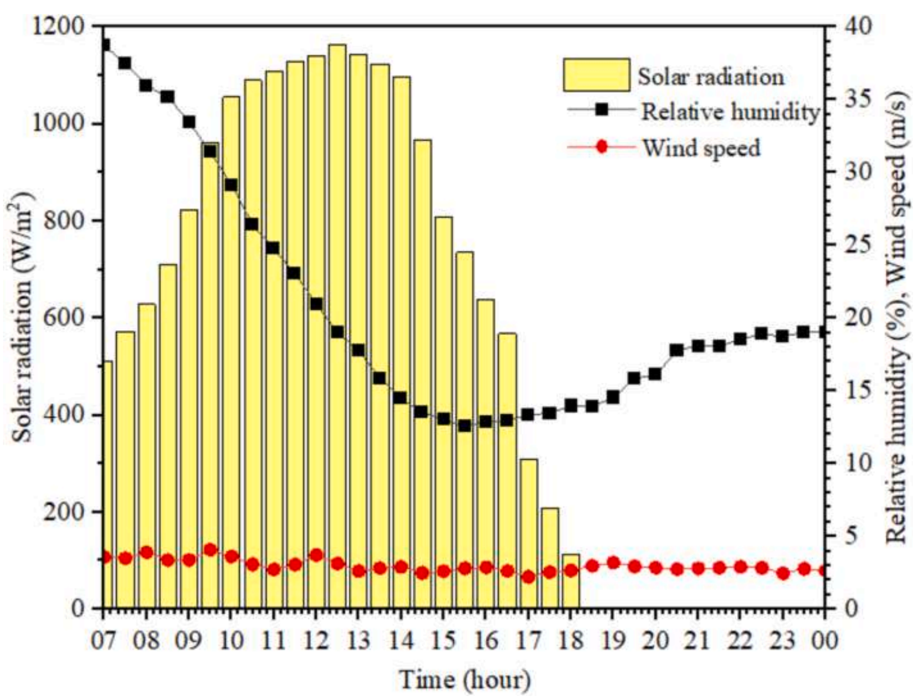

Fig. 5. In-site outdoor conditions during experiments.

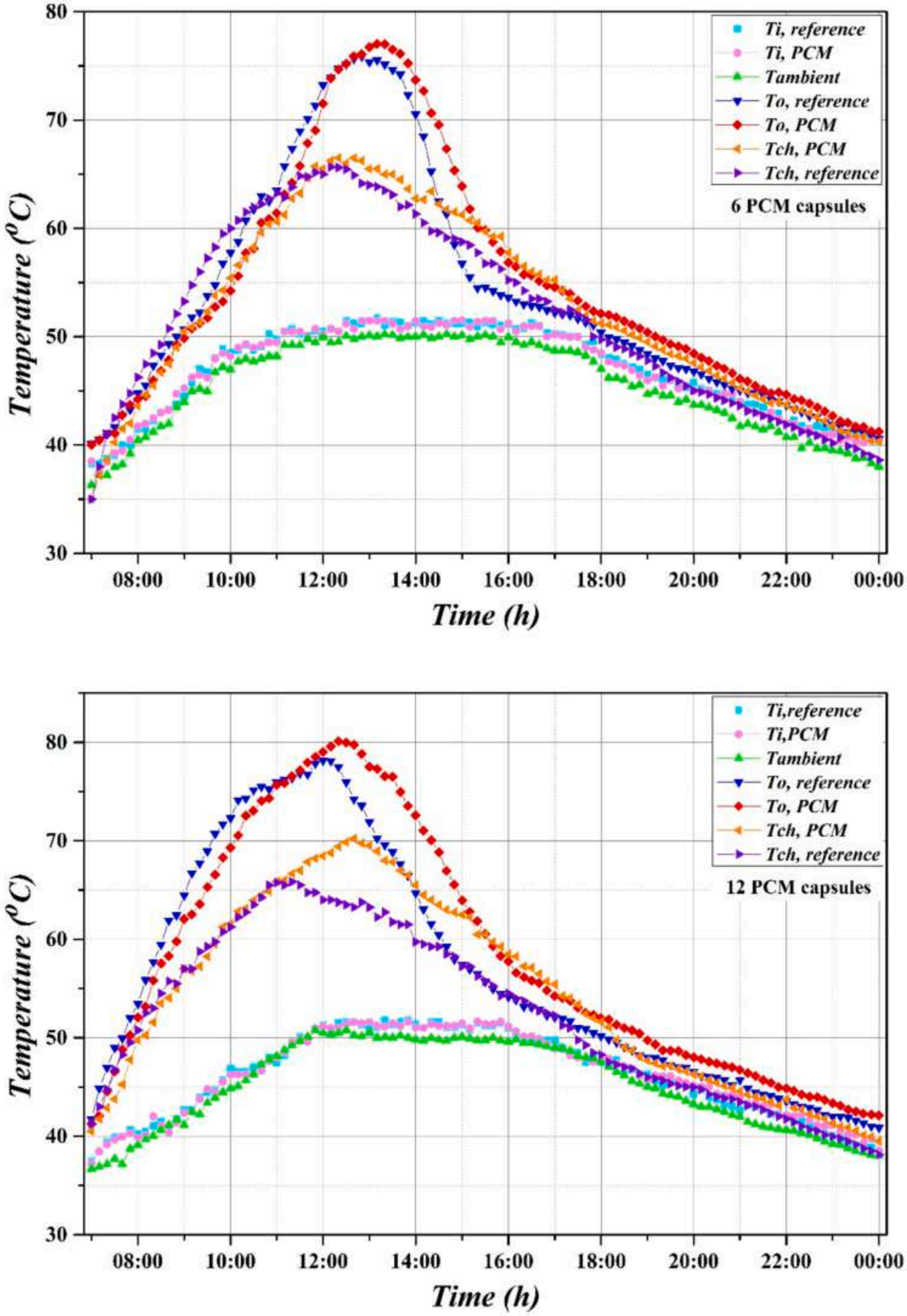

Fig. 6. Temperature profile of solar dryers.

