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Study of the Performance of an Indirect Forced Convection Solar Dryer Incorporating a Thermal Energy Storage Device on a Granite Bed for Drying Tomatoes

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Authors' contributions

This work was carried out in collaboration among all authors. All authors read and approved the final manuscript.

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ABSTRACT

Indirect solar dryers combining a solar collector and an enclosure enable the drying process to be run smoothly, with good quality dried products. However, when the process lasts longer than one day, some of the products may be damaged when the drying process is interrupted. The integration of a thermal storage system into indirect solar dryer systems can make up for the unavailability of solar energy and enable the drying process to continue over longer periods without the need for additional energy. With this in mind, the present study investigates the performance of a forced convection indirect solar dryer coupled with a thermal energy accumulator for drying tomatoes. The experiments were carried out with a drying air flow rate of 0.01 kg/s during the drying period. The air flow rate during storage tank charging was 0.013 kg/s. Solar drying performance with and without storage was compared. The results show that to reduce the water content in the dry tomato base from 16.78 kg_{water}/kg_{ms} to 0.125 kg_{water}/kg_{ms}, the indirect solar dryer requires 15 hours of cumulative sunshine spread over two drying days, while the indirect solar dryer coupled with the heat accumulator enables the water content in the dry base to be reduced from 19.81 kg_{water}/kg_{ms} to 0.117 kg_{water}/kg_{ms} over 17 continuous hours, i.e. approximately one sunny day and one night. The overall average efficiency of the indirect solar dryer with heat storage is around 23.31%, compared with 17.47% for the indirect solar dryer.

Keywords: Indirect solar dryer; thermal storage; solar collector; tomato.

NOMENCLATURES

C_{Pa}	*: Specific heat of drying air (J/kg.K)*
I_G	*: Overall solar irradiation at the surface of the collector (W/m²)*
L_v	*: Latent heat of water vaporization (J/kg)*
$\dot{m}_a$	*: Mass rate of the drying air (kg/s)*
m(t)	*: Instant mass of the product (kg)*
m_{water}	*: Mass of water evaporated (kg)*
m_0	*: Initial mass of the product (kg)*
m_{sec}	*: Dry mass of the product (kg)*
Q_{stck}	*: Total energy stored (W)*
Q_{destck}	*: Total energy discharged (W)*
S_{cap}	*: Surface of the solar collector (m²)*
t	*: Time (s)*
T_{in}	*: Entrance temperature of storage tank (K)*
T_{out}	*: Temperature at the exit of storage tank (K)*
$W_{pv,tot}$	*: Overall power provided by the values (W)*
X_0	*: Initial water content on dry basis of the product (kg_{water}/kg_{ms})*
X(t)	*: Water content on dry basis of the product at a moment (kg_{water}/kg_{ms})*
$\eta_{sech-stck}$	*: Efficiency of solar drying with storage*
η_{stck}	*: Efficiency of solar drying with overnight storage*
$\eta_{g,sech}$	*: Global efficiency of solar drying*

