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Review Article

A Review of Performance Improvement Methods for Solar Dryers and Phase Change Materials (PCM) in Solar Drying Applications

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Abstract *- In this review article, the research focuses on methods to improve the performance of Solar Dryers (SDs) and the utilization of Phase Change Materials (PCMs) in solar drying applications. This highlights the advantages of PCMs, such as reduced heat loss, High Energy Storage (HES) density, and increased thermal conductivity in solar drying systems. The document emphasizes the possibility of PCM-based solar dryers as environmentally friendly and cost-effective thermal energy storage solutions for agriculture and renewable energy systems. It entails a review of experimental investigations and theoretical modeling from previous decades to determine the most effective arrangement of PCMs in solar dryers, ensuring optimal performance. This research digs into the substantial improvements in sun drying systems, with a focus on harnessing renewable energy potential through the use of PCMs. It also focuses on ways to improve their efficiency in solar drying applications. Also, using PCM for energy storage is a highly efficient strategy, providing greater storage density via Latent Heat Storage (LHS) and maintaining a moderate, steady temperature, both of which are required for effective crop drying. Similarly, using PCMs in solar dryers has been shown to reduce heat losses and improve system performance. This article also describes approaches used to improve the thermal conductivity of commonly used PCM in solar drying systems, particularly paraffin wax. It implies that Expanded Graphite (EG), Graphite Foam (GF), High Thermal Conductivity (HTC) and Carbon Fibers (CFs) particles have the possibility of High Thermal Efficiency (HTE) of Solar Energy (SE) devices that use paraffin wax (PW) as a storage medium. Finally, resolving these issues and research gaps is critical for determining future trends and improving PCM dryer technology generally.*

Keywords - *Solar dryers, Phase change materials, Thermal performance, Efficiency, Moisture content, Paraffin wax.*

1. Introduction

Recently, there has been a considerable rise in global demand for dried agricultural products, medicinal plants, and marine products. Renewable energy has the potential to significantly contribute to satisfying global demand. In fact, the most environmentally friendly and dependable energy is solar energy. It can be utilized in a range of agricultural applications, including solar thermal or solar PV, for drying and pumping crops. It is a viable alternative energy source that is preferred above other options since it is abundant, free, and non-polluting, as compared to the more expensive Fossil Fuels (FFs) [1]. Agricultural and marine items must primarily be dried to safeguard the qualities of the last products. Solar energy has the lowest environmental impact of any renewable energy source, including air, wind, and water. One useful and affordable method of preserving food for a sustainable future is drying food products using solar-energy, which is also a sustainable and eco-friendly energy source. Sustainable energy solutions like solar drying can considerably help in the development of agricultural product processing systems, hence boosting economic growth, particularly in developing countries [2]. As a result, continued research to improve solar-drying equipment, particularly, indirect and direct dryers, is required. Thermal Storage Materials (TSMs) like PCMs are used to increase the thermal performance of an Indirect Sun dryer (ISD) [3].

Using a single or many PCMs with varying melting temperatures allows solar energy to be used while preventing temperature variations in the drying chamber that occur when using a normal solar dryer. Solar energy can provide Hot Air (HA) for drying crops and heating homes throughout the winter. Solar dryers are categorized into ISDs, Mixed-Mode SD (MMSDs), Direct SD (DSDs), and Hybrid SD (HSDs) [4]. The two primary kinds of sun-drying systems are natural and forced convection solar dryers. In DSD mode, the drying material gets heated straightly from the solar radiation, and hot-air occurs in the drier enclosure [5]. A Solar-Air-Heater (SAH), a drier room, and a blower that drives hot-air into the drier room comprise the indirect solar drier. During maximum solar radiation, the materials are dried in the mixed-mode SD, which receives heat from the sun as well as the warm air from the solar air heater. The materials used for storing energy are to store excess energy for usage during off-sun hours or when energy supplies are inadequate since solar energy is intermittent [6].

Energy systems benefit from storage materials because they smooth output and improve dependability. Chemical energy, Latent Heat (LH), and Sensible Heat (SH) are three different ways that thermal energy can be stored. The SH storage absorbs thermal energy and stores it when the temperature of the thermal storage medium rises [7], [8]. PCM-based LH-storage systems offer a high ES density and the capability to store energy at a steady temperature [9]. At melting temperatures, the thermo-physical characteristics of PCM are crucial in assessing material suitability. Before the PCM can be used, some key physical characteristics must be identified [10]. A few of these characteristics are the Heat-Of-Fusion (HOF), high heat, thermal-conductivity, steady composition, high density, chemical inertness, and non-toxicity, respectively. On the other hand, there are some barriers to PCM use, including its novelty, limited area availability, erratic sunlight, and expensive initial cost [11].