In both cases, it could be witnessed that the inlet temperature variation of the reference and modified solar dryers is too close throughout the experimental period. The maximum T_i recorded in the reference solar dryer collector was 50.61 °C, against 50.57 °C in the solar dryer with 6 PCM cans. However, the outlet temperature (T_o) of the reference solar dryer and that modified with 6 PCM cans showed different behaviour although they were relatively similar at the beginning of the experiment until 8:00. Later, the T_o of the reference solar dryer started to increase more than that of the 6 PCM cans-based solar dryer till 12:50. From 12:10 to 12:50, the T_o of reference and modified solar dryers were relatively equal, recording about 75.85 °C, and 76.02 °C. Then, the T_o of the PCM solar dryer increased gradually more than the reference solar dryer due to the heat charging phase of PCM cans in which a notable heat amount starts storing in the PCM till reaching the full melting phase. At this time, the maximum To attained for the PCM-based dryer was 77.02 °C at 13:10 while that of the reference dryer was 75.54 °C and a certain amount of heat is expected to be charged in a latent form in the PCM cans, till around 13:00. Afterwards, the PCM-integrated solar dryer start to provide extra heat energy to the drying chamber thanks to the PCM cans which work as an extra heat supplied and this is obvious in the T_o in both solar dryers which was high for the PCM-integrated dryer till the end of experimental day.

The figure also indicates that in Case 1, the drying chamber temperature with 6 PCM cans demonstrated the same value at 12:20, recording a maximum of 66.65 °C and then kept higher than that of the reference dryer till the end of the experiment. Increasing PCM cans in

Case 2 has improved the thermal performance of the solar dryer as a result of increased T_o, which increased the chamber temperature eventually. In this regard, the maximum chamber temperature attained in the 12 PCM cans-based dryer was 80.12 °C at 12:20, corresponding to a maximum T_o of 70.22 °C recorded at 12: 40. From the other side, Fig. 6 shows the effect of integrating 12 PCM cans on the thermal performance of the solar dryer system. As could be observed from the figure, the effect of PCM cans was in progress after 12:30 by increasing the T_o and drying chamber temperature and augmenting the moisture content of the product.

Fig. 7 shows thermal images for the solar air collectors and drying chambers of the reference and modified solar dryer with 12 PCM cans at different times. Regarding the solar air collectors, it could observed in the figure photos that the outer surface temperature of the modified dryer is lower than that of the reference dryer by 0.7 °C at 7:00. Similarly, this temperature behaviour was continued, recording temperature difference of 4 °C at 9:00. This behaviour is expected since the heat was charging the PCM cans in the first half of the day, maintaining the solar collector of the modified solar dryer with lower temperature than the reference dryer. At noon, the temperature behaviour of collectors was reversed in which the outer surface temperature of the modified dryer's collector was higher than that of the reference dryer by 1.2 °C. The PCM inside cans are expected to reach full melting phase and start providing extra heat to the air steam towards the drying chamber. This is also observed in Fig. 6 which designated reversed temperature behaviour around 11:10 in both dryers. The high temperature difference of dryers was kept until 15:00 which showed 2.6 °C. At sunset time, around 18:00, the collector's outer surface temperature difference was almost the same, recording 2.7 °C, which reveals the role of PCM cans in maintaining the air temperature at high values due to the heat discharging phase. The temperature difference of collectors tends to be minimized gradually with obviously high values for those equipped with PCM cans. This is obvious in the thermal photos at 21:00 which show that the outer surface temperature of the PCM collector was higher than that of the reference dryer by 1.5 °C. The temperature difference of solar dryers gradually converged after 21:00 till all stored heat inside PCM cans was released around 00:00, as could be observed in Fig. 7.

The temperature difference between the modified and reference dryers fluctuates throughout the day due to the interaction between PCM phase transition and stored solar energy. During the melting phase, heat is charged into PCM cans when the air temperature flowing inside the FPSC is within the PCM melting range, dropping the temperature of the modified solar dryer for a certain period. This temperature drop is continued as the PCM reaches its full thermal energy storage capacity, which is obvious in Fig. 6, leaving a negative effect on the drying efficiency of the modified dryer. Afterwards, the reference and modified

