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Enhancing Solar Drying Efficiency Through Indirect Solar Dryers Integrated with Phase Change Materials

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ABSTRACT

Since time immemorial, solar radiation has been harnessed for drying a myriad of products such as vegetables, fruits, fish, and meat, primarily through direct exposure to sunlight for moisture removal and desiccation. In recent years, the incorporation of Thermal Energy Storage (TES) systems, capable of storing thermal energy in various states, has emerged as a pivotal innovation for enhancing energy efficiency and utilization. This study elucidates the development and performance evaluation of an indirect-mode solar dryer, augmented with Phase Change Materials (PCMs) for food dehydration. The solar dryer, operating in an indirect mode, channels solar radiation as the heat source from the collector's inlet, directly linked to the drying chamber. Within this setup, potato slices were subjected to dehydration under controlled conditions. The peak temperature recorded in the dryer was 63°C, with the relative humidity plummeting to 40%. Initial moisture content of the potato slices was determined to be 78.58% (w.t). The experimentation, involving a 1kg sample, revealed a marked improvement in drying efficiency with the integration of PCMs. The sample attained the target moisture content of 10% (w.t) in a span of 24 hours with PCM, compared to 33 hours in its absence. Conventional sun drying methods, without any enhancements, necessitated 38 hours for reducing the moisture content to the same level. Notably, the application of a single container of PCM resulted in a 3.26% reduction in heat flux, while the utilization of two different types of wax as PCMs yielded a 2.24% reduction. These findings underscore the significant role of PCMs in optimizing the thermal performance of solar dryers, promising substantial advancements in the field of solar drying technologies.

1. INTRODUCTION

Solar drying is a cutting-edge and endorsed technique that efficiently addresses the problems of product degradation and reduction in quality. It is progressively gaining acceptance. The technology can be classified into two main categories: direct solar drying and indirect solar drying. The process of solar drying can be carried out through either direct or indirect means, with the latter option proving to be notably more efficient in terms of the resulting product quality post-drying. The usual and fundamental method for drying cereals and other things is known as direct drying. This approach involves exposing the products directly to sun radiation, allowing the moisture to escape into the atmosphere. Furthermore, the fluctuation in drying temperatures resulting from climatic shifts will have an effect on the quality of food products during the drying process. These limitations can be alleviated by utilizing two forms of PCM, specifically medical and industrial. Many researchers have conducted comparative studies on thermal systems for solar air collectors, examining the differences between systems with and without PCMs.

2. LITERAURE REVIEW

Gatea [1] created a sun drying device in the form of a cylinder and evaluated the effectiveness of a heat drying system. The system is designed to dehydrate a 70 kg bean crop and includes a solar collector plate of 1.10 m in length and 1.10 m in width, a cylindrical drying chamber, and a fan. The efficiency of the solar air collector has been evaluated using three different air flow rates. The solar collector outlet reached its peak temperature of 71.4 degrees Celsius around 11 a.m. At a radiation intensity of 750 W/m^2, the measured air flow rate was 0.0401 kg/s. When the air flow rate increased to 0.0675 kg/s, a minimum temperature of 40.0°C was obtained at a radiation level of 460 W/m^2. The solar air collector exhibited an average thermal efficiency that varied between 18.63% at the lowest air flow rate of 0.0405 kg/s and 25.64% at the highest air flow rate of 0.0675 kg/s. For the purpose of drying cashews, Dhanushkodi et al. [2] developed an indirect forced convection solar dryer that has a capacity of 40-50 kilograms. As part of the performance analysis, measurements were taken for the drying rate, thermal efficiency, air flow rate, and temperature of the input or output air. The relative humidity decreased from 10% to 4% in six hours. The results demonstrated that forced convection is an effective drying method. By situating parabolic reflectors on both sides of the solar dryer, its efficiency can be increased.

Bharadwaz et al. [3] have created a forced convection indirect solar drying method specifically for preserving food. In order to make it more cost-effective, locally accessible materials were utilized in its design. The solar collector propelled the warm air into the dryer using a mechanical pump. Internal baffles were incorporated within the solar collector to facilitate the passage of non-linear airflow from the intake to the outflow. The food items were kept within the dryer in rows of horizontal piles of stainless steel trays. Desiccant silica gel packets were also added, acting as a source of moisture absorption inside the drying chamber. Variations in the experiment's solar collector, drying chamber, and outside temperature were noted. The drier's thermal efficiency was determined to be roughly 13.8%, while the average efficiency of the collector was measured to be 38.5%. Elevated temperature, enhanced circulation, and reduced relative humidity accelerate the drying process of the dryer. El-Sebaii et al. [4] designed a solar dryer with indirect natural convection. The setup comprises a flat-plate solar air heater connected to a cabinet serving as a drying chamber. The air heater is designed to allow for the placement of various storage objects underneath the absorber plate, hence enhancing the drying process. Sand serves as the storage medium. They tried both storage-based drying and storage-free drying of various fruits. The seedless grapes reached their equilibrium moisture content within 60 and 72 hours when the method was used with and without storage material, respectively. The storage substance significantly reduced the drying time by 12 hours. The goods were partitioned into sections and subjected to chemical treatment by immersing them in a solution consisting of 0.4% olive oil and 0.3% sodium hydroxide for a duration of 60 seconds. This treatment was employed to expedite the process of drying. Vijayakumar et al. [5] designed and tested a new form of indirect natural convection solar dryer that is highly efficient. To mitigate the effects of sun-induced fading, the product in this dryer was positioned below the absorber plate. Two axial flow blowers were utilized at the air entrance to accelerate and regulate the drying rate. A quantity of 4 kilograms of bitter gourd was placed in the drier. The bitter gourd had an initial moisture level of 95%. After 6 hours, the bitter gourd reached the desired moisture content of 5% without any loss of color. In comparison, it took 11 hours for the bitter gourd to reach the same moisture content using open solar drying. The projected price of 1 kilogram of bitter gourd is Rs. 17.52, and the cost of an electric dryer is also Rs. The solar dryer was expected to have a lifespan of 20 years, and its payback period was determined to be 3.26 years. They ultimately concluded that the quality of the dehydrated items was equivalent to that of branded products available on the market. Berinyuy et al. [6] developed and built a solar tunnel drier with a double-pass system and incorporated heat storage. They assessed its effectiveness in drying green vegetables and other agricultural goods by utilizing locally sourced resources. The dryer's surface receives a daily solar energy of 12.13 kJ/m^2. The dryer is oriented with a 6° southward slope. The dryer's internal temperature, thanks to its heat storage system, remained 5 degrees Celsius higher than the ambient air temperature far into midnight. In a span of five days, the drier effectively decreased the moisture content of 17 kg of sliced cabbage from 95% (wet basis) to 9% (dry basis). Their conclusion was based on the following metrics: An overall efficacy of 17.68%, a moisture extraction efficiency of 79.15%, and an airflow rate of 9.68 m^3/hr. They put the dryer through its paces on various high-moisture items and found that, depending on the item, it might cut drying time by 30% to 50%.