2. Solar Drying Process and its Applications

The solar drying process dries several materials, like agricultural products, by utilizing the sun’s energy and heat. It consists of exposing the material to direct sunlight to remove moisture and reduce water content. It is a cost-effective and eco-friendly approach to preserving and drying a wider variety of agricultural products like vegetables, dry fruits, grains, herbs, and even meat and fish. These drying techniques can be completed in two phases: (1) The product’s moisture is raised to the surface and steadily dried in the air as water vapour, and (2) involves drying products gradually at a rate regulated by the characteristics of the thing that needs to be dried.

The most popular technique is open-air drying, which is especially popular in subtropical and tropical countries. To maintain an acceptable voltage adjustment during the consideration of enhanced damping of the virtual resistance was accepted. However, numerous drawbacks like product degradation due to direct exposure to storms, rains, dews, and sunlight; product damage from insects, birds, and rodents; probable cracking and loss of germination capacity; and contamination with gases and particles from air pollution are common. To remedy these problems, the solar drying technique is performed. Using the solar drying technique, the products can be dried without being harmed by insects or the elements.

According to the report, solar-drying is utilized in the industrial sector for biomass, timber materials, bricks, polymers, cement, papers, textiles, and related products. Additionally, a range of procedures are employed, including wastewater treatment, pharmaceutical procedures, and porous material drying. Today, waste-water treatment uses solar dryers to reduce the time and expense of traditional drying methods. Based on energy conservation, solar dryers have shown to be quite successful. They avoid a couple of the most significant disadvantages of traditional drying. Solar dryers are one of the most fascinating applications of solar energy technology. Whether SE is used as the main heat source or as a supplement, air movement in solar dryers can be achieved by natural or artificial convection. Numerous technical developments, including as compact collector designs, integrated storage, high efficiency, and durable drying mechanisms, have been included in the growth of solar dryers. Therefore, as standalone solar-powered applications, special Photovoltaic (PV) technologies for the simultaneous generation of heat and electricity are suitable [12], [13].

3. Solar Dryer Classification

Solar dryers are categorized into mixed-mode, indirect, hybrid, and direct, which have been successfully employed to dry horticulture items. In reality, these dryers mostly rely on natural or forced air circulation.

3.1. Direct Solar Dryer

The product is simply dehydrated in direct solar dryers since they expose it directly to sunlight. To gather and absorb sunlight and then turn it into heat, this kind of solar dryer features a black-painted heat-absorbing panel. The dried product that has dried is put straight onto the absorber plate. The DSD could have glass lids and vents to raise the effectiveness of heat.

3.2. Indirect Solar Dryer

A drying room and a sun collector comprise an indirect solar dryer. Instead of directly exposing a product to sunlight, the black-colored heat absorber surfaces of the Solar Collector (SC) heat the nearby air. After that, the HA is blown completely in the product, which is put in a drying room to absorb moisture before leaving through the chimney.

3.3. Mixed Solar Dryer Mode

The ISD and DSD are integrated with the mixed-mode solar drier. The dried material receives a combination of heat from the sun’s intensity and the preheated air inside a solar collector.

3.4. Hybrid Solar Dryer

In order to maintain optimal drying conditions, the hybrid solar dryer can employ a variety of energy sources in addition to solar energy. Furthermore, the drying process is not simply determined by the strength of the sun. The blower is used to guarantee correct air circulation in a hybrid sun dryer driven by photovoltaic. Any agricultural product can be dried with a hybrid sun drying system while keeping the required quality [14].

4. Phase Change Materials

At certain temperatures, phase change materials can shift from solid to liquid and liquid to solid. PCMs have a high heat of fusion property, which allows them to melt and solidify at specific temperatures. PCMs store and emit large quantities of thermal energy, and also it has three types of PCMs: inorganic, eutectic, and organic. Fatty acids, Paraffins, alcohols, and esters are instances of organic PCMs. The instances of inorganic PCMs are salt hydrates, salts, metal alloys, and metallic compounds. Inorganic-inorganic, organic-inorganic, and organic-organic are the instances of eutectic PCMs. Thermal conductivity and latent heat must be high in PCM used in Thermal Energy Storage (TES). Furthermore, with only a tiny temperature difference between the processes of heat-storing and heat-releasing. Moreover, the method of latent heat storage offers a higher density of storage than the storage of SH.