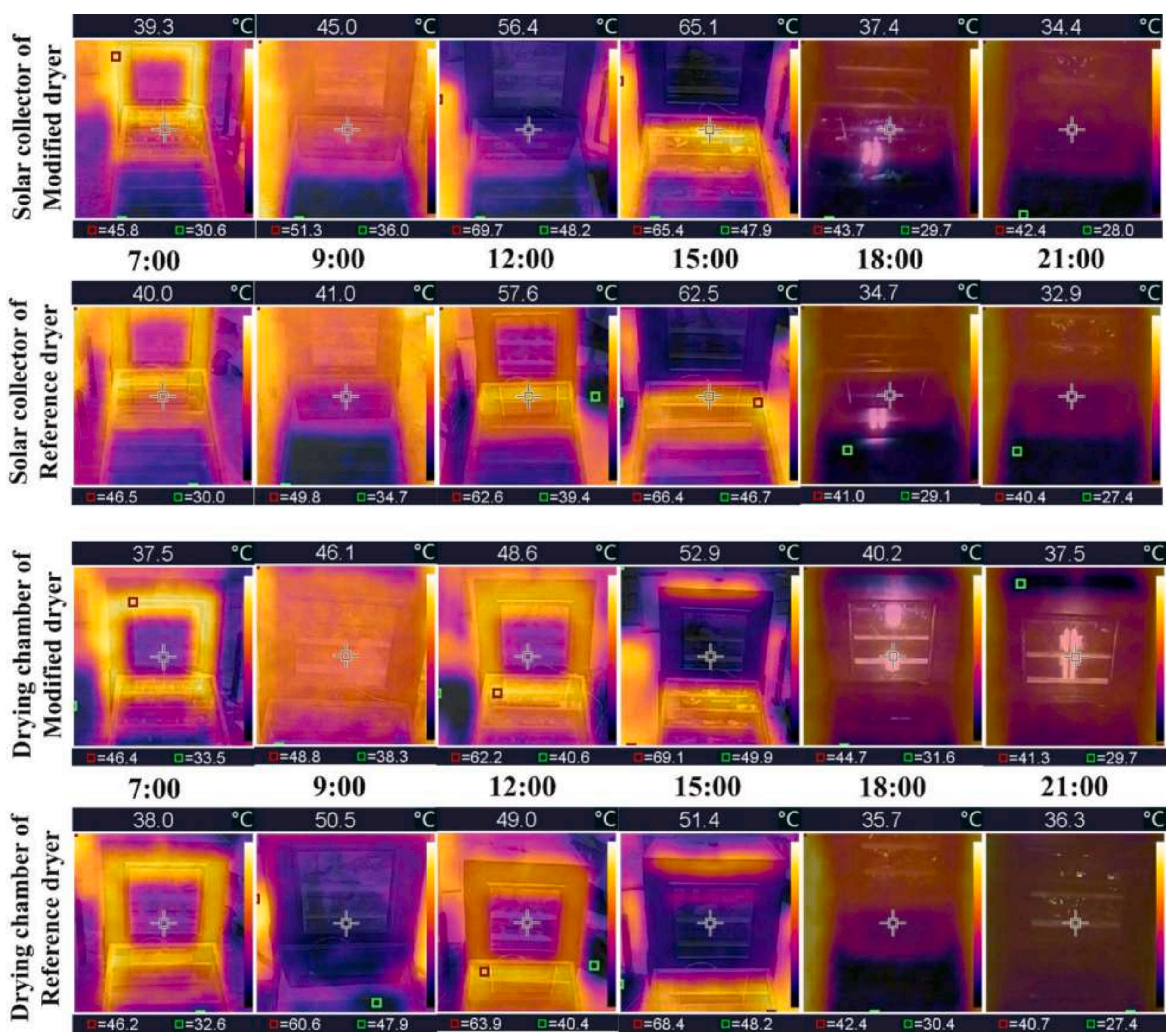

Fig. 7. Thermal images for the solar air collectors and drying chambers of solar dryers.

solar dryers perform relatively the same for a short time, and then an obvious temperature difference could be observed for the modified dryer over the reference one till the rest of the experiments. Moreover, PCM cans release charged heat as the outdoor ambient temperature drops, assisting the high drying temperature inside the modified dryer until all stored heat is discharged. Conclusively, the fluctuating temperature difference between the reference and modified dryers is attributed to the dynamic thermal interaction between outdoor weather conditions and the phase transition phenomenon.

The temperature trend of the drying chambers of modified and reference dryers was relatively the same as that of the solar air collectors. This is reasonable since the air stream inside the drying chamber is coming from the solar air collectors. However, the outer surface temperature of drying chambers was generally lower than that of the solar collectors since a huge amount of heat was utilized to dry melon slices. The temperature difference reported at 7:00 was relatively equal for both drying chambers with a 0.5 °C difference. At this time the PCM inside the collector is still in the solid phase and slightly starts to melt as the solar radiation on the collector increases. However, the temperature difference was increased to 4.4 °C at 9:00, indicating a remarkable difference between the drying chambers during the PCM melting phase which influenced the drying process at this time. Afterwards, the PCM is expected to reach its full melting phase nearly as time goes towards midday (i.e., at noon), in which the temperature difference was narrowed to 0.4 °C only. Later on, the drying chamber of the modified solar dryer started to be warmed up more than that of the reference dryer thanks to the extra heat source supplied by PCM cans, indicating 1.5 °C at 15:00. Then, the temperature difference increased remarkably at 18:00, reaching 4.5 °C due to incessant hot air stream accumulation inside chambers. Eventually, the temperature of drying chambers decreases gradually as the PCM cans release all stored heat, reporting an outer temperature difference of 1.2 °C over the reference chamber at 21:00.

Conclusively, integrating PCM cans helps to stabilize the drying temperature throughout the drying process and extend the time of drying after sunset. During day hours, PCM can absorb heat accumulated in the FPSC when reaching the melting temperature in a latent form. When the PCM cans reach their full melting state, which could be noticed around 11:10, the PCM start to work as an external heat source in addition to the FPSC. In other words, PCM cans start providing heat once the dryer temperature drops under the PCM melting point, stabilizing the drying temperature during the process. Besides, the PCM cans play a key role in providing a continuous heat supply in the late afternoon and after sunset, sustaining the drying process for a longer time. This property is necessary for drying fruits that are sensible for temperature as well as those with high water content.