1. INTRODUCTION

Numerous studies have been carried out on solar thermal dryers in recent years. These studies have covered direct solar dryers, indirect solar dryers, hybrid solar dryers and mixed solar dryers [1,2]. Dryers can be classified according to their operating modes. In the case of direct solar dryers, the product is exposed directly to the sun's rays inside a glass enclosure, the inside of which is painted black. Indirect solar dryers generally consist of a solar collector and a drying chamber containing the products to be dried. The solar collector converts the sun's rays into heat and this heat is sent into the drying chamber either by forced convection (using a fan) or by natural convection (using a solar chimney) [3]. Mixed solar dryers combine the two solar drying methods (direct and indirect). Hybrid solar dryers use solar energy with other energy sources, the most commonly used of which are: electricity, gas, biomass and diesel [4]. However, burning fossil fuels is a source of pollution and is not appropriate in developing countries where fossil fuels are not available. The initiative to be encouraged in these regions is the use of dryers powered by renewable energy sources. Indirect solar dryers using forced convection provide good control over the drying process and good product quality. However, most of these solar dryers depend heavily on the effective presence of solar radiation. Solar energy is renewable, but it is not available every day and/or for the entire duration of the day. This intermittency of solar energy limits the applications of solar dryers when the drying time exceeds one day. Under these conditions, some of the products may be damaged when the drying process stops. The integration of a thermal storage system into indirect solar dryer systems makes it possible to compensate for the unavailability of solar energy and to keep the drying process going over long periods without the need for additional energy [5-7]. Solar energy can be stored in sensible, latent or thermochemical form [8]. Sensible heat storage is the oldest and best mastered of the other storage methods. The materials commonly used to store heat sensitively are water, rock, sand, concrete, etc. [8-10]. The aim of the present work is to develop a forced convection solar dryer with an integrated sensitive heat storage system for drying tomatoes. The storage system uses granite as the storage material because of its availability, its relatively lower cost, its interesting physical properties and its proximity to the experimental site. The experiments were carried out between March and April 2023. The performance of the forced convection solar dryer with and without heat storage and the drying characteristics of the tomato are discussed in this article.

2. DESCRIPTION AND OPERATING PRINCIPLE OF THE EXPERIMENTAL SET-UP

2.1 Description of the Experimental Set-Up

The solar dryer system studied consists of two solar collectors, a storage tank and a drying chamber. The two solar collectors measure 205 cm x 180 cm and 260 cm x 60 cm respectively. The first is connected to the drying chamber and the second to the storage tank. The absorbers are made up of several columns, 24 columns in the 1st collector and 9 columns in the 2nd collector. These columns are made from cylindrical aluminium tubes 5 cm in diameter and 13.5 cm long. They are completely open at one end (heat transfer fluid inlet) and have three 1 cm holes at the other (heat transfer fluid outlet). The tubes, 14 in number for the first collector and 17 for the second, are placed side by side along the entire length of the collector, with successive rotations of the bases used for the heat transfer fluid outlet to ensure that the outlet openings are not aligned. This configuration allows the heat transfer fluid to develop a turbulent effect for better heat exchange. All the columns of tubes are laid out on a sheet of 1mm-thick aluminium sheet and the whole thing is covered in matt black paint to ensure maximum absorption of solar radiation. Each collector is fitted with a fan that circulates the heat-transfer fluid air inside the columns of absorbing tubes. The collectors were placed on a support inclined at 12° to the horizontal and facing south according to the latitude of the Ouagadougou site (Burkina Faso). The cylindrical storage tank consists of a metal frame made from stainless steel sheet. It is insulated with 5 cm thick glass wool and covered with an aluminium sheet to protect it from the elements. The storage tank is 120 cm high and 60 cm in diameter. The drying chamber is cubic in shape, 1 m high, 0.5 m long and 0.5 m wide, giving a volume of 0.25 m^3. The drying chamber is made entirely of wooden plywood 0.025 m thick. The roof of the drying chamber is conical in shape. It has a chimney to allow moisture-laden air to escape after contact with the products. The entire drying chamber sits on a 0.5 m high wooden support above the ground, protected from running water. The door to the drying chamber is also made of plywood. Inside the drying chamber, there are two racks, each with a surface area of 0.25 m², to support the products to be dried.

2.2 Operating Principle of the Experimental Device

2.2.1 The operating principle of the experimental set-up is as follows

During the day (Fig. 1), the air heated by the solar collector is sent into the drying chamber by forced convection. As it passes through the drying chamber, the hot air exchanges heat with the product on the racks. It picks up moisture from the product and exits the drying chamber cooled through the chimney. During the same period, the air heated by the other solar collector is sent to the storage tank by forced convection for thermal charging. During this tank charging phase, the air arriving from the solar collector enters the top of the storage tank, exchanges its heat on contact with the crushed granite balls and exits through the bottom of the storage tank, having cooled down.