In accordance with IS 1933, 2003, Salve and Fulambarkar [7] created and constructed a solar air collector within a controlled laboratory environment. The total performance of a newly constructed solar collector is evaluated by using three different mass flow rates (0.01 kg/s, 0.008 kg/s, and 0.006 kg/s) to dry 15 kg of green chilies. To account for the critical radius of the insulation, a selective coating substance, consisting of a mixture of activated charcoal and black board paint, is applied to the curved cylindrical surface of the tubes. For different mass flow rates, the air temperature at the intake and outflow has been monitored, and the overall collector efficiency has been computed. Additionally, throughout the day, measurements of the rate of moisture evaporation from green chilies are taken every 30 minutes. Research has revealed that an increase in the mass flow rate leads to a decrease in efficacy. The optimal moisture extraction rate is shown to be 88% when the mass flow rate is 0.01 kg/s, while the solar collector achieves its highest efficiency at 0.006 kg/s. Akmak and Yildiz [8] investigated the drying kinetics of a solar-powered grape drier. One of the solar air collectors in their system, which consists of a chamber connected to two of them, produced PCM. Using particular components inside the drying chamber and swirling components at the entry, they attempt to produce a swirling circulation. Furthermore, calcium chloride hexahydrate was utilized as a latent heat storage substance in the lower section of a collector to facilitate the drying process during periods without sunlight, as the grapes' drying duration needs to be exact. To maximize the quantity of solar energy that was absorbed by the collector surface, a mirror was put on top of the PCM-applying collector. They also looked at the impact of air velocity in their experiment and found that it had an inverse relationship with drying time. When they used their system with PCM and swirl effect instead of situations without PCM and swirl effect or open solar day (OSD), the initial moisture content (MC) dropped from 75% to 8.26% in just 56 hours. Shalaby and Bek [9] proposed a new type of indirect solar dryer. To retain the heat from the heated air, paraffin wax was positioned at the base of the drying compartment. Various mass flow rates ranging from 0.0664 to 0.2181 kg/s were tested on the ISD, both with and without PCM, while it was in a relaxed state. The PCM increases the temperature of the drying air by 2.5 to 7.5 degrees Celsius for a minimum of five hours after sunset. In their study, they experimented with the medicinal plants O. basilicum and T. neriifolia, which contain volatile oils. It was determined that their system was reasonable for volatile-oil medicinal plants. Following sunset, the temperature of the drying air was elevated by 7.5 degrees Celsius compared to the surrounding air temperature. The requisite moisture content was achieved in 12 hours, whereas it would have taken 18 hours without the presence of PCM. Esakkimuthu et al. [10] introduced an ISD with a thermal storage vessel. In their investigation, the inorganic salt HS58 was used as a latent heat storage material and was placed in spherical polyethylene balls in a storage tank. The air was propelled at a mass flow rate of 200 kg/h following a double-pass SAH utilizing a V-corrugated absorber, a packed bed thermal storage tank, and a drying cabinet. Based on observations, this particular dryer system has the ability to maintain a continuous rate of heat exchange with minimal energy consumption, thanks to the use of PCM spheres. Their research demonstrates that the improvement in collector efficiency is a result of an augmentation in the velocity of drying air flow, potentially resulting in a reduction of heat losses. Consequently, the mean temperature of the solar air collector decreased. El-Khadraoui et al. [11] introduced and developed the blueprint for a solar dryer that utilizes forced convection and PCM. The utilization of a solar energy accumulator and solar air collector facilitated the provision of heated air to a drying cabinet. The solar energy accumulator had paraffin wax underneath the absorber. Their research aims to calculate the energy charging and discharging behavior of paraffin wax. The solar air heater (SAH) utilizing paraffin wax achieves a thermal efficiency of 33.9% and an energy efficiency of 8.0%. The implementation of PCM led to a temperature difference of 4 to 16 degrees Celsius between night and day in the cabinet. The solar dryer with PCM resulted in a reduction of 17-34.5% in the relative humidity within the drying chamber compared to the ambient relative humidity. Devahastin and Pitaksuriyarat [12] studied the influence of paraffin wax on drying kinetics. The equipment employed for sun-drying sweet potatoes consisted of an air compressor, a heater, a cylindrical acrylic tank filled with low-temperature solar medium (LTSM), and a drying chamber. In the LTSM tank, a U-shaped copper tube with a diameter of 1.27 cm was connected to 18 copper fins. Each fin had a diameter of 8 cm, and there was a 1 centimeter gap between each pair of fins. Paraffin wax was then added. The compressor supplied the radiator with air, whose temperature was controlled between 70 and 90°C. Prior to entering the drying chamber, the heated air maintained its circulation by passing through copper conduits within the LTSM vessel. According to their findings, the use of LHS with an air velocity of 1 m/s resulted in a 40% reduction in the energy required to dry sweet potatoes. El-Sebaii and Shalaby [13] fabricated and studied a solar dryer for 6kg of Thyme leaves (Thymus vulgaris) that utilized indirect solar energy. The researchers investigated four scenarios, which encompassed the dehydration of whole leaves both with and without PCM, as well as the drying of sliced leaves. They gather plant leaves in order to decrease the amount of time it takes for them to dry. The moisture content of entire leaves was reduced from 95% (w.b.) to 12% (w.b.) in 126 hours without the use of PCM, whereas it required 84 hours when PCM was employed. The inclusion of PCM in the integrated solar dryer (ISD) enabled a significant reduction in the moisture content of chopped leaves. In just 28 hours, the moisture content decreased from 11.7% to 12%, but without PCM, it took 56 hours. As a result, cut leaves took 70 fewer hours to dry than whole leaves, while PCM cut drying times for cut leaves and whole leaves were 28 and 42 hours, respectively.

