**Review of Recent advancement in Performance, and Thermal Energy Storage studies on indirect solar dryers for agricultural products.**

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**Abstract.** Efficient drying methods and post-harvest processes are crucial to reduce waste in fruits, vegetables, and agricultural products. Factors like moisture-related deterioration, climate change, mishandling, delayed shipping, improper storage, and sales delays contribute to post-harvest losses and quality degradation. Solar dryers, especially indirect-type solar dryers, provide a practical and environmentally friendly way to preserve these goods. In comparison to other types of solar dryers, indirect-type dryers have a number of advantages. This review focuses on evaluating the performance of different configurations of Indirect-type solar dryers in terms of drying time, maximum air temperature, drying efficiency for collectors, and overall dryer efficiency. The influence of various operating conditions on the thermal efficiency of Indirect-type solar dryers is also investigated. The study provides detailed information on the sensible and latent storage units and materials used in Indirect-type solar dryers, including those operating through natural or forced convection. The review also explores the utilization of advanced technologies, such as desiccant systems, recycling processes, the use of Nano fluids and nanoparticles, and thermal energy storage, to enhance the thermal performance of solar dryers. Additionally, the paper examines potential difficulties and suggestions for selecting, using, and testing thermal storage for indirect-type solar dryers. In summary, this review provides a comprehensive examination of indirect-type solar dryers, their performance. It highlights the potential for improving drying efficiency through the integration of advanced technologies and thermal energy storage.

1. Introduction

The worldwide population, which was 7.7 billion in 2020, is expected to increase by approximately 2 billion in the next three decades. This growth poses significant challenges to global sustainability, with food supply and security emerging as major concerns alongside energy and water [1]. The rising energy consumption worldwide necessitates the prioritization of a reliable, affordable, environmentally friendly, and renewable energy source [2]–[4]. In both developed and developing countries, a significant portion of food production (around 30-40%) is lost during post-harvest and processing stages. In developed countries, this loss occurs mainly at retail and consumer levels [1], [5]. Implementing drying methods for raw agricultural products can substantially reduce post-harvest losses [6]. To preserve agricultural products while retaining their essential nutrients over an extended period, it is crucial to reduce their moisture content [7].

Solar drying, which involves exposing the materials to solar radiation directly or indirectly, is an effective process in enhancing the quality and shelf life of products. It facilitates the simultaneous transmission of heat and moisture [8], [9]. Moisture is moved from a material's inside to its surface during the drying process, and then that surface moisture vaporizes into the environment. To change the temperature of the product being dried, heat transfer is required[10], [11]. During the drying process, it is essential to remove moisture rapidly at a temperature that does not significantly affect the flavor, texture, and appearance of fruits, vegetables, and other food items [12]–[15]. Additionally, the Along with limiting losses, guaranteeing process control, and requiring less ground surface than open sun drying methods, the drying process also attempts to protect the items from damage, birds, insects, and unexpected rainfall [16], [17]. However, there is a substantial technology gap in the creation of low-cost, energy-efficient dryers that can handle items of excellent quality. Careful model and component selection is necessary for solar dryers to use solar energy as efficiently as possible [17], [18]. Due to the intermittent nature of solar radiation, manufacturing dried goods of sufficient quality via solar drying is extremely difficult. During times of low insolation or at night, when sun radiation is not accessible, dehydration is interrupted. There have been various attempts to solve this problem, but the use of thermal storage materials has proven to be the most successful strategy [19].

Phase-change materials (PCMs) have demonstrated significant potential among thermal storage materials for their ability to store thermal energy during periods of solar radiation and release it when sunlight is unavailable [20], [21]. Depending on the presence or absence of solar radiation, PCMs go through a phase change, absorbing and releasing thermal energy (latent heat) [22]. This property makes latent heat storage systems advantageous, as they can store a significant amount of heat with minimal temperature change and high storage density [23], [24].  Solar energy can be used more effectively as a dependable energy source by including thermal energy storage (TES), especially PCMs [25]. Concrete, boulders, sand, and bricks are examples of sensible materials that can be employed as solid-state thermal storage for heat storage in addition to PCMs [26]. The use of sensible heat storage devices accelerates the drying process and reduces product mass losses compared to conventional solar drying methods [27]. Additionally, using thermal energy storage allows for improved control over external drying factors including moisture content, temperature, and drying air flow rate while providing total protection for the goods against dust, rain, wind, insects, and animals. [28].This leads to an improvement in product quality. A significant portion of current research on solar drying involves experimental investigations and performance evaluations.

Indirect-type solar dryers (ITSDs) are preferred over open sun drying (OSD) and direct-type solar dryers due to their ability to provide the necessary temperature, better drying control, color preservation, and crop protection. They are particularly recommended for photosensitive fruits, vegetables, and agricultural products [29], [30]. While there is some available literature on ITSDs, there is currently no specific study that comprehensively addresses their features, types, energy storage techniques, and performance. This review aims to fill this gap by thoroughly examining ITSD research and providing meaningful insights [19], [31], [32]. It explores various ITSD designs, operating characteristics, and energy storage techniques. The review's primary objective is to explore the fundamental concepts of solar drying methods, focusing on indirect solar drying mechanisms. The review analyzes the usefulness of various thermal energy storage materials used in ITSDs, covers several types of ITSDs for drying various agricultural goods, and assesses various design and performance factors. Ultimately, it aims to determine the most suitable dryer under different operating conditions for various product categories.