3.2. Analysis of product moisture removal

Increasing the shelf life of an agricultural product is the key objective of exploring solar dryers, which work effectively to remove the moisture of crops. Determining the quantity of moisture removed from melon slices depends on the initial weight (before drying) of melon slices (i.e., 850 g for each tray of solar drying chamber) and the final weight (after drying) of the product. Fig. 8 shows the initial and final weight of melon slices graphically. In Case 1 after 18 h of solar drying, the product weight in the reference solar dryer was reduced from 850 g in each tray to 123 and 176 g, in which the moisture content removed from the product was about 82.4 %. In this time case, the solar dryer enhanced with 6 PCM cans showed moisture content removal of about 86.5 % (equivalent to 96 and 133 g final weight on trays), which indicates an extra 4.1 % moisture removal. The increasing number of PCM cans has positively increased the moisture content removal from melon slices due to maintaining a longer period of high temperature inside the solar dryer after sunset. Accordingly, in Case 2 when 12 PCM cans were integrated with the solar dryer, the final weight of melon slices dried in the reference dryer was 120 and 171 g against 73 and 102 g attained from the solar dryer integrated with 12 PCM cans. Equivalently, the moisture content removed from the melon slices using the reference and modified solar dryers in Case 2 was 82.9 % and 89.7 %, respectively, indicating an extra 6.8 % moisture content removal. Accordingly, it could be concluded that the solar dryer integrated with 12 PCM cans has helped increase the moisture content removal from the product slightly compared with the dryer integrated with 6 PCM cans.

The increased number of PCM cans has elevated the temperature provided to the drying chamber, as can be observed in the temperature profile in Fig. 6. In this regard, doubling the number of PCM cans has increased the chamber temperature to 70.22 °C at noon when the

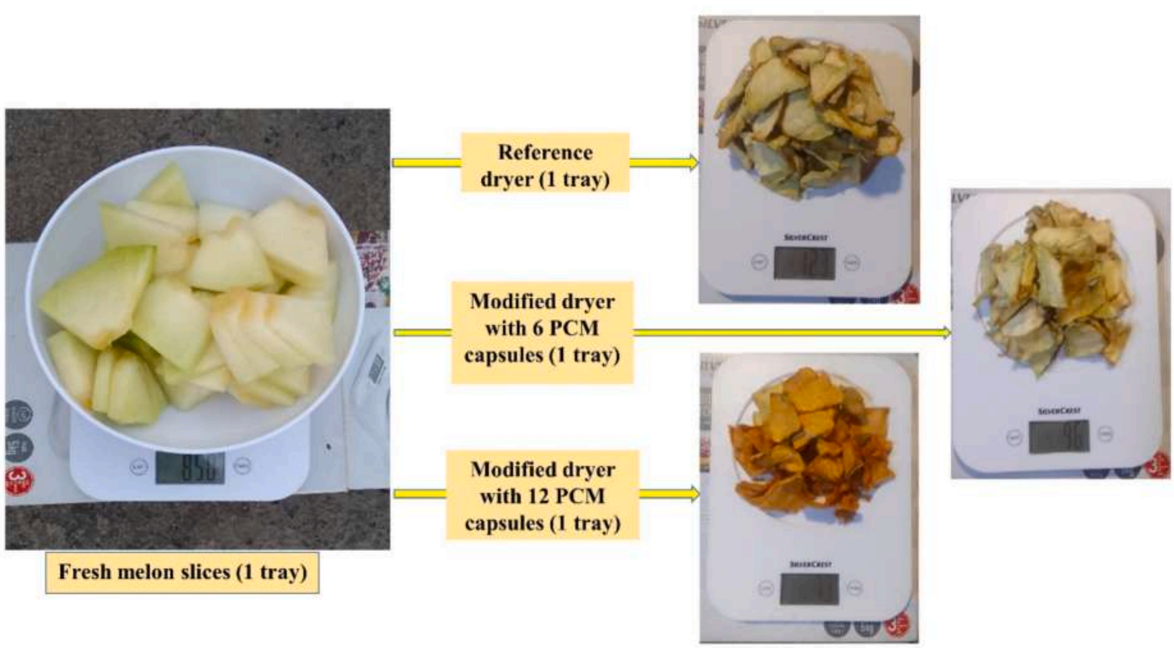

Fig. 8. Photo of moisture removed from melon slices by solar dryers.

maximum outlet temperature was 80.12 °C. Comparatively, equipping the FPSC with 6 PCM cans has increased the drying chamber temperature to 66.65 °C while the maximum outlet temperature was 77.02 °C. Therefore, doubling the number of PCM cans has achieved better moisture content removal from melon slices by up to 89.7 %, compared with 82.4 %, attributed to increased solar chamber temperature which accelerates the evaporative dry from melon slices. Besides, melon slices have high water content which requires high temperatures for a longer period inside the solar dryer chamber, which eventually increases the drying efficiency.

3.3. Energy analysis of solar dryers

Evaluating the useful heat energy gain and thermal efficiency of solar dryers is an important metric to comprehensively assess the solar dryer performance. Besides, harvesting excessive useful heat energy with high efficiency leads to faster drying of products with a shorter payback period and proper cost is a main feature of the solar dryer system. Fig. 9 demonstrates the useful heat energy obtained from solar dryers with and without PCM cans during the day and night. The temperature difference of solar dryer collectors in terms of T_o and T_i has a significant impact on the useful heat gain, which is variable from daylight hours to night. For reference solar dryer, the average useful heat gain has been approved due to the convergence of heat gain values during measurements. Through daylight hours, it could be observed that the useful heat gain of the reference solar dryer was higher than that integrated with 6 and 12 PCM cans at the beginning of the experiment until 10:50. This could be attributed to the partial heat charging into PCM cans during melting phase. The maximum calculated useful heat gain from the reference solar dryer collector was about 606.6 W and then lowered gradually. Integrating 6 PCM cans has lowered the useful heat gain compared to the reference solar collector during the first half of the day due to heat charging into PCM cans. Afterwards, the useful heat gain was increased to 630.4 W at 12:10 when the PCM cans were fully charged and started to work as an extra heat source. In the other case, integrating 12 PCM cans into the solar dryer's collector has increased the useful heat gain to a maximum of 671.3 W against 612.8 W due to duplicating PCM cans which maximized the outlet temperature.