Vigneshkumar et al. [14] did an experimental study to investigate the process parameters for dehydrating sliced potatoes in two types of solar dryers: one without PCM (Plain Dryer) and one with PCM (PCM Dryer). The study focused on measuring the moisture removal rate, moisture ratio, and dryer inlet temperature. The dryer operated continuously from 10 a.m. to 7 p.m. with an air mass flow rate of 0.065 kg/s. The collected findings were contrasted, and the impact of utilizing PCM in conjunction with the solar dryer was analyzed and reported. The findings revealed that the inclusion of PCM in the solar collector had a substantial impact on elevating the temperature of the drying room, namely two hours after solar noon. In addition, the use of paraffin increased the daily rate of moisture extraction from potato slices by 5.1%. Ebrahimi et al. [15] investigated the impact of using PCM within the flat plate collector (FPC) on its thermal performance and overall drying efficacy. Investigating four PCM placements within the collector, the outcomes were contrasted with those of a collector without PCM. The experiment's results revealed that the process of drying tomato segments necessitated a specific energy range of 11.12 to 9.01 MJ/kg. The utilization of a collector with PCM at the end section resulted in a reduction of approximately 21.87% in the drying time of the segments. The Ansys 2015 CFD simulation of the system demonstrated the ability to accurately predict the thermal performance of the collector with a high level of precision (R2>0.9432). Utilizing PCM at the terminal portion of the collector resulted in a uniform drying process, an ambient temperature, and a decrease in drying duration. The solar dryer yielded tomato segments of exceptional quality.

Prior studies have predominantly examined the effectiveness of indirect solar dryers, both with and without a single-PCM serving as a TES medium. The current study on indirect solar dryers using numerous PCMs is inadequate and necessitates additional exploration. The aim of this work is to evaluate the heat efficiency of an indirect sun dryer that utilizes evacuated tube solar collectors and two different phase change materials with differing thermophysical properties. The study is motivated by the insufficiency of effective food preservation methods, resulting in food spoilage. Additionally, cold storages rely on power supplies, and in the event of a power failure, a significant amount of food is wasted. In rural locations, the implementation of solar dryers helps mitigate food spoilage caused by inadequate access to electricity.

3. MATERIAL AND EXPERIMENTAL SETUP

3.1 Performance evaluation of solar dryer

The simple design of solar collector and solar dryer includes the estimations of:

The following formula can be used to calculate the rate of heat (Q_w) acquired by water moving through the collector channel:

$$Q_w = m_w Cp_w (T_{w2} - T_{w1}) \tag{1}$$

where:

T_{w2}: Outlet temperature of the water from the collector tube (°C).

T_{w1}: Inlet water temperature for the collector channel (°C).

The formula provided calculates the rate of heat transfer (Q_{PCM1}) to the $PCM1$ in the drying chamber specifically during a period of maximum sunlight:

$$Q_{PCM1} = m_{water} Cp_{water} (T_{w2} - T_{a1}) - \frac{E_w}{t_d} \tag{2}$$

where, the drying time (T_d) is the amount of time it takes for the food product sample to dry. Eq. (3) can be utilised to calculate the estimated heat energy (E_w) required to remove the moisture content from the sample, measured in joules (J):

$$E_w = m_{water} . h_{fg} \tag{3}$$

where:

m_w: Water removed from the product sample in terms of mass;

h_{fg} is determined at 100°C from the steam tables.

The drying chamber's rate of heat transfer (Q_{PCM2}) to the *PCM*2 during a peak sunlight time is calculated as follows:

$$Q_{PCM2} = m_{water} Cp_{water} (T_{a1} - T_{a2}) - \frac{E_w}{t_d} \tag{4}$$

The charging time (t_c) of *PCM*1 during the melting process under peak solar conditions can be estimated using Eq. (5):

$$m_{PCM1} . L_{t1} = Q_{PCM1} . t_c \tag{5}$$

where:
L_{t1}: latent heat of fusion of *PCM*1 (J/kg).

Eq. (6) can be used to approximate the charging time (t_c) of *PCM*2 throughout the melting process through a peak solar period(s):

$$m_{PCM2} . L_{t2} = Q_{PCM2} . t_c \tag{6}$$

where:
L_{t2}: latent heat of fusion of *PCM*2 (J/kg).

An estimation of the mass of *PCM*1 (m_{PCM1}) needed for drying the product sample can be calculated using the following equation:

$$m_{PCM1} = \frac{E_w}{L_{t1}} \tag{7}$$

The mass of *PCM*1 (m_{PCM1}) required for drying the product sample can be estimated by:

$$m_{PCM2} = \frac{E_w}{L_{t2}} \tag{8}$$

The solidification process during a period of reduced solar radiation can be estimated by the discharge time (t_d) of PCM1:

$$m_{PCM1} . L_{t1} = m_{water} Cp_{water} (T_{dr} - T_{w2}) . t_d \tag{9}$$

where, the T_{dr} refers to the specific temperature range (40-43°C) that is necessary for drying the food product sample in the drying chamber.

The discharge time (t_d) of *PCM*2 during the solidification process under a period of relatively low solar radiation can be approximated as follows:

$$m_{PCM2} . L_{t2} = m_{water} Cp_{water} (T_{dr} - T_{a1}) . t_d \tag{10}$$

Based on the initial food product sample's (wet material) mass of water removal, an estimate of that amount is made by [16]:

$$m_w = m_{pr} \times \left(\frac{ms_w - ms_d}{100 - ms_d} \right) \tag{11}$$

where:
m_{pr}: Mass of the food product sample (kg).

The terms "ms_w" and "ms_d" refer to the moisture content of a substance, measured on a wet and dry basis, respectively. These values are represented as follows:

$$ms_w = \left(\frac{m_{pw} - m_{pd}}{m_{pw}} \right) \times 100 \tag{12}$$

$$ms_d = \left(\frac{m_{pw} - m_{pd}}{m_{pd}} \right) \times 100 \tag{13}$$

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The moisture ratio (MR) can be mathematically represented as [17]:

$$MR = \left(\frac{ms_{wt}}{ms_{wi}} \right) \tag{14}$$

where, the term "ms_{wt}" refers to the moisture content on a wet basis at any given time, while "ms_{wi}" represents the initial moisture content on a wet basis.