The storage of thermal energy is hybridized with solar energy to lessen energy consumption and to use STE when it is unavailable, allowing them to consume and store STS effectively. To process TES, latent, sensible, or thermo-chemical heat-storage can be employed. Latent heat TES has seen considerable use in recent years due to its adaptability. When heat energy is absorbed during a charging cycle, PCM transforms the phases from solid-to-liquid. Similarly, during a discharging cycle, PCM transforms the phases from liquid-to-solid. There are four types of PCM phase shifts for latent-heat TES: solid-to-gas, solid-to-solid, liquid-to-gas, and so on. Because of their high melting points and high energy storage densities, solid-to-liquid and liquid-to-solid phase transitions occur most frequently. Because of the high volumetric shift that happens in phase transitions, latent heat TES systems do not use solid-to-gas or liquid-to-gas phase transition materials. The most dependable material for TES applications is solid-to-liquid PCM because of its many benefits, which include consistent melting, non-toxicity, eco-friendliness, low vapor pressure, dependability, and abundance in nature [15].

5. Modelling of Solar Dryers and PCM

This section shows the modelling of solar dryers with PCMs in SD to improve the performance of drying. The cabinet SD with static trays was built at a laboratory scale, and the collector was outfitted with a solar panel and a sun tracking system to obtain additional solar energy. A system consisting of a photocell sensor, a DC motor, connection cables, and an electric circuit were investigated to rotate the collecting plate. The process begins when the rays of the sun contact the collector plate vertically in the morning. Depending on the plate surface, the angle of the beams altered over time. The photocell sensor detects sun radiation; at this moment, the electrical resistance in the circuit decreases, and the driver motor begins to circulate the collector plates. Moreover, the photo-cell sensor spins with the collecting plates and penetrates the shadows. In this instance, the circuit's resistance rises, and the motor shuts down. This process will last till the sun sets. Figure 1 shows the structure of solar dryers with PCM in solar drying.

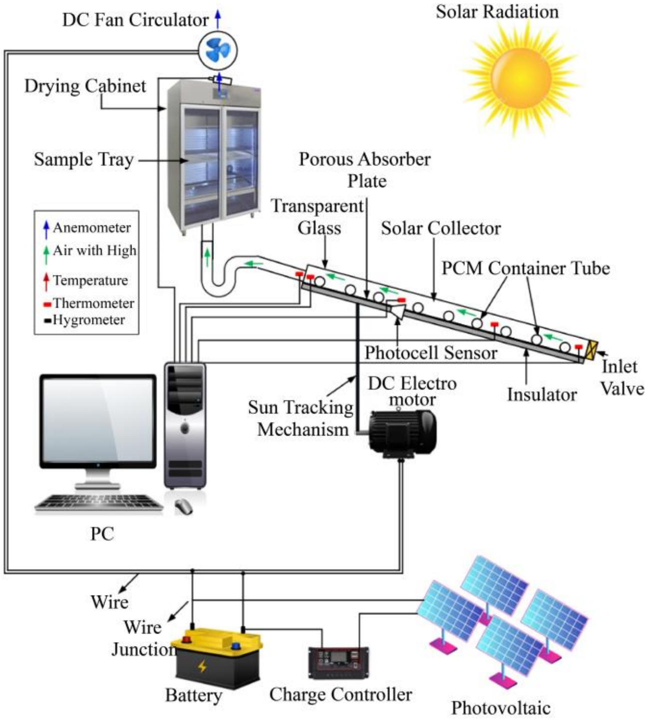

Fig. 1 Structure of solar dryers with PCM in solar drying

Due to its high latent heat and strong thermal properties like phase transition temperature variation, low vapour pressure in the melting state, and self-nucleating tendency, the appropriate material for paraffin wax is selected to employ in thermal systems. The non-corrosive material paraffin has a long shelf life and constant characteristics. The thermal performance of Paraffin remains constant in the phase transition cycle, which is a distinct attribute of these materials. The standardized K-type thermo-couples were installed to manage the changes in dryer temperatures (cabinet and collector) during the drying process. The thermo-couples were connected to a 0.1^0C accurate automated temperature controller [16].

5.1. Theoretical Calculation

5.1.1. Solar Dryer and PCM's Thermal Performance

The rate of usable absorbed energy (Q_U) is calculated by Flat Plate Collector (FPC),

$$Q_U = MC_p(t_o - t_i) \tag{1}$$

A considerable amount of the collector losses, solar energy collector, and residual energy can be calculated as the usable thermal energy rate, and its Equation (2) is given below:

$$Q_U = a_c f_r\left([i_0(\alpha\beta)] - u_l(t_o - t_i)\right) \tag{2}$$

Where, $(\alpha\beta)$ implies the coefficient of absorption transmittance. The thermal performance can be calculated by Equation (3):

$$x = \frac{Q_U}{a_c i_o} = \frac{MC_p(t_o - t_i)}{a_c i_o} \tag{3}$$

The storage system, which consists of a copper spiral tube, is organized in 10 rows on the absorber plate's surface. Paraffin wax was used to fill the tube. When there is much solar radiation during the charging cycle, the fluid air warms, and the form of solid paraffin is formed into the spiral tube and is turned into liquid form by soaking heat from the fluid. Similarly, when the radiation of solar drops, the fluid temperature inside the collector falls below ambient. Also, the phase transition reverses, and PW discharges the energy of thermal to the air passing via the drying cabinet, and the collector [17].