The PCM inside cans is influenced by the changeable temperature during the day and night while transitioning from melting to solidification phases, and vice versa. During the day, the useful heat gain gradually increased with a temperature rise at a specific influence on the useful heat gain during early morning hours compared with the reference solar dryer since part of the harvested heat by the FPSC is worked to melt the PCM, effecting the drying process. Accordingly, the drying chamber of the dryer-equipped PCM cans examines a temporary decrease of heat which impacts the drying process. As the PCM melts entirely, a significant amount of heat is expected to be stored in latent form inside PCM cans, leaving a notable influence on the drying chamber temperature. This behaviour is obvious in Fig. 9 around 11:00 in both 6 and 12 PCM cans cases. Afterwards, the PCM inside cans is expected to reach its full storage capacity and no heat is charged any more, stabilizing the drying temperature and increasing the useful heat gain in the solar chamber till the night time. Overall, PCM cans work to enhance the useful heat gain of the solar dryer and enrich the drying process with stabilized heat for a longer time, enhancing the drying process.

Increasing the solar collector outlet temperature has a noteworthy influence on accelerating the moisture removal of the product due to the inverse relationship between the increased temperature and moisture content removal. Fig. 10 displays the thermal efficiency of the solar dryers during daylight and night hours. The figure undoubtedly indicates the positive influence of PCM cans on the solar dryer's thermal efficiency, specifically from the afternoon to the end of the day. During the daylight hours, integrating PCM cans increased useful heat gain, which was visualized from 11:20 until the end of the experiment period, which was more than that obtained from the reference solar dryer. Increased useful heat gain has a major role in determining the thermal efficiency of the solar dryer system. Accordingly, incorporating 6 PCM cans into the solar air collector has augmented the thermal efficiency to a maximum of 63.8 %, against 61.3 %, while the maximum thermal efficiency of 12 PCM cans incorporated collector and reference one was about 68.4 % and 61.6 %, respectively. The thermal efficiency of the reference solar dryer is equal to zero at 18:10 since the input energy became zero (i.e., $Q_i = 0$) as the solar radiation was zero at sunset. On the other hand, incorporating PCM cans has improved thermal efficiency after sunset with superior performance for the dryer with 12 PCM cans till the day end. This is undoubtedly attributed to the massive amount of heat stored in the 12 PCM cans which work to sustain the temperature inside the solar dryer for a longer time during the PCM solidification period.

Increasing the number of PCM cans indicates more heat to be captured from the sun during the charging phase. As a result, more total heat storage capacity is available for the drying process which eventually increases the dryer's thermal efficiency. As PCM can reach the full melting phase, the temperature inside the drying chamber is augmented since the PCM cans provide an extra heat source, maintaining a higher temperature for the solar dryer-equipped PCM cans compared with the reference one, as presented in Fig. 6. After sunset, the PCM cans begin discharging heat as the solar radiation disappear and ambient temperature drop, corresponding to the PCM quantity in each case. This would demonstrate the importance of PCM as a thermal energy medium to

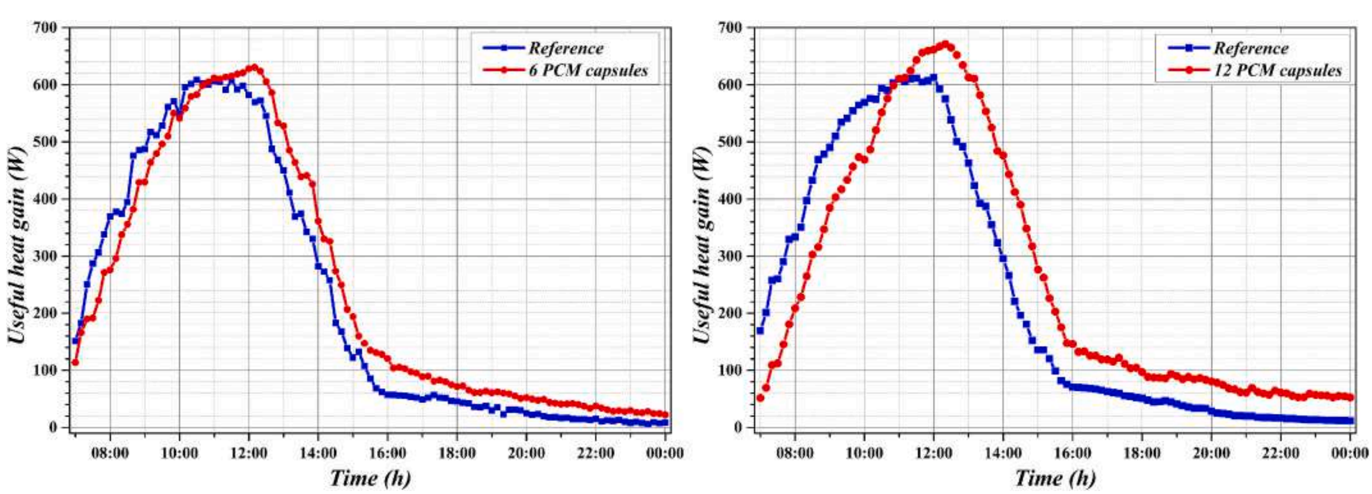

Fig. 9. Useful heat gain of solar dryers.