At sunset (during the night), the sensors are disconnected and the tank is connected to the drying chamber for the drying process to

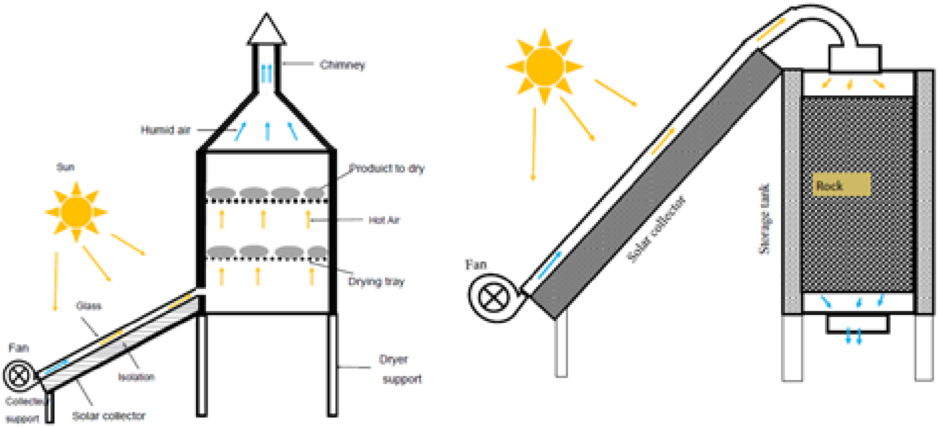

Fig. 1. Operation of the solar dryer and storage tank during the day

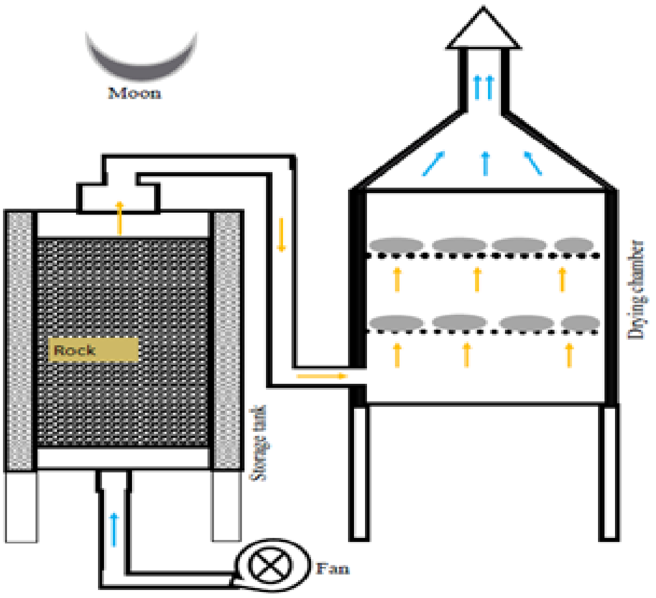

Fig. 2. Dryer operation after sunset

continue (Fig. 2). During this storage tank unloading phase, cold air is introduced at the bottom of the storage tank by forced convection using a fan. As it circulates through the tank in contact with the hot granite, it heats up and is sent into the drying chamber via a perfectly insulated connecting tube. In this way, the storage tank ensures the continuity of the drying process overnight until it is discharged, i.e. until the temperature at the tank outlet is close to the temperature of the ambient air.

3. MEASUREMENT INSTRUMENTS

Roughly six pre-calibrated type K thermocouples (measuring range: -100°C to 1370°C; accuracy ± 0.05% of reading + 1.0°C) were attached to different parts of the solar dryer and storage tank. All these thermocouples were connected to a data acquisition unit (midi LOGGER GL220), which recorded the data at 10-minute time intervals. Incident solar radiation was measured using an SR03 pyranometer. The humidity of the drying air at the dryer inlet and outlet and the ambient air was measured using an MSR 5.28.32 hygrometer accurate to ±2% for humidity and ±0.5°C for temperature. The air speed at the dryer inlet was measured using a testo 480 anemometer (accuracy ±0.03m/s). An electronic balance with an accuracy of ±0.01 g was used to weigh the samples.