The PCM unit absorbs energy through two components: a spiral copper tube and paraffin, which serves as a cover. To characterize the thermal performance of the SC and storage system, the FPC thermal circuit, which included fluid, wall, and PCM, was used.

$$Q_F = MC_p\left(t_{F,in} - t_{F,out}\right) \tag{4}$$

The convective heat transfer from the higher temperature fluid to the PCM wall cover (Q_{conv}) is affected by the temperatures of the average cover $(t_{F,M})$, and the fluid $(t_{C,M})$,:

$$Q_F = H_c a_{CO}\left(t_{F,M} - t_{C,M}\right) \tag{5}$$

The heat transmission to PW within the spiral copper tube and its eqn is given as follows:

$$Q_{cond} = K_w a_{CO} \frac{(t_{C,M} - t_{PCM})}{T_c} \tag{6}$$

5.1.2. Specific Energy Consumption (SEC) and Drying Efficiency

The efficiency of drying should be calculated to investigate the influence of PCM in various settings on sample drying processes [18]. The moisture ratio of the samples is calculated below:

$$mr = \frac{m_T - m_E}{m_O - m_E} \tag{7}$$

The drying rate can be calculated at any moment during the drying process:

$$dr = \frac{Dm}{DT} = -K(m_T - m_E) \tag{8}$$

The thermal energy injected into the dryer is $Q_{in,dryer}$ and is computed in Equation (9):

$$Q_{in,dryer} = 10^6\left[\left(\int_0^T M(T) \times C_P\left(t_{in,coll} - t_{out,coll}\right)DT - \int_0^T M(T) \times C_P\left(t_{in,S} - t_{out,S}\right)DT\right)\right] \tag{9}$$

The dryer's outlet-energy $(Q_{O,dryer})$is calculated by Equation (10):

$$Q_{O,dryer} = w \times l_v \times 10^{-3} \tag{10}$$

From the above Equation, w and l_v are calculated below,

$$w = \frac{w_a(m_o - m_F)}{100 - m_F} \tag{11}$$

$$l_v = 2502.54 - 2.309t_{CA} \tag{12}$$

The rotation of air flows by the dryer and collector is necessary to speed up the process of drying. Hence, the energy spent by the circulator-fan is estimated using Equation (13):

$$e_{MEC} = P_{fan} \times T \times 10^{-6} \tag{13}$$

At 1 second intervals, the power demand of a fan was calculated using the power measurement instrument. The amount of energy needed to heat the crops and the dryer and extract water from the crops, as well as the total energy (thermal and electrical) that goes into the dryer, is addressed when presenting the efficiency of the drying,

$$x_{dryer} = \frac{Q_{out,dryer}}{Q_{in,dryer} + e_{mec}} \tag{14}$$

The efficiency of SD is estimated using a variety of factors. For this purpose, the specific energy consumption is widely used. As illustrated in Equation (15), SEC is the amount of energy necessary to dry 1 kilo-gram of products:

$$SEC = \frac{Q_M}{w_O} \tag{15}$$

5.1.3. Quality Consideration

To increase the water content of samples, various technologies, like integrating hot, microwave, and solar-drying processes, are utilized to speed up the drying processes and enhance the temperatures of drying air. To verify that the utilization of various drying techniques has no negative influences on the qualities of dried samples is regulated, and then consider the quality consideration. As a result, the quality of dried samples is crucial when selecting a drying technique[19]. Three characteristics were used to assess the quality of the slices: rehydration ratio, shrinkage, and color. The variations of color were determined by knowing the difference between dry and fresh slices:

$$\delta e_{rgb} = \sqrt{(r-r_0)^2 + (g-g_0)^2 + (b-b_0)^2} \tag{16}$$

The shrinkage of the solar-dried slices is defined as:

$$S_B = 1 - \frac{v}{v_0} \tag{17}$$

The re-hydration ratio (rr) is shown as,

$$rr = \left(\frac{w_R}{w_D}\right) \tag{18}$$

6. PCM Integrated Solar Dryers

An SD is a mechanism that heats air using solar radiation for a range of applications, such as drying fruits, seeds, vegetables, and agricultural items. A chimney and a blower, respectively, are used to create natural and forced air movement. Fruits and vegetables, for example, require an operating temperature of 40-60 °C. The quality of products cooked in a sun dryer is enhanced. The product quality and moisture content can be controlled by adjusting the working temperature and humidity level. These variables vary based on the product. Because it streamlines the preservation process, the solar drying method has sparked much interest in the food and agriculture industries. It also has significant environmental benefits. The PCM can store additional solar energy and discharge it whenever needed [20]. Many parameters were evaluated during charging and discharging, including heat-transfer features, intake and output temperature, and the influence of air velocity.