The rate at which the food product sample dries, denoted as the moisture drying rate (m_{dr}), can be mathematically represented as a function of the drying time (t_d) in hours:

$$m_{dr} = \frac{m_{pri} - m_{prf}}{t_d} \tag{15}$$

where:
m_{pri}: Initial mass of the food product sample (kg).
m_{prf}: Final mass of the food product sample after drying (kg).

The thermal efficiency of the evacuated tube solar collector is determined by [18, 19]:

$$\eta_c = \frac{Q_{water}}{(I.A_c.\alpha.\tau)} \tag{16}$$

where:
I: solar irradiance (W/m^2).
α: Absorptivity of the absorber plate.
τ: Transmissivity of the collector glass cover.

Thermal efficiency of the drying chamber (η_{dc}) can be evaluated as follows [20]:

$$\eta_{dc} = \frac{E_w}{Q_{water} . t_d} \tag{17}$$

The thermophysical properties of *PCM*1 and *PCM*2 are illustrated in the Table 1.

Table 1. Thermophysical properties of double PCMs [21]

Properties	PCM 1 (Paraffin Wax)	PCM2 (RT-42)
Melting temperature	57°C	38-43°C
Latent heat of fusion	204kJ/kg	174kJ/kg
Specific heat capacity	2.1kJ/kg.°C (liquid) 2kJ/kg.°C (solid)	2kJ/kg.°C
Thermal conductivity	0.25W/m.°C (liquid) 0.23W/m.°C (solid)	0.2W/m.°C
Density	810kg/m^3 (liquid) 910kg/m^3 (solid)	760kg/m^3 (liquid) 880kg/m^3 (solid)

3.2 Experimental setup and methodology

Figure 1 depicts the schematic diagram of the experimental setup. Evacuated tube solar collector, one of the most commonly utilized solar water heaters. It is simple to produce and maintain, and it is suitable for thermal applications requiring medium or low temperatures. The solar heater is the source of heat energy for the specified application, converting solar energy into heat energy and transferring it to the working fluid. Glass is commonly used to cover solar radiators because it transmits more than 90 percent of short-wavelength solar radiation while blocking long-wavelength radiation. Transparent double glass coaxial tubes with a low iron content and a thickness of (1.6 mm) are advantageous because of their low iron content. The collector, which is protected by a glass cover, consists mostly of the absorber. It transforms the solar energy that passes through the glass into heat energy. Copper is a typical absorber metal with high absorbance and exceptional thermal properties. In addition, it is coated with a special black coating to increase absorption of radiation with short wavelengths and decrease emission of radiation with long wavelengths (selective surface). Riser pipes fixed in parallel on the absorber plate by laser welding. In order to enhance the flow of heat from the fins to the pipes, it is necessary for the welding material to possess a high thermal conductivity. The insulation material is applied to the rear of the tank and the sides of the collector. It minimises the heat loss between the collector and the surrounding environment. Fibre glass is employed for thermal insulation.

For the selection and specification of the materials used in the construction of this solar drier, consideration was given to the affordability and accessibility of materials, particularly in rural communities. Two primary components composed the solar dryer: a PCMs and a drying cabinet. The two components were designed to be detachable in order to facilitate maintenance and mobility as necessary. The front of the cabinet was fitted with a single hinged door for access to the compartments. The dryer's framework was constructed predominantly from 20 mm plywood. Two varieties of PCM slabs are positioned at the bottom of the dryer to maintain elevated temperatures throughout the drying system. The cabinet, constructed primarily of plywood and measuring 60 cm×50 cm, contains four wire mesh trays intended for spreading potato segments. Each tray is comprised of a wooden structure with expanded metal grating made of stainless steel. It was decided to save money on investments and materials because stainless steel resists corrosion, especially in humid areas. To make washing and loading easier, the trays are made to be removable. To maintain consistent drying between each tray, the containers are also replaceable. In order to facilitate the dispersion of the entering warm air, the front end of each tray is constructed with a wider frame. A fan with a fixed speed was attached to the outlet of the solar dryer. The solar dryer's inside and exterior surfaces were both covered with a matte black finish to enhance heat absorption. The drying cabinet seen in Figure 2.