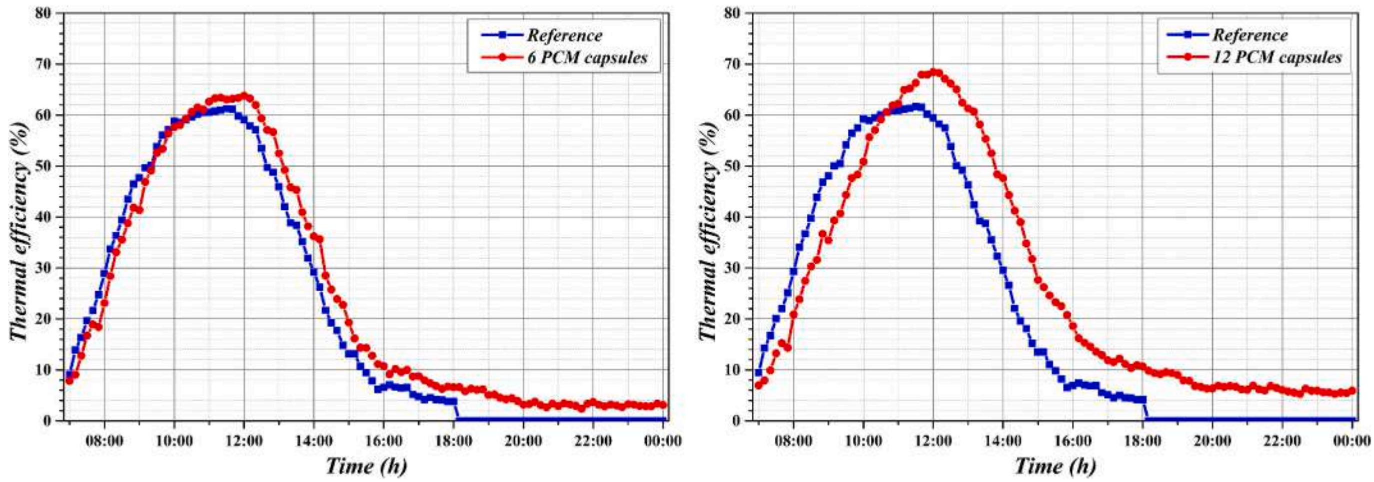

Fig. 10. Thermal efficiency of solar dryers.

prolong the drying process at night, improving the thermal efficiency notably compared with the reference dryer, as displayed in Fig. 10. In addition, higher heat stored inside dryers would prolong the time of which the dried melon slices are kept dry with stable temperature during the drying process.

3.4. Exergy analysis of solar dryers

Evaluating exergy is an important metric to show the maximum work gained from a solar dryer when it is in equilibrium with the environment. To understand the dryer's actual thermal performance, it is essential to calculate the exergy gain and thermal exergy efficiency obtained when the performance of the solar dryer collector is directly proportional to the dryer chamber's performance. Fig. 11 demonstrates the exergy gain with and without integrating PCM cans during the experiment period. It could be perceived that the exergy gain of the reference solar dryer was higher than the dryers modified with PCM cans in the early morning hours till 11:20 and then gradually lowered afterwards. Conversely, dryers integrated with PCM cans showed better exergy gain after 11:20 till the end of the thermal cycle since the PCM cans effectively provided extra heat supply until late night hours. The maximum exergy gain of the solar dryers was achieved in the midday at about 576.5 W for the reference dryer and bout 582.8 W for the dryer equipped with PCM cans. Besides, the exergy gain calculated for the solar dryer with 12 PCM cans reached a maximum of 593 W, while the reference dryer showed a maximum of 578.6 W. The increased number of PCM cans has a decent effect on the increased exergy gain specifically in the afternoon when provided heat to the dryer chamber. The growing exergy gain of the reference solar dryer in the early morning could be attributed to the looseness of heat provided by the solar collector to be stored in PCM cans for later usage. Nevertheless, PCM dryers achieved increasing exergy gain more than the reference solar dryer in total, which increased the exergy efficiency eventually.

Fig. 12 displays the exergy efficiency of dryers that was determined from Eq. (7) until sunset at 18:00 when the solar radiation values equalled zero. The exergy efficiency improvement in the solar dryers integrated PCM cans was superior to the reference dryer although the exergy efficiency was higher for the reference one in the early morning. The maximum exergy efficiency was calculated for the solar dryer integrated 12 PCM cans with about 19.96 % at 12:20, while the reference dryer achieved a maximum of 17.2 %. Besides, the maximum exergy efficiency of the solar dryer integrated 6 PCM cans reached about 18.3 %, while the reference solar dryer achieved a maximum of 17.5 % in the midday too. The exergy rate was increased in the solar dryer chamber during the earlier hours of experiments until midday and reduced at the beginning of the evening due to the deficiency of solar radiation. The exergy losses were affected by the inflow and outflow of exergy in solar dryers during the experiment period, in addition to the moisture content impact. In this regard, the uppermost drying rate was exhibited in the first hours of the drying process until the afternoon, then the exergy losses get lower with reduced product moisture content due to reduced temperature. The experiments revealed that the exergy loss values are variable depending on the input and output exergy gain, in which the exergy loss of the reference solar dryer was 153.52 W, while that of the