A solar dryer with LHS that stores excess solar energy during the day and releases it when there is insufficient or no solar energy available. Changing the air flow rate determined the exit temperature while changing the flow rate determined the PCM discharge time. It shows that as the air flow rate rises, the outlet temperature decreases because the fluid velocity rises, implying less time for absorbing heat energy from the PCM to the fluid. They have enough contact time to absorb heat from the PCM; thus, when the flow rate rises, the discharging rate also increases directly. It was also revealed that adding PCM significantly improved the system's thermal efficiency. Large surface areas for high latent heat and heat transfer are needed in PCMs to improve the thermal performance of SD. This decreases the loss of heat and the supply-demand imbalance while also increasing the system's energy efficiency. At high sunlight, the paraffin undertakes phase change and preserves the LH energy. Solar dryer performance with PCM paraffin wax contained in a rectangular chamber[21].

7. Drying Models

Water is transferred from the solid's core to the drying air by complex mass transport and heat transfer phenomena, which can be expressed in terms that accurately depict the drying process. This model can replicate unidirectional diffusion, simple geometries, and a variety of beginning and boundary conditions. The convective drying of agricultural products causes' shrinkage, and temperature results in the d_{EFF} variation throughout the process. Simplifying assumptions in drying process analyses assume air conditions and d_{EFF} remain constant, and the shrinkage, and external mass-transfer-resistance are less. The constant diffusivity model for an infinite-slab thickness of 2L and diffusion exclusively in the x-direction, obtained through the combination of using Fick's law yields, is expressed below,

$$\frac{x(T)-x_{EQ}}{x_o-x_{EQ}} = \frac{x(T)}{x_o} = \frac{8}{\pi^2}\sum_{N=1}^{\infty}\frac{1}{(2N-1)^2}EXP\left[-(2N-1)^2\,\frac{\pi^2}{4l}\left(\frac{d_{EFF}T}{l}\right)\right] \tag{19}$$

Where, x_0 implies the initial moist content, $x(T)$ implies moist content at T time, and l is the semi thickness.

Furthermore, it can also be disregarded because the equilibrium moist content $\left(x_{EQ}\right)$ is less. The simplified-constant-diffusivity method permits an approximation of d_{EFF} by using the above mentioned norms and by removing the facto of $\frac{8}{\pi^2}$ and examining the 1st-term of the infinite series alone.

$$moisture\ ratio = mr = \frac{x(T)}{x_0} = EXP\left(-\frac{\pi^2}{4l^2}d_{EFF}T\right) \tag{20}$$

As previously stated, convective drying of agricultural goods is frequently accompanied by considerable shrinkage [22], which is produced by modifications in the micro-structures caused by gradients in the moisture content. When shrinkage is significant, the ratio of moisture can be expressed as a function of semi-thickness $l_{(x)}$ as its moisture-content function,

$$moisture\ ratio = mr = \frac{x(T)}{x_0} = EXP\left(-\frac{\pi^2}{4{l_{(x)}}^2}d_{EFF}T\right) \tag{21}$$

8. Thermal Performance of SD

Here, the thermal and drying efficiencies of solar dryer collectors are discussed. The following formula is widely used to measure the efficiency of SD,

$$(During\ Day);\ x_{SOLARDRYER} = \frac{M_L l}{ia_T} \tag{22}$$

At night, when there is no solar radiation, the dryer efficiency can be expressed as,

$$(During\ Night);\ x_{DRYER} = \frac{M_L l}{M_{PCM}c_{P,PCM}\left(t_{PCM,I}-t_{PCM,F}\right)} \tag{23}$$

The efficiency of SC is computed as,

$$(During\ Day);\ x_{SOLARCOLLECTOR} = \frac{q}{ia_s} \tag{24}$$

Similarly, the collector efficiency can be written as

$$(During\ Night);\ x_{COLLECTOR} = \frac{q}{M_{PCM}C_{P,PCM}(t_{PCM,I}-t_{PCM,F})} \tag{25}$$

Where,

$q = MC_p(t_i - t_o)$ and $M = \varepsilon \times V \times a_c$

When solar radiation falls on the collector after sunset, when it is 0, PCM provides input energy in sensible heat forms until the PCM temperature reaches the ambient temperature [23]. This is done to calculate the effectiveness of the dryer and collector.

9. Energy Analysis

9.1. Pick-up Efficiency

Another essential component in determining the quality of ISD is its pick-up efficiency. It measures how well heated air removes moisture from various materials. The first rule of thermodynamics is used to calculate this energy consumption. The ratio of pick-up efficiency is the amount of moist taken out by the air in the drier room to the air's theoretic ability [24], and it is calculated using Equation (26),

$$x_P = \frac{M_L - M_{FT}}{M_A T(H_{AS} - H_I)} \tag{26}$$

Where, M_{FT} implies the mass of the specimen at the time of measurement, M_A is the mass flow rate of air, H_I implies the ambient air humidity, and T is the time at which the drying chamber's inlet air has an adiabatic saturation humidity.