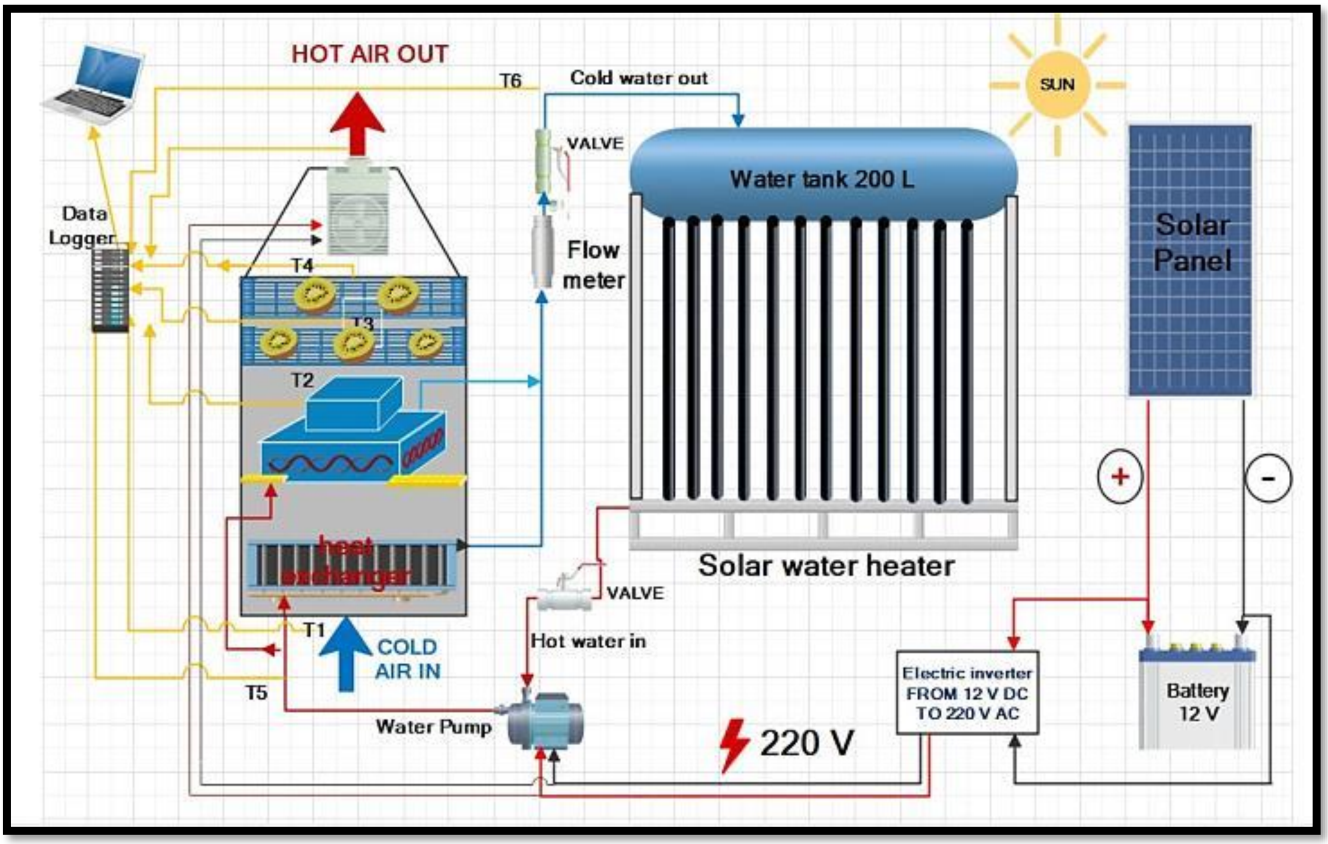

Figure 1. Schematic diagram of the experimental setup

Figure 2. Chamber painted black showing trays with two types of PCMs

The system's components are connected with polyethylene plastic conduit. Where the solar water heater tank's supply conduit is connected to the water supply and load. Through the electric pump, a second conduit returns working fluid from the radiator to the collector. The length of the supply and return pipelines is approximately (4 m). Long distances along the pipe's route led to the emergence of issues. The first, which increased thermal losses, and the second, which minimized thermal losses by insulating the pipelines. As shown in Figure 3, two valves were installed on the supply and return pipelines to regulate the fluid flow rate. The use of a water pump was required for this task. They are electric motors that are used to obtain the required water flow for valve control experiments. The water pump has a volumetric discharge of 10-30 LPM, a maximum head of 30 m, and a power output of 0.5 kW. There are five thermocouples of type (k) with an accuracy of (1℃) fitted in five different positions on the solar dryer. Out of these, two thermocouples are used to measure the temperature of the input and outflow of the collector's working fluid.

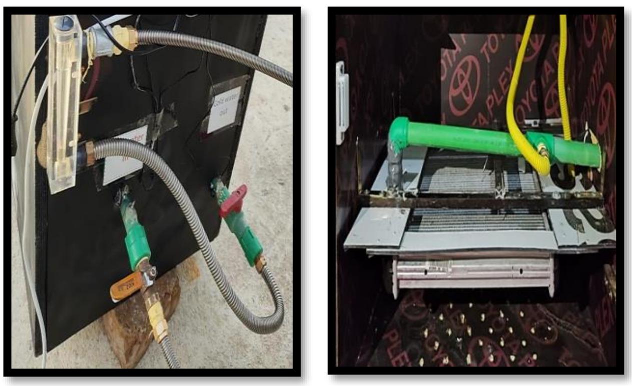

Figure 3. The supply and return pipes with control valves

During the months of and March and April, the effectiveness of the newly developed solar drier was assessed in Baghdad. To evaluate the thermal efficacy of the dryer, preliminary tests were performed with the cabinet empty. Further investigations were conducted using potato slices as a load. The operation of the dryer was evaluated in terms of both the state of the drying air and the desiccated potato slices. The solar drier was initially evaluated without any product inside the cabinet. Experiments were conducted over the course of two complete daylight days (39 hours), beginning at 10:00 a.m. on the first day and concluding at 4:00 p.m. on the second. Since the weather is known to have a direct impact on the dryer's efficacy, ambient air conditions were gathered from the weather station. Every 15 minutes, this weather station took measurements of the sun's rays, the temperature, the relative humidity, the wind speed, and the wind direction. K-type thermocouples were used to measure the temperatures inside the solar dryer and to record them to a data-logger every five minutes with an accuracy of (1.0℃) [22]. The water input, water exit, PCMs bed, and each tray level were all equipped with thermocouples inside the dryer. Every five minutes, the relative humidity at the chamber exhaust was measured using a Temperature and Relative Humidity Sensor (B098D337J4).

With load, Fresh, ripe potatoes were acquired from a local market and hastily cleaned in a 15ppm bleach solution and a new set of potato slices were used for each trial. The potato was manually examined to determine its overall level of ripeness. In this tactile evaluation, each potato's firmness was manually inspected to determine its maturity. Potatoes that were found to be unusually soft or excessively firm were excluded from these investigations because they were either overripe or under ripe. On each tray, an average of 1 kg of sliced potato was distributed and dispersed evenly. In an effort to ensure that all potato segments dried uniformly, special care was taken to prevent overlap. The drying cabinet was loaded at 10:00 a.m., and the investigations lasted for two full sunlight days (9 hours). Based on preliminary investigations, it was determined that product loaded on upper trays dried more unevenly than product placed on lower trays. Each tray received four tagged potato segments, which were removed hourly for weight measurements. The weight measurements of these segments were used to determine their moisture content. When the moisture content of the tagged samples fell below 10% (w.b.), it was determined that the product distributed on the same tray was sufficiently dry. Alternately, tactile evaluations or visual examinations can be used to determine the drying stage of potato slices. While manual evaluation of the product's texture for adequate dryness, suppleness, and pliability is straightforward, colour evaluation is somewhat more complex. As the potato segments dry, a colour change from yellow to brown is observed.