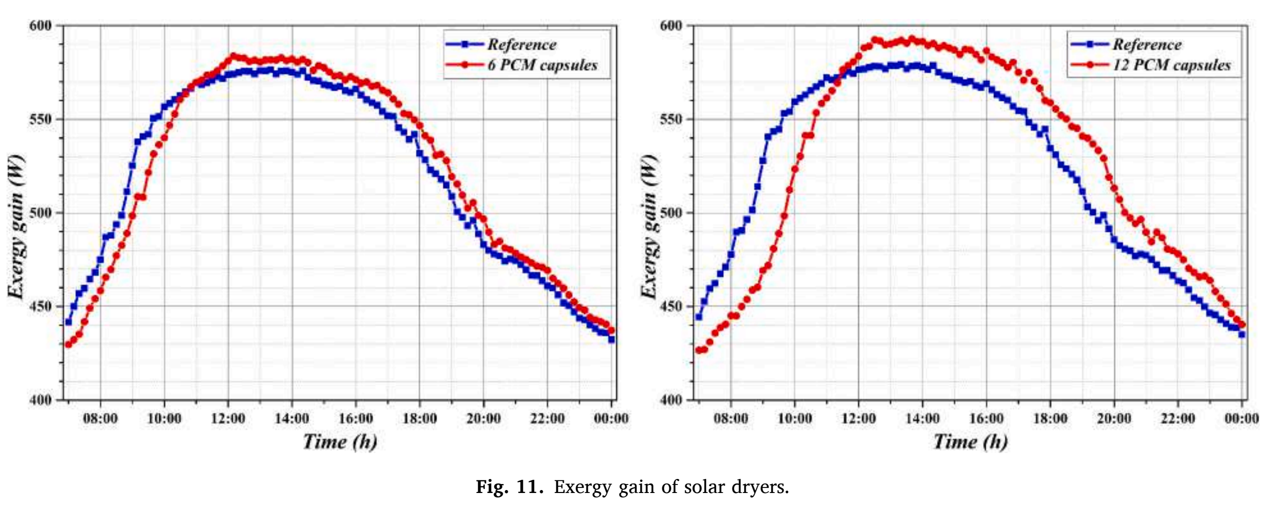

Fig. 11. Exergy gain of solar dryers.

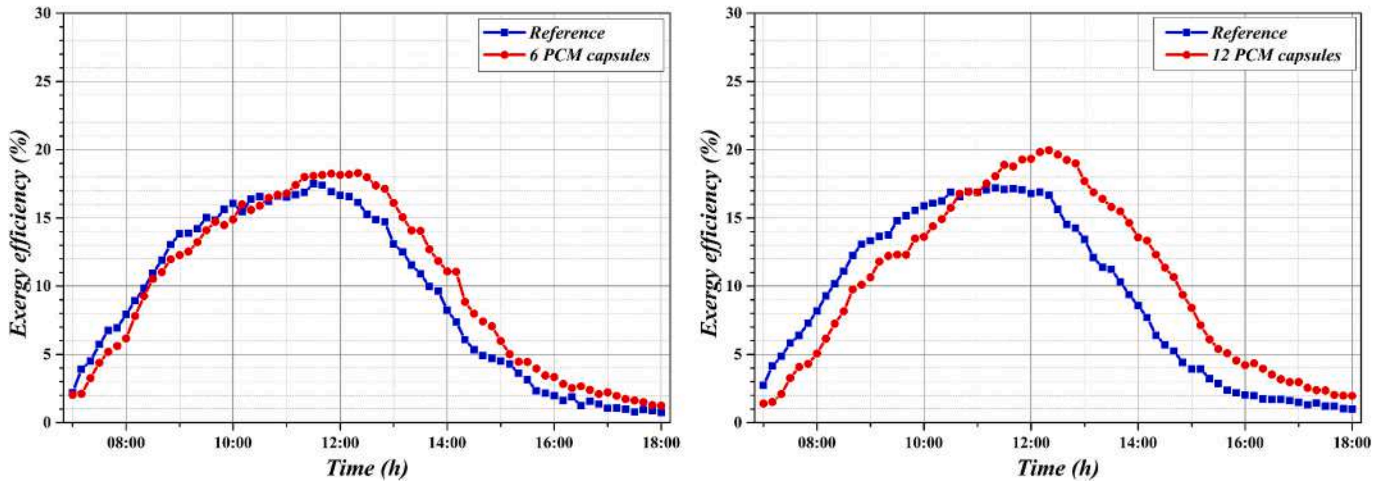

Fig. 12. Exergy efficiency of solar dryers.

dryer modified with 6 and 12 PCM cans reported 164.64 W and 177.35 W, respectively.

The sustainability index (SI) metric was calculated based on the exergy efficiency with and without PCM, which reported 2.21, 2.91, and 3.23 for the reference solar dryer, and the dryer integrated with 6 and 12 PCM cans, respectively. This indicates an improvement in solar dryer sustainability by about 32 % and 46 % when integrating PCM with 1 and 2 kg, respectively. The SI improvement is mainly attributed to the increased exergy efficiency of solar dryers as a result of increased WER in the current work by 5.46 for the reference solar dryer, and 5.82 and 6.11 for the dryer with 6 and 12 PCM cans, respectively. On the other side, the IP metric which shows the effectiveness of a solar dryer towards an environment in terms of the exergy efficiency and losses indicated remarkable outcomes for the PCM-integrated solar dryer. In this regard, the calculated IP for the reference solar dryer and the one integrated with 6 and 12 PCM cans was respectively about 0.049, 0.62, and 0.81 kW.

Conclusively, the inlet and outlet temperatures of solar dryers have the main role of specifying the exergy and exergy efficiencies, as indicated in Eqs. (7), (8), and (9). PCM cans are expected to be in a solid phase at 7:00, melting and charging heat as the time progresses towards 11:20 which affects the outlet temperature of modified dryers. Then, lower exergy gain and exergy efficiency are observed in this period, with a better performance for the reference dryer. As the case after 11:20 when the PCM reached the full melting phase, PCM cans provided extra heat to the air steam towards the drying chamber. This process augments the exergy and exergy efficiencies of the modified dryer, performing better than the reference one, and increases the exergy gain and efficiency due to extra heat supply until night hours.