9.2. Total Thermal Efficiency

It is the ratio of the energy used effectively to dry the wet content of the specimens to the total energy delivered. The corrugated-absorber plate solar collector and TES unit provide all of the energy for drying. A drier without heat storage produces large temperature fluctuations; therefore, food drying is not viable during off-sun hours or cloudy. A thermal energy system unit was fitted to prolong the drying time during the off-sunshine months. Thermal energy is a sort of stored energy that can be kept as LHS, sensitive heat, or both [25], [26]. The amount of heat accumulated is commonly calculated using Equation (27) and is dependent on the volume of processing material, temperature differential, and specific heat capacity,

$$q = M_{PCM}C_{p-PCM}(t_4 - t_1) \tag{27}$$

The latent heat energy is the charge or discharge of energy when a storage media changes from solid-to-liquid or both. In a solid phase, the rate of heat gain of the LHS device must be given as

$$q_{SOLID} = \frac{M_{PCM}C_{PS-PCM}\delta t_{S-PCM}}{3600} \tag{28}$$

In a liquid phase, the rate of heat gain of the LHS device must be given as

$$q_{LIQUID} = \frac{M_{PCM}C_{PL-PCM}\delta t_{S-PCM}}{3600} \tag{29}$$

The LHS device's heat gain rate during phase change must be defined as

$$q_{PHASE\ CHANGE} = \frac{M_{PCM}H_{LE-PCM}}{3600} \tag{30}$$

Where, M_{PCM} implies the mass of PCM material at solid and liquid phases, C_{PS-PCM}, C_{PL-PCM} and δt_{S-PCM}, δt_{L-PCM} are the specific heat and temperature variations of PCMs and H_{LE-PCM} implies the latent heat of PCM material.

The first rule of thermodynamics describing the device's inlet and output energy balance is utilized to compute the thermal efficiency of the ISD, which is the ratio of total energy supplied to the energy effectively used to evaporate the moisture content of the products [27]. The computation of overall thermal efficiency without PCM is given below,

$$x_{DO} = \frac{(M_L - M_f) \times H_{LE}}{\beta_S \times e_S} \tag{31}$$

Where, β_S implies the corrugated surface coefficient, H_{LE} implies the latent evaporation heat, and e_S is the solar irradiation.

10. Factors and Methods Used for Enhancing SD Efficiency

A number of characteristics and methods influence the thermal performance of SD systems. The determination and specification of these parameters contribute to the improvement of solar dryer efficiency by guaranteeing that the drying process will continue through the night without sacrificing the excellent quality of the dried goods.

The three major types of hazards affecting the execution and construction of solar dryers are construction risks, financial risks, and external risks.

Crops are dried so that they can be preserved for a long time. Drying is an important step in preserving commodities so that they remain available to consumers all year; however, the drying process is influenced by a number of factors. The key factors that influence drying efficiency are mentioned below.

10.1. Operating Conditions

The drying properties of air impingement, thin layer, and slice quality are all affected by air velocity, sample thickness, and drying temperature. When compared to conventional drying techniques, thin-layer air-impingement drying considerably improves rates of drying. The drying temperature, air velocity, and sample thickness all affected the rate of rehydration and drying duration of dried slices [28]. The influence of air temperature, air flow rate, and recycled-air-percentage is on drying energy consumption. When the air-temperature dryer rises, the thickness of the slices lowers, and the speed of drying and duration increase. When compared to the effect of temperature, the effect of air velocity is less substantial. Thermal modeling has been proven to be highly beneficial in increasing drying parameters, which leads to improved dryer performance.

10.2. Geometrical Factors

Various kinds of SDs with air-related SCs have been built, verified, and developed in different nations, with variable degrees of technological performance. These strategies were created in a variety of geometries to increase the drier time and dried product quality. The chimney was discovered to increase the buoyant force applied to the airflow, resulting in increased velocity of airflow, which is one side of removing moisture. In the absorber plate, the U-shaped corrugations run parallel to the direction of air flows. The gap between the bottom and the boxes of air-duct is used to fill with the insulation of glass wool. For unloading and loading of the trays, a gate is placed at the back end of the drier region delivered [29]. To create the necessary draft, a funnel is installed at the upper of the drier chamber. The air-flow rate of the dryer increases as the ambient temperature rises because of thermal resilience in the collector.