4. EXPERIMENTAL PROCEDURE

The tomatoes used in our experiment were bought fresh from the local market and selected uniformly on the basis of very specific criteria. These criteria included size, degree of ripeness and external shape. The selected tomatoes were washed in lukewarm water to remove impurities, then cut into 1cm-thick slices. The sliced tomatoes were placed on the various trays (around 1.125 kg for each tray). The experimental measurement protocol consisted mainly of measuring temperature, relative humidity, sample mass and drying air velocity. The initial water content was calculated by taking three different samples. The air speed at the entrance to the drying chamber was set at 1 m/s. The drying experiments during sunny periods lasted about 10 hours, and those carried out with the storage tank lasted about 6 hours. The experiments were repeated three times and an average value was taken for the analyses. The process is stopped when the wet mass of the product reaches its final moisture content of around 11%. To determine the dry mass of the product, samples were taken from the racks at the end of the drying process. These samples were weighed and placed in an oven at 70°C for 24 hours.

4.1 Determination of Water Content

All food products are characterised by their water content. The initial moisture content on a dry basis X0 is the weight of moisture present in the product per unit weight of dry matter in the product and the instantaneous moisture content X(t) is the weight of dry matter in the product over a period t are determined using the following formulae [11]:

$$\mathrm{X}_0 = \frac{\mathrm{m}_0 - \mathrm{m}_{\mathrm{sec}}}{\mathrm{m}_{sec}} \tag{1}$$

$$\mathrm{X(t)} = \frac{\mathrm{m(t)} - \mathrm{m}_{sec}}{\mathrm{m}_{sec}} \tag{2}$$

With the initial mass m_0 of the product in kg, the dry mass m_{sec} of the product in kg and the instantaneous mass $\mathrm{m(t)}$ of the product in kg.

4.2 Determining the Thermal Efficiency of the Dryer

The efficiency for an indirect solar dryer system with thermal storage can be defined as follows:

- Dryer efficiency during the day: ratio of the energy used to evaporate the water contained in the product during the day to the sum of the energy supplied to the drying chamber during the day:

$$\eta_{sech\text{-}stck} = \frac{m_{\mathrm{water}} L_v}{I_G S_{cap} t - Q_{\mathrm{stck}} + W_{\mathrm{pv,tot}} \times t_{\mathrm{day}}} \times 100 \tag{3}$$

- The efficiency of the dryer during the night: ratio of the energy used to evaporate the water contained in the product during the night to the sum of the energy supplied to the drying chamber during the night:

$$\eta_{stck} = \frac{m_{\mathrm{water}} L_v}{Q_{\mathrm{destck}} + W_{\mathrm{pv,tot}} \times t_{\mathrm{night}}} \times 100 \tag{4}$$

- The thermal efficiency of an indirect solar dryer ($\eta_{g,sech}$) is defined as the ratio between the total energy required to dry a given quantity of product and the solar energy received at the collector surface during the drying period (5) [12].

$$\eta_{g,sech} = \frac{m_{\mathrm{water}} L_v}{I_G S_{cap} t + W_{\mathrm{pv}} \times t} \tag{5}$$

- With respectively $\mathrm{Q}_{\mathrm{stck}}$ and $\mathrm{Q}_{\mathrm{destck}}$ the total energy stored during the day (equation (6)) and the total energy removed during the night (equation (7)).