4. RESULTS AND DISCUSSION

The tests were administered on a daily basis for a duration of one week, commencing at 8:00 a.m. and concluding at 3:00 p.m. Multiple tests were carried out to assess the efficiency of the solar dryer that was equipped with a thermal energy storage system once its design was finished. Potato chips were chosen as a sample for dehydrating in the drying test. In two days of continuous drying under the same climatic conditions using the solar drier, 78.58% of the sample's moisture content was removed, compared to four days of open sun drying. The experiments were conducted without loading, and load drying testing began at 8:00 h and concluded at 18:00 h daily for five days. Potato slices were placed in the dryer to gauge the drying rate. The significant parameters influencing the dryer's performance were measured and recorded accordingly. The experimental setup included of a solar collector equipped with evacuated tubes, a temperature regulation system, glass, a drying chamber, and a main frame. Two types of paraffin wax were utilised as heat storage materials. An analysis was performed and documented to assess the efficacy of the solar dryer with integrated thermal energy storage system. Figure 4 illustrates the range of ambient air temperature across a six-day period of trials, which varied from 20.4 to 38.6℃.

The results indicated that temperature fluctuates in response to changes in solar radiation intensity, which varies throughout the day and decreases in the evening. The air temperature is often influenced by the intensity of solar radiation received during the day. Additionally, we observed variations in temperature across the months in which the tests were carried out.

The mean solar radiation measured 585.7 W/m², with solar intensity varying between 1.5 and 1289 W/m², observed from 8:00 a.m. to 18:00 p.m. across a span of five experimental days. The evacuated tube solar collector was oriented manually to ensure high efficient as shown in Figure 5.

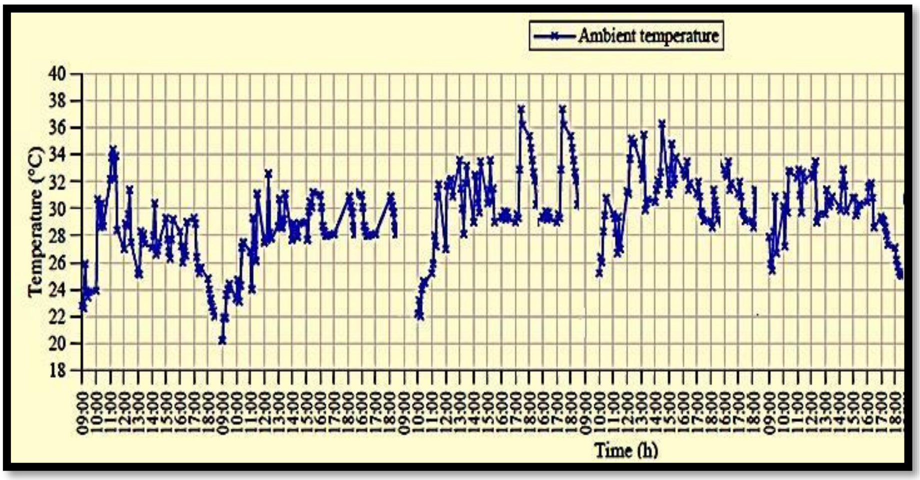

Figure 4. Variations of ambient temperatures with time

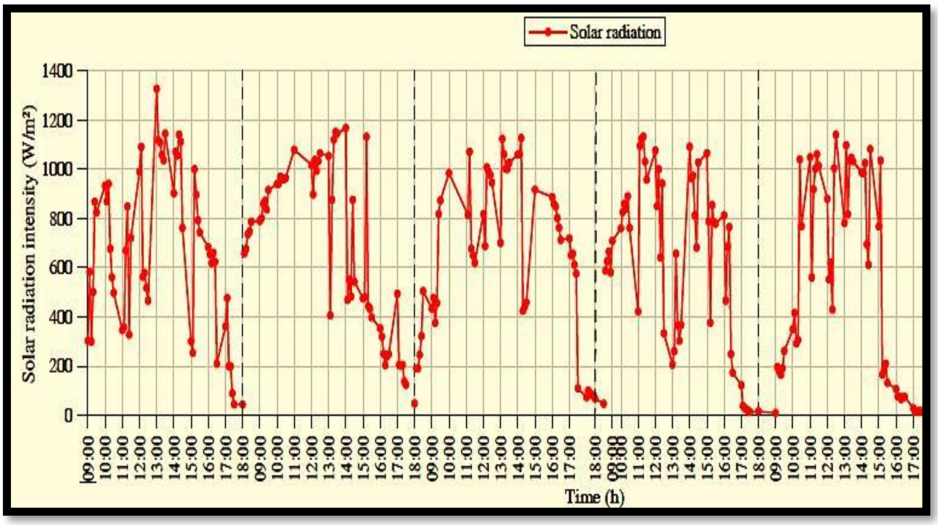

Figure 5. Variation of solar radiation intensity with time

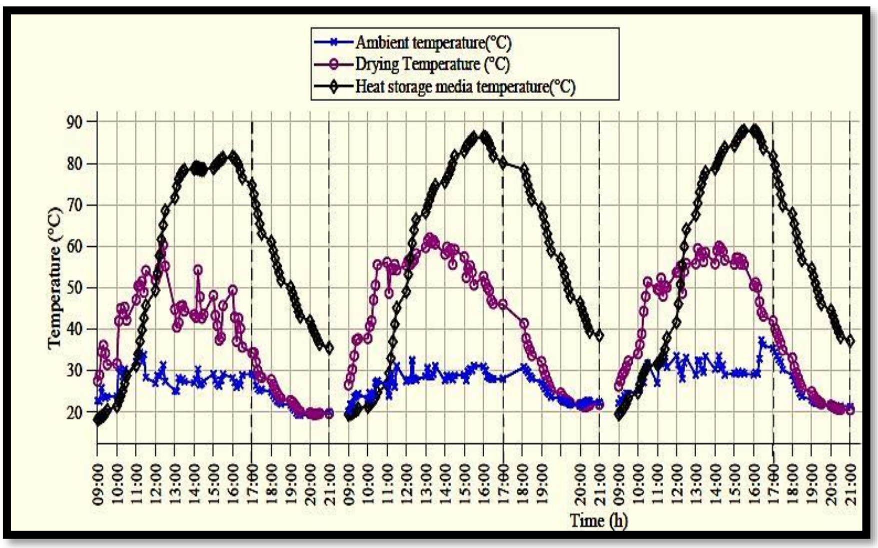

Figure 6. Temperature variation with time without load tests

During the experiment, it was found that the intensity of incident solar radiation is greatly affected by the clouds present in the sky, as they cause the scattering and reflection of solar rays into space, and thus the intensity of radiation decreases during the day and successive months.