10.3. Adding of Reflectors and Concentrators

The concentrators were constructed with hardwood L-shaped frames and were shown to be efficient and lessening the time of drying to 21percent by raising the air temperatures of the dryer, which reduces relative humidity. A later examination of the quality of dried and fresh slices revealed that there was no difference in quality based on pH, acidity, color, vitamin C, and lycopene between dried without and with the concentrator. Concentrating Solar Panels (CSPs) are used to optimize the drying process in a mixed-mode SD. To maximize the incidence of solar radiation on the solar dryer, solar panels were employed, and one of the dryers uses a mobile and easily movable flat. The rate of faster drying is achieved in simulating sunny and gloomy conditions, which demonstrates the capability to dry items into suitable moist content in a sensible amount of time with the aim of lessening post-harvest loss. A batch-type solar drier with natural convection and North-South reflectors was used for drying. Reflectors were found to boost collector efficiency without load from 40-58.5% during peak sun irradiation levels on a usual day.

10.4. PV Source

To analyze the drying actions of different items at 50°C with varying rates of mass-flow for drier analyses, maintain a constant air-temperature drying with proportional integral derivative to achieve a uniform air temperature inside the drier chambers. It shows how the heat pump unit, PV unit, and solar collector all work together to generate a dried product with optimum chemical and physical properties. A blower, heat pump, grain stirrer, air ducts, and flat-plate-air-collectors are presented to lessen the electricity demand and maximize incident solar energy. The performance of the in-store drying process was shown to be enhanced by the sun-assisted heat pump drier system [30]. The drier rate was raised, and the grain moist content uniformity was improved. The solar dryer was constructed with two distinct sun collectors: a flat-plate SC for storing the produced heat energy and an air-type SC for heating the items. By taking advantage of the accumulation of energy and combining two different solar collectors, it is possible to use solar energy for drying constantly and everlastingly while ensuring the stability of the drying process by solar radiation correction. The technology may store solar energy in water during the day and use it to raise the temperature of drying air on cloudy and night days.

10.5. Forced Air Mode of Circulation

There are numerous convection forces of SD system designs that have been developed, tested, and built. Also, a drier chamber is covered with a transparent sheet, and a fan/blower circulates drier air through the product in this system. The main parts of an indirect-mode forced sun drier system are a drier chamber, a blower/fan, and an air heater, to deliver heated air to the drier chamber.

The SC and the drier chamber are the two main parts of the drying unit. Forced convection is provided by an electric fan, and transmits heat to the product in the drying room. It was observed that using a fan to combine forced and natural convection is critical for accurately managing the drying process[31]. Even when the airflow rate is low, the inclusion of baffles in a solar collector boosts its efficiency.

When the indirect and direct modes are compared, forced convection eliminates more moisture from the slices than natural, and forced convection has a faster heat transfer rate than natural convection. The solar dryer proved to be highly successful, with various advantages, including environmental protection and enhanced dried product quality. This form of dryer has been found to be effective in rural places where electricity and FFs are prohibitively expensive.

11. Description of SD with PCM as TES

An SD with a flat-plate-absorber and heat-storage was invented to use natural convection. A packed bed for heat storage, an FPC, a natural ventilation system and a drier chamber comprise the SD.

11.1. Flat Plate Collector

In front of the drying system, a flat plate with an inclined slope and insulation at the base was built. The toughened glass was installed on the flat plate by the collector. The gap allows air to move within the dryer [32]. Solar light absorption on the plate heats the air as it flows from the input to the drying mechanism.

11.2. Packed Bed

A TES device based on phase change materials was built beneath the cylindrical drying chamber. The tubes were securely packed and filled with PCM to prevent leakage. The tubes were organized in a zigzag pattern to hold paraffin wax material, which melts during the day and stores energy as noticeable and latent heat. During the night, this stored heat is used to dry crops [33].

11.3. Drying System

Above the packed bed, 3 rows and 2 columns of six rectangular drying trays made up the drying system. For drying samples, a drying tray was built with a mesh and stainless steel frame.

11.4. Natural Draft System

Above the drying room, a natural draft system with an absorber plate was installed. To prevent top losses, a hardened glass was installed on the top absorber plate. A packed bed of PCM is put beneath the absorber plate, providing vent space for warm air movement and enhancing convection [34].

11.5. Reflector Mirror

A south-facing reflector mirror was installed near the drying room. The intention was to improve air heating by reflecting the majority of dropping radiations to the FPC underneath. This enhanced dropping radiation improves the effectiveness of the dryer [35].