3.5. Economic analysis

The energy payback period (EPB) could be estimated using Eq. (15) concerning the embodied energy and the annual energy output. The embodied energy of the reference solar dryer parts was 504.917 kWh, while that of the modified dryer with 6 and 12 PCM cans was respectively 531.117 kWh and 557.317 kWh. Besides, the annual energy output is a result of multiplying the solar radiation by working days, thermal efficiency, number of sunshine hours and collector area [46]. Considering the drying process under the maximum solar radiation of 1223 W/m^2, the working time of the reference dryer was about 12 hr per day, while the solar dryer modified with 6 and 12 PCM cans was extended to work for 18 hr a day. In addition, with the maximum thermal efficiency of dryers and 180 working days per year, the annual energy output can be calculated. The calculated EPB showed that the solar dryer without PCM was about 6.38 years, while it reduced to 4.23 and 4.14 years when integrating 6 and 12 PCM cans with the same solar dryer. The EBP obtained defends the benefit of using PCMs to improve the performance of solar dryers.

The economic analysis performed on the solar dryers with a lifetime of 7 years and 12 % interest rate showed that the capital recovery factor (CRF) was 0.12 of the initial investment when the operation period was 180 days, and the initial capital expense was 352500, 352500, and 358,500 IQD for the reference dryer, dryer with 6 and 12 PCM cans, respectively. Concerning the capital cost of the solar dryer and the CRF, the FAC determined for the reference solar dryer was about 46.776 IQD, 47.377 IQD for a dryer integrated with 6 PCM cans, and 48.18 IQD for the one with 12 PCM cans. The annual salvage value (ASV) was variable due to various PCM cans which were increased as the number of PCM cans increased, as indicated in Table 5. The annual maintenance cost (AMC) values deviate according to the number of PCM cans used as heat storage units. Accordingly, using 12 PCM cans achieved 8.08 AMC, and this value decreased with lower PCM cans. The annual cost (AC) is affected by the ASV, AMC, and FAC, and these parameters are influenced by the PCM capsule's cost specified in Table 5. The current work proves that the solar dryer with PCM units is economically feasible due to the lower cost of hot air produced by solar collectors and achieves a payback period of 1.2–1.6 years depending on the interest rate, savings, and other associated costs.

4. Conclusion

In the current research, a solar dryer integrated with phase change material (PCM) cans was designed, fabricated, and tested to dry melon slices under harsh weather conditions against a reference one. The modified dryer was assessed considering various energy, exergy and economic parameters loading 1 and 2 kg of PCM. Key conclusions derived from the achieved findings in the study are as follows:

- Integrated PCM has a superior role in sustaining the drying process during nighttime, acting as an extra heat source during the day, and improving the drying process and efficiency.

Table 5
Evaluation of economic parameters (in IQD).

Solar dryer	IC	CRF	FAC	ASV	AC	AMC	CPL
Reference	352,500	0.12	46.776	2.15	73.74	7.64	0.0071
6 PCM	355,500	0.12	47.377	2.18	75.34	7.89	0.0068
12 PCM	358,500	0.12	48.18	2.21	69.79	8.08	0.0063

- The moisture content removal of dried fruit was notably improved by increasing PCM quantity in the solar dryer. Incidentally, the solar dryer equipped with 12 PCM cans achieved high moisture content removal by about 89.7 %, while the dryer equipped with the PCM quantity reported a maximum of 86.5 %.
- The maximum useful heat gain improvement of the modified dryer with 6 and 12 PCM cans was 3.9 % and 9.5 %, respectively, over the reference one.
- The modified dryers' thermal efficiency was improved by up to 2.5 % and 6.8 % loading 6 and 12 PCM cans, respectively.
- The solar dryer modified with 12 PCM cans achieved a maximum exergy gain, exergy efficiency, and sustainability index of 593 W, 20 %, 46 %, and 0.81 kW, respectively, indicating exceptional exergy advancements.
- Integrating PCM cans into the solar dryer is feasible to attain cost-effective solar dryers for food drying processes. The solar air collector has an intrinsic role in minimizing the payback period of the solar dryer by 1.2–1.6 years. Concerning the energy payback period, integrating 1 and 2 kg of PCM into the solar dryer could shorten the period by about 33.7 % and 35.1 %, respectively, compared with the reference dryer.

It is worth affirming that the outcomes of this research are restricted to the tested solar dryers, PCM type involved and examined harsh weather conditions. For upcoming research in this field, the current research could be extended by incorporating the following insights:

- Various fruit types with low water content could be tested, considering different PCM quantities. This would show different drying mechanisms, providing various economic visions.
- A numerical exploration could be conducted to verify the drying process under the PCM effect for a longer period. Besides, optimization methods could also be adapted to show further improvements in the system design and PCM quantity towards better system performance.
- The environmental benefits of adopting solar dryers with different enhancement methods could be explored to drag the technology towards the United Nations' sustainable development goals.

CRediT authorship contribution statement

Mohammed Alktranee: Writing – original draft, Investigation, Formal analysis, Data curation, Conceptualization. **Qudama Al-Yasiri:** Writing – original draft, Formal analysis, Data curation, Conceptualization. **Karrar Saeed Mohammed:** Writing – original draft, Methodology, Investigation, Data curation. **Müslüm Arıcı:** Writing – review & editing, Supervision, Formal analysis, Conceptualization. **Márta Szabó:** Writing – review & editing, Supervision, Project administration, Funding acquisition. **Péter Bencs:** Writing – review & editing, Supervision, Project administration, Funding acquisition.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

Data will be made available on request.

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