Without performing a load test, the temperature control valve was left open daily from 9:00 to 21:00 h for three days to evaluate the solar dryer when employing a heat storage system. As seen in Figure 6, the maximum air-drying temperature, heat storage medium temperature, and sun intensity were 61.7°C, 86°C, and 1289 W/m^2, respectively. The average ambient air temperature was 28.3°C.

Regarding the relationship between dryer temperature and PCM, the top and bottom maximum heat storage media temperatures for experiments conducted without a load ranged between 85.2°C and 121.6°C, respectively. As depicted in Figure 7, the weather during the experiments was sunny. As depicted in Figure 8, the maximum temperature of heat storage material on the top and bottom sides during drying experiments with a load was 80.3°C and 122.4°C, respectively.

Two kilogrammes of fresh potato slices were chosen to be dried for comparative experiments between the solar dryer and sun drying. The potatoes were evaluated and found to have an initial moisture content of 78.58 percent (w.b.). One kilogramme of sample was dried in a solar dryer and reduced to the desired moisture content of ten percent (w.b.) in twenty-four hours in the presence of (PCM), but it took thirty-three hours in the absence of PCM. Similarly, open sun drying required 38 hours to reduce the moisture content of 1 kg to 10% (w.b.), as shown in Figure 9.

The convective heat transfer coefficient is primarily responsible for the system's heat loss. These include the temperature emissivity caused by the radiative coefficients on transparent glasses and collector absorbing plate, as well as the coefficient heat transfer due to the wind blowing on the system. The curve of the coefficients of heat transfer is shown in Figure 10 below. The heat loss to the environment was greatest between 11 a.m. and 3 p.m., however there was only a slight trend in heat losses because of radiative heat transfer coefficients at that time. The graph's trend indicates that during the solar hours, when the system is somewhat hotter due to more intense solar radiation, the performance of the solar collector can be improved. The experimental findings from this study's solar dryer have shown good thermal improvements and performance when compared to earlier literature research that were carried out utilising the identical design and development of evacuated tube solar collector.

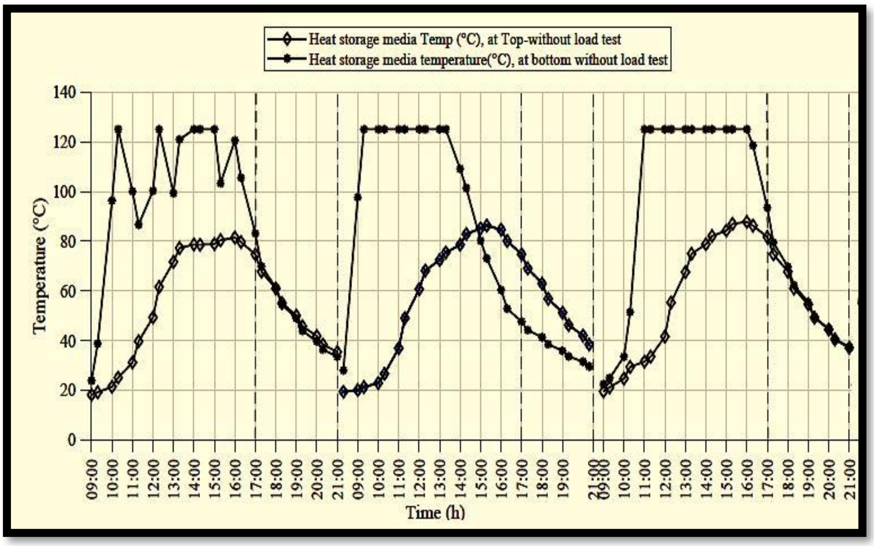

Figure 7. Heat storage temperature variation with time (without load tests)

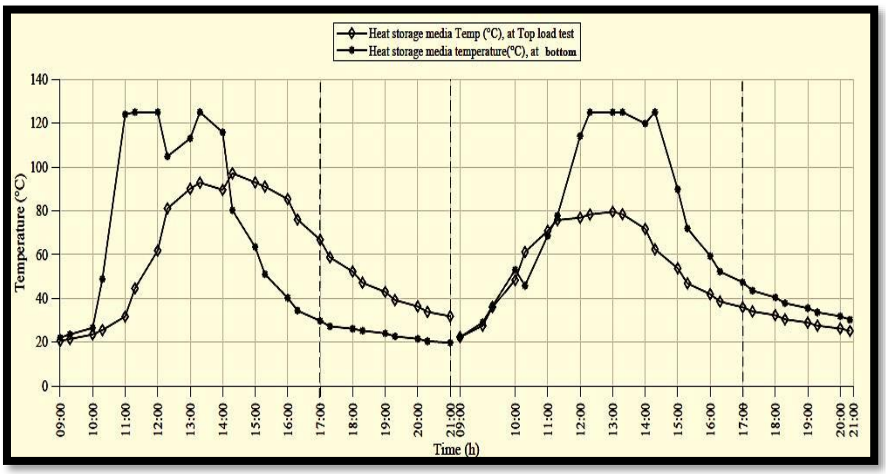

Figure 8. Heat storage temperature variation with time (with load tests)