$$\mathrm{Q}_{\mathrm{stck}} = \int_{\mathrm{t}_0}^{t_{\mathrm{end}}} \dot{m}_{\mathrm{a}} C_{\mathrm{Pa}} \left(T_{\mathrm{in}} - T_{\mathrm{out}}\right) dt \tag{6}$$

$$\mathrm{Q}_{\mathrm{destck}} = \int_{\mathrm{t}_0}^{t_{\mathrm{end}}} \dot{m}_{\mathrm{a}} C_{\mathrm{Pa}} \left(T_{\mathrm{out}} - T_{\mathrm{in}}\right) dt \tag{7}$$

5. RESULTS AND DISCUSSION

5.1 Change of the Ambient Temperature and the Solar Radiation

Figs. 3 and 4 show the evolution over time of the ambient temperature and solar irradiation arriving on the solar collector surfaces during indirect solar drying experiments with and without a storage tank. These different curves show the same trends, i.e. they increase progressively over the course of the day, reaching their maximum between 11am and 1pm and then decreasing progressively at the end of the day. The maximum values of ambient air temperature and solar irradiation during the test phases of indirect solar drying with and without storage tank are 42.3°C and 901 W/m² and 42.5°C and 925 W/m² respectively.

5.2 Change in Temperature at the Entrance to the Drying Chamber and on the Various Drying Racks

Figs. 5 and 6 illustrate the evolution, as a function of drying time, of the air temperature at the outlet of the solar collector and of the temperatures at the level of the two racks during indirect solar drying with and without a storage unit. These temperatures show the same trends as before. After sunset, the storage tank is connected to the drying chamber. Once again, we see an increase in air temperature at the entrance to the drying chamber and also at the level of the two racks. They reach their maximum and then gradually decrease until the end of the discharge. The temperature difference between racks 1 and 2 shows that the tomato slices on rack 1 dry more quickly than those on rack 2. The maximum temperature values obtained during the day of solar drying without storage are respectively 96°C for the temperature at the outlet of the solar collector, 55.5°C for the temperature of tray 1 and 49.3°C for the temperature of tray 2 (Fig. 6). Those recorded during the test day of indirect solar drying with energy storage are 99.8°C, 60.4°C and 52.5°C respectively for the air temperature at the dryer inlet, on rack 1 and rack 2 (Fig. 5). The maximum temperature supplied by the tank to the drying chamber during the night is 55.6°C. The maximum temperatures for rack 1 and rack 2 were 45.7°C and 40.2°C respectively.

5.3 Evolution of Tomato Drying Kinetics

Figs. 7 and 8 show changes in the water content (on a dry basis) of the tomatoes on the various drying racks as a function of time. The water content curves in the two figures do not show any phases in which the product is brought up to temperature or drying at a constant rate. This has also been noted in previous studies on tomato drying [2,13,14]. Experimental water content trends in the two drying racks followed a decreasing trend as a function of drying time.

The initial water content of the tomato during solar drying with energy storage (Fig. 7) fell from 19.8 $\mathrm{kg_{water}/kg_{ms}}$ to 2.85 $\mathrm{kg_{water}/kg_{ms}}$ at the end of the first day of drying and from 2.85 $\mathrm{kg_{water}/kg_{ms}}$ to 0.5 $\mathrm{kg_{water}/kg_{ms}}$ during the night. During the second day of drying, the water content rose from 0.26 $\mathrm{kg_{water}/kg_{ms}}$ to 0.115 $\mathrm{kg_{water}/kg_{ms}}$. For indirect solar drying without a storage unit (Fig. 8), the water content fell from 16.8 $\mathrm{kg_{water}/kg_{ms}}$ to 2.2 $\mathrm{kg_{water}/kg_{ms}}$ at the end of the first day of drying and to 0.103 $\mathrm{kg_{water}/kg_{ms}}$ at the end of the second day of drying.