11.6. Working Principle

It is assumed that the system will face the midday sun. The radiation is entrapped to the greatest extent possible because it directly hits the flat-absorber-plate-I and is then reflected to the absorber-plate-I via the reflector, while the glazing-I prevents the loss of heat. When convection heats the drying setups, the air starts heating and then flowing across the gap between glazing-I and absorber plate-I [36]. A natural draft is generated as a result of thermal buoyancy, and air begins to flow through the system. The hotter air is utilized to heat and melt PCM for thermal storage, and the rest of the crops are transferred to drying trays, which start drying during the sun's shining hours. As moist air rises and comes into contact with absorber plate II, it is discharged from the system, which will be heated again and contribute to the creation of a draft because of thermal buoyancy. To produce thermal buoyancy for the natural circulation of damp air during off-sun hours, an angled absorber plate-II is positioned in cylindrical tubes across the drying plenum. The heat put in storage in the PCM is discharged while there is no sunlight, and the PCM is solidifying and releasing latent heat [37]. Crops employ this latent heat to continue drying during off-sun hours, which improves crop drying. The basic purpose of intermittent drying remains to improve drying hours, use maximal available energy, and reduce moisture-related microbiological and physicochemical losses.

11.7. Thermal Performance

An efficiency of SD can be computed based on the system drier and collector thermal efficiencies. Also, the efficiency of system drying is the energy ratio needed to dissolve moist to heat delivered to the drier. The heat delivered to the dryer by the SC is the result of solar radiation striking the collection. The efficiency of the system dryer (x_0) is an amount of its total effectiveness [38], and it describes how well the drier system is employed during product drier. The heat delivered to the dryer by collector type natural convection solar dryers is the incident solar radiation on the plane of SC and is computed as,

$$x_0 = \frac{l_c \sum_{T=1}^{T=24} m_{EV}}{3600(a_c + a_p) \sum_{T=1}^{T=24} i_H} \times 100 \tag{32}$$

Where, a_c is the collector region; i_H implies the intensity of solar radiation; l_c implies the LH of vapourization of water; m_{EV} implies the hourly moist evaporation of the product; a_P implies the absorber plate of natural ventilation.

11.8. Economic Performance of SD

Solar dryer products have the same hygiene and quality as branded products. The economic analyses of solar technologies are critical for defining their commercial viability. Solar dryers have been demonstrated to be both technologically and economically effective food drying equipment [39]. In this study, the profit, net present value (NPV), Simple Payback Period (SPB), and Return-On-Capital (ROC) were estimated. Solar technology's commercial viability is enhanced by its short payback period.

The price of the dry product (p) is,

$$p = C_R + C_O + C_M + l_W + P_K + i_R \tag{33}$$

Where, C_R is the raw material cost; C_O, C_M, l_W, P_K, i_R implies the operation, maintenance, annual labour, packing, and dryer insurance costs. The output of an investment can be used to study its performance. Profit (p_R) is the difference between total sales and total expenses, and it is expressed as,

$$P_R = P_S - P \tag{34}$$

Where, P_S implies total retail product price.

Return on capital (r_c) is also known as return from investments and is impacted through time. It is stated as the profit to the system cost (c) ratio.

$$r_c = \frac{P_R}{C} \qquad (35)$$

The simple payback (p_B) is calculated by dividing the cost of investments by the annual net income average. Also, it assists in the calculation of investment returns.

$$P_B = \frac{C}{P_R} \qquad (36)$$

The impact of capital rate-of-return and payback-time parameters on value for money is difficult to assess. During the project time, the NPV computes the Present-Value (PV) of extra cash flow. The net present value is the variance amongst the PV of cash in- and out-flows for each year, and it is computed as follows,

$$p_n = \sum P_N (1+I)^n - C \qquad (37)$$

From the above, $P_N = S(1+i)^{-N}$ implies the discounted PV (s) of the investment over N years [40].

12. Conclusion

Solar dryers and PCM have been discovered to enhance the efficiency of solar dryers, resulting in improved drying performance and lower energy usage. The use of PCM in SD aids in the maintenance of a more steady and ideal drying temperature, which is critical for producing high-quality dried items. PCM operates as thermal energy storage materials, absorbing surplus heat during the day and releasing it at night when solar radiation is insufficient. This aids in keeping a consistent drying temperature throughout the drying process, lowering the risk of over- or under-drying. Furthermore, it has been discovered that using PCM in solar drying applications increases the drying rate because the latent heat generated in the phase-change process improves heat transfer within the drying chamber. As a result, drying periods are reduced, and throughput is increased, making the drying process more efficient and productive. PCM reduces dependency on external energy sources, such as electrical or fuel-based heating systems, by storing and releasing thermal energy, leading to energy savings and cost reduction. The fundamental problem addressed in this review is to enhance the thermal conductivity and effectiveness of solar drying systems employing PCMs such as paraffin wax while lowering heat losses. This problem is addressed using several research techniques, including empirical and numerical approaches. The successful implementation of PCM in solar drying applications necessitates careful consideration of factors such as PCM selection, integration design, and system optimization, and it has great potential for improving drying performance, reducing energy consumption, and increasing overall solar dryer efficiency.

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