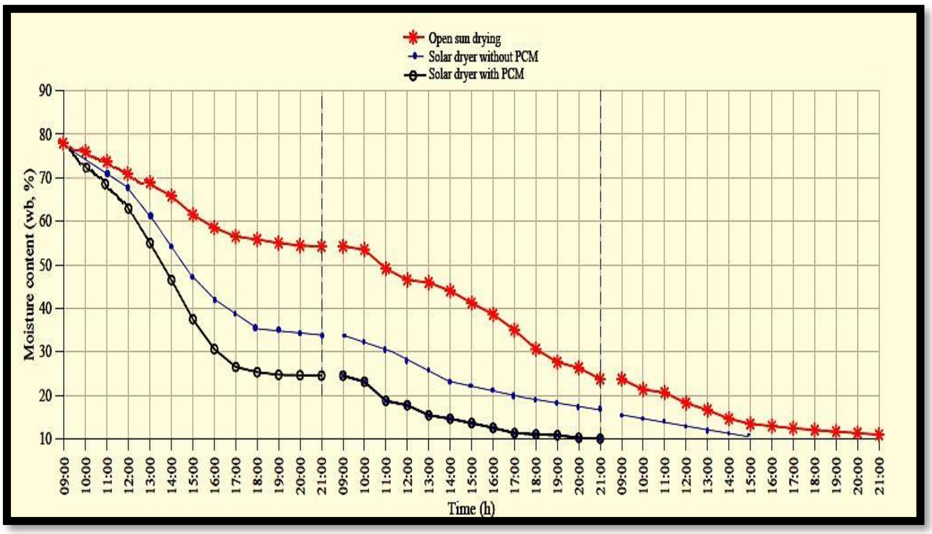

Figure 9. Moisture content loss with time for solar dryer and open sun drying

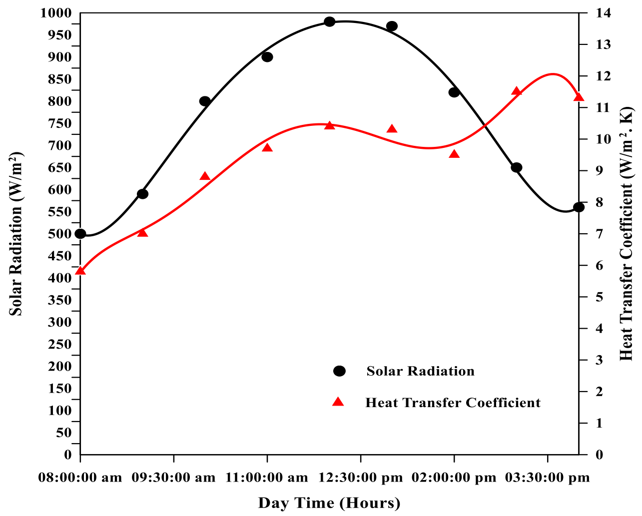

Figure 10. Graph of convective heat transfer coefficient and solar radiation

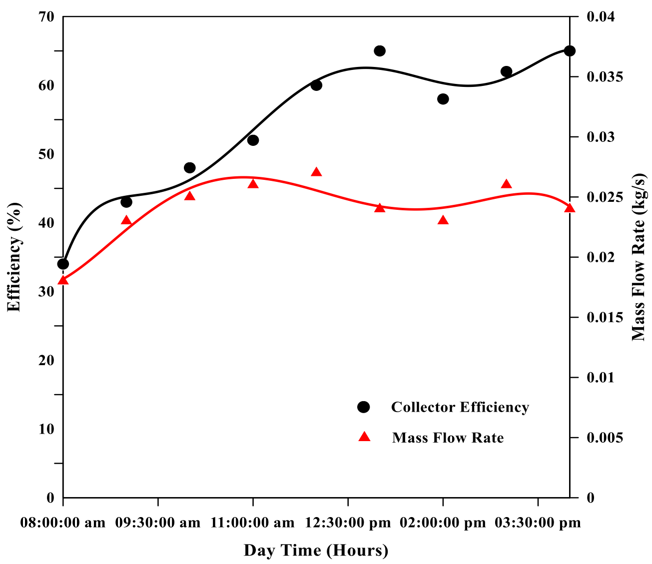

Figure 11. Variation of collector efficiency and mass flow rate with time with PCMs

As shown in Figure 11, the efficiency of the collector increased as mass flow rates increased over time, this is because the mass flow increasing lead to increase the energy of water passes through the evacuated tubes and as a result increasing the efficiency according to Eq. (17), and it is known that the relationship between energy and efficiency is a direct relationship. However, it continued to stabilise even after mass flow rates decreased. The placement of the gap underneath the absorber plate assisted to sustain and stabilise the percentage rise in collector efficiency by releasing extra stored heat, especially during low solar radiation, according to a good prediction from the graph because the air gape helps to reduce the heat losses from the evacuated tube system and thus increasing efficiency. However, the efficiency was under 54% from 08:00 a.m. to 11:00 a.m. due to the fact that, the useful heat gain is low and the surrounding wind velocity was high. After 11:00 p.m. Since these two factors affect the efficiency of the collector, the air gap in the evacuated tube caused poor heat dispassion and caused a disparity between the inlet and output temperatures of the collector.

As a result, from the above mentioned figures we observed that the intensity of solar radiation affected by the clouds in the sky and the temperature of air varied during day. Another finding, we show that the increasing of mass flow rates lead to significance increasing in the collecter and dryer efficiency. The presence of PCM(s) have the big role in drying process and help to minimize the time of dryness with spoilless product.

5. CONCLUSIONS

An experimental potato dryer's size was determined through simulation and calculation as a result of the simulation procedure. It contained a centrifugal fan and a drying cabinet that measured 0.6 m×0.5 m. A 3m^2 area served as the collector for the solar water heater. The temperature within the drying chamber did not rise over the maximum permitted temperature at any point during the trial, from loading to unloading. A test was run, and information was gathered to assess the system's performance. The observations have led to the following inferences:

1. Moisture Elimination if potato layer thickness remained constant, rate increased with air velocity and temperature, this contributes to preventing potato damage.

2. The drying efficiency decreased with drying air temperature at constant air velocity and potato layer thickness, rising from 6.3% to 10.2% as air velocity rose from 0.33 to 0.51 m/s, and this gives us a clear indication of the necessity of taking into account the effect of wind on the efficiency of the solar collector.
3. The moisture content of the product reduces as the drying process continues. The drying procedure took 2 days, or approximately 24 hours, when PCM(s) were present. However, without PCM(s), the drying process took 33 hours. The potato slices were dried until they reached a final moisture content of 10%. Similarly, the process of sun drying required a total of 39 hours to reduce the moisture content of 1 kilogramme to reach a level of 10%.
4. In addition, the end goods' quality (taste, colour, and appearance) were examined and maintained in this designed solar dryer. According to the trials, dried potato slices on netting trays can at least keep their spheroidal shape without becoming heavier bent into another shape.
5. Because copper, a material with a high conductivity, was utilised to make the absorber plate, it has a great capacity to absorb solar radiation. Additionally, the evacuated tube solar collector's temperature can reach 60 to 70℃, and this means an increase in the collector and dryer chamber efficiency.

Another type of thermal energy storage like sand or stones with using flate plate solar collector can be suggested for future work.

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