The duration of indirect solar drying with storage was 17 hours (i.e. approximately one day and one night) whereas that of indirect solar drying without a storage unit was 15 hours (i.e. approximately two days of sunshine). This decrease in drying time shows a high drying rate during the night during the indirect solar drying process with storage compared to indirect solar drying without storage. The reduction in drying time helps to preserve product quality [1,6,15]. The final moisture content of the wet-base product during indirect solar drying was 11.11% and that of indirect solar drying with storage was 10.34%. These results are in line with those obtained by Sinon et al. [13], who obtained a final water content in the wet base of 9.1% during experimental tomato drying with a convective dryer. These results are also close to those obtained by BOUGHALI Slimane et al. [16] in a study on the optimisation of solar drying of agri-food products in arid and desert areas, which gave a value of 11%.

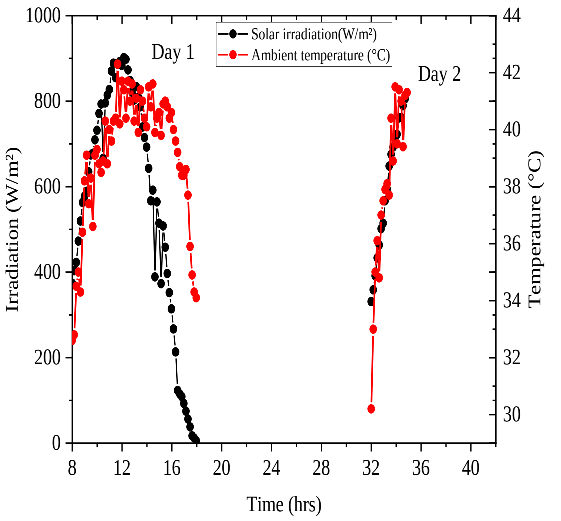

Fig. 3. Evolution of solar irradiation and ambient temperature during solar drying with storage

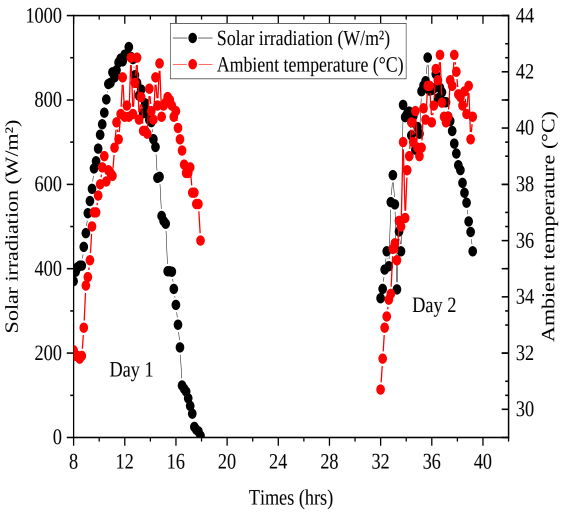

Fig. 4. Evolution of solar irradiation and ambient temperature during solar drying without storage unit

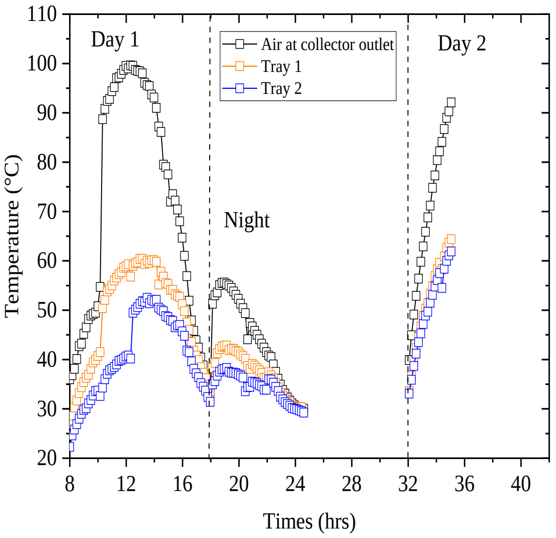

Fig. 5. Evolution of the temperature at the collector outlet and the temperature of the racks as a function of time for solar drying with energy storage

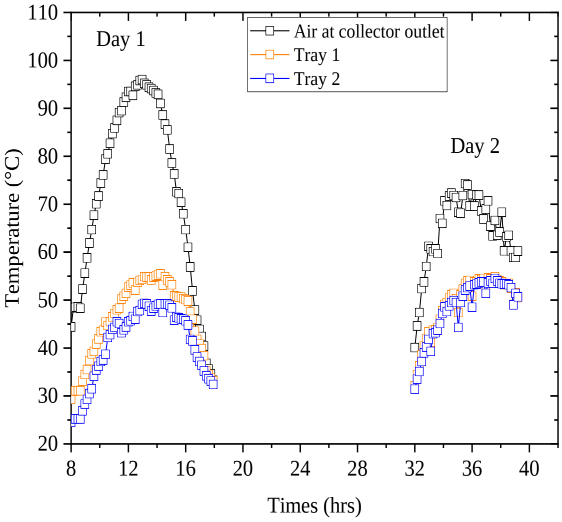

Fig. 6. Evolution of the temperature at the collector outlet and the temperature of the racks as a function of time for solar drying without energy storage

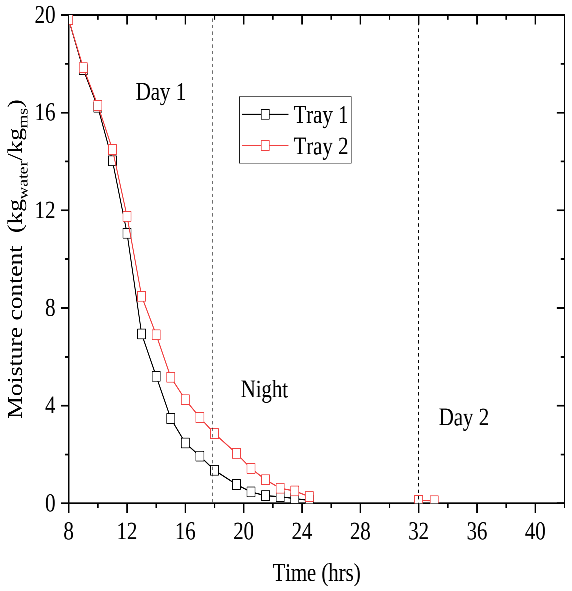

Fig. 7. Changes over time in the water content of the product during the indirect solar drying process with a thermal storage system

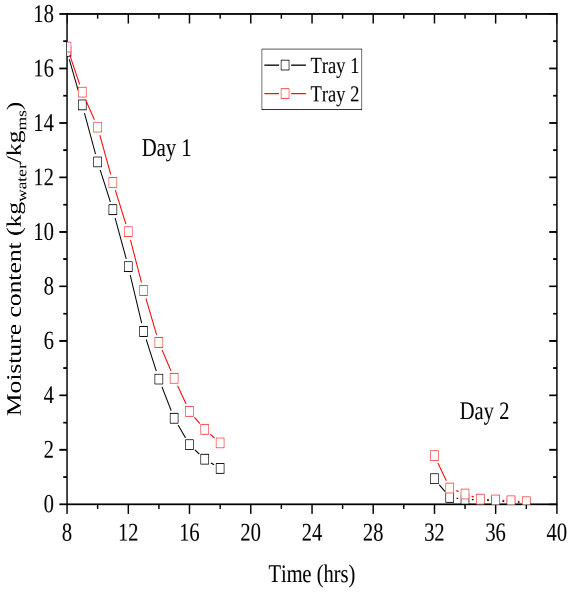

Fig. 8. Changes over time in the water content of the product during the indirect solar drying process

Table 1. Contribution of the solar collector and storage tank to indirect solar drying with energy storage

Solar drying with storage (test of 25-26/03/2023)	**Day 1 (Solar collector)**	**Night (Storage tank)**	**Day2 (Solar collector)**	**Total**
Average drying energy (kWh)	19.53	5.938	0.3845	25.852
Average energy consumed by tomatoes (kWh)	8.18	0.374	0.00231	8.55
Fraction of energy consumed(%)	41.88	6.29	0.6	33,07
Times (hours)	10	6	1	17
Overall average drying efficiency (%)	22.3	1.01	0.0063	23.31

Table 2. Energy contribution of the solar collector to indirect solar drying

Solar drying (test of 31/03/2023-01/04/2023)	**Day 1 (Solar collector)**	**Night (Storage tank)**	**Day2 (Solar collector)**	**Total**
Average drying energy (kWh)	21.11	-	11.7	32.81
Average energy consumed by tomatoes (kWh)	6.578	-	0.1816	6.7596
Fraction of energy consumed (%)	31.12	-	1.55	20.6
Times (hours)	10	-	5	15
Overall average drying efficiency (%)	17	-	0.47	17.47

5.4 Contribution of Solar Energy and Storage Tank in the Indirect Solar Dryer System and Tomato Drying Efficiency

The energy contributions of the solar collector and storage tank during indirect solar drying with and without energy storage are presented above in Tables 1 and 2 respectively. The average energy contribution of the solar collector and storage tank provided during indirect solar drying with storage unit is 25.852 kWh for the test of 25-26/03/2023, with an average energy contribution of the storage tank during the night of 5.938 kWh. Excluding the energy consumed by the fans, only 33.07% of the energy supplied by the two systems (collector and accumulator) was consumed by the product during the entire drying process. Under these conditions, the fraction of energy consumed by the products during the night is 6.29%. If the energy consumed by the fans is included, the overall average efficiency of indirect solar tomato drying with storage unit is 23.31%. This result is close to the energy contribution of a hybrid solar-gas dryer for tomato drying obtained by López-Vidaña et al. [17]. In fact, of the energy supplied by the solar collector and the combustion of the gas burner, only 33% was used for tomato drying. This is higher than the overall drying efficiency of 21% obtained by Mohanraj et al. [18] in their study of the thermal performance of a forced convection solar dryer incorporating a gravel bed as a heat storage material for drying peppers.

The total energy contribution of the solar collector to the indirect solar drying system without storage during the two successive sunny days (31st March to 1st April) was 32.81 kWh. However, due to heat losses through the solar dryer, only 20.6% of this energy was consumed by the 2.25 kg of tomatoes. The overall average yield of indirect solar drying was estimated at 17.47%. This result is comparable to the contribution of solar energy from the solar collector to tomato drying obtained by López-Vidaña et al. [17], who found that only 16.22% of the energy supplied by the collector was used for tomato drying [19].

6. CONCLUSION

The performance of integrating a sensitive thermal energy storage system on a rock bed was studied experimentally for tomato drying. The results showed that the storage system made an effective contribution (around 5.938 kWh) to the energy supply of the dryer during the night. This reduced the tomato drying time by around a day. This is interesting for products with a high water content, as reducing the drying time means that organoleptic properties such as vitamins and the colour of the product are preserved, as well as reducing the risk of mould. The final moisture content of the tomato wet base at the end of the indirect solar drying was 11.11% and that of the indirect solar dryer with storage was also 10.34%, which is in line with the literature. The use of an indirect solar dryer with a heat storage system improves the overall efficiency of the system, which averages 23.31% compared with 17.47% for the indirect solar dryer without storage. However, the performance of the indirect solar dryer system with storage unit can be improved by significantly reducing the heat losses through the dryer.

DISCLAIMER (ARTIFICIAL INTELLIGENCE)

Author(s) hereby declare that NO generative AI technologies such as Large Language Models (ChatGPT, COPILOT, etc) and text-to-image generators have been used during writing or editing of manuscripts.

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COMPETING INTERESTS

Authors have declared that no competing interests exist.

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