1. Advanced in solar dryer systems

In order to decrease post-harvest losses and boost product quality, many kinds of solar dryers have been created recently. Only a small number of these dryer varieties are, however, commonly used or offered for sale [33]. The size, system design, and solar energy consumption mode of solar dryers for agricultural and marine products can all be categorized. The sun dryers shown in Figure 1 are passive, active, and hybrid, with natural or forced air circulation, as well as direct or indirect heat transfer [7]. Overviews of the benefits and drawbacks of each type of dryer are given in Table 1.

Open sun drying, which involves exposing products directly to sunlight, leads to significant losses due to factors such as birds, rodents, insects, microorganisms, and unpredictable weather conditions like storms or rain [7], [34]. Furthermore, it causes color fading from UV radiation, uneven drying, impurities from outside contaminants such as dirt, dust, insects, and bacteria, and uneven drying[18], [35], [36].. Open sun drying is a long procedure that can lead to significant losses, and the dried goods frequently fall short of quality standards [37].

Passive solar dryers have a simple construc1tion and rely on natural air circulation driven by the buoyancy effect. Air that has been heated by the solar is forced through the drying chamber by air pressure, buoyancy forces, or a combination of both. Moist air is evacuated through a chimney or an exit at the top of the dryer [38], [39]. These dryers can be used to preserve fish, vegetables, and fruits at home by drying modest quantities of agricultural items at temperatures between 40°C and 50°C. Due to the fact that the goods being dried are not exposed to sun radiation directly, indirect passive solar dryers with forced convection have a drying chamber and a solar air collecting system, which solve the issue of cracking and safeguard vitamins and color [40].

Drying modes

Hybrid dryers

Forced convection

(Active dryer)

Natural convection

(Passive dryer)

Direct dryers

**Indirect dryers**

Mixed-mode dryers

Solar drying methods

Open sun drying

Solar drying methods

Drying designs

* Back pass and multi-pass dryers
* **Chamber type dryers.**
* **Cabinet dryers**
* Green house dryers
* Tunnel dryers
* In house dryers
* polyethylene vent dryers
* staircase dryers

Figure 1: Solar drying methods [33], [41], [42].

In active dryers, such as the drying chamber or solar collector, hot air is circulated using a ventilation system. A fan maintains the required airflow rate in the dryer, resulting in more efficient moisture evaporation from the product [34]. Compared to passive dryers, active dryers require higher investment and are more complex to operate and maintain. In order to obtain high drying efficiency and product quality, temperature and airflow rate management must be done properly [18] [33].

A hybrid solar dryer is a form of solar dryer that also uses power from other sources, such as biomass or electricity, or combines energy storage technologies, such as thermal storage. As a result, drying can proceed even when there is no sunlight [40]Simulated research on the drying of wood using a hybrid solar-electric dryer coupled with a thermal energy storage (TES) system was carried out by Lamrani and Draoui [43]. The TES keeps the drying chamber at a temperature that is between 4 and 20 degrees Celsius higher than the ambient air throughout the night to ensure that the wood is dried continuously.

Table 1: Here are the main advantages and limitations of various solar dryer types [5], [19], [40], [42], [44], [45]**.**

|  |  |  |
| --- | --- | --- |
| Type  | Advantages  | Limitations  |
| Direct type | * Least expensive
* Simple design
 | * UV rays have the potential to damage the product;
* small capacity;
* lengthy drying times; and
* Low efficiency.
* Additionally, the product itself works as a solar energy absorber.
 |
| Indirect type | * Less damage to the product from high temperatures
* Protection from UV radiation
* High efficiency
 | * More complex and expensive compared to direct type
 |
| Mixed mode | * High efficiency
* Less damage to the product from high temperatures
 | * UV rays might harm the product more difficult and expensive than direct sun drying
 |
| Hybrid type | * Ability to work without sunlight reduces dependence on solar energy availability
* Minimizes product loss
* Allows better control of drying process
* High efficiency
* Short drying time required
* Good quality of the final product
 | * Expensive
* May require fuel dependence
 |

Indirect-type solar dryers (ITSD) are widely regarded as more advantageous compared to other solar dryer types, despite the benefits they offer. One of the key advantages is that they enable the production of clean final products that retain their color, flavor, and nutritional content. By incorporating energy storage systems to address the intermittent nature of solar energy, the drying period can be reduced, leading to further improvements in the quality of the end product.

* 1. Performance analysis of indirect-type solar dryer
		1. Working principle of indirect-type solar dryer

The working principle of an indirect-type solar dryer (ITSD) involves two main components: a drying cabinet where materials are placed on trays, and a solar collector setup consisting of a glass plate and an absorber plate. The process begins by heating the food inside the drying cabinet and drawing out moisture by circulating hot air over it. The drying chamber contains wire mesh trays to hold the product being dried [46]. The solar collector setup, attached to the drying chamber at a specific inclination determined by the location's latitude, comprises a selectively coated absorber plate and a glass cover. The absorber plate is coated with a black hue to optimize sunlight absorptio. When solar radiation reaches the glass cover, various heat transfer processes occur. Some energy is reflected back, some is transmitted through the glass, some is lost to the atmosphere, and some is absorbed by the absorber plate. Convection transfers heat to the air entering the drying chamber, causing the food item to absorb heat and undergo dehydration [47], [48].

* + 1. Flat plate collector efficiency

The insufficient efficiency of solar dryers has been a point of contention from the start. Thermal performance, drying kinetics, environmental variables, economic evaluations, and dried product quality are just a few of the metrics that may be used to gauge how effective a solar drying system is [49]. The effectiveness of the solar flat plate collector depends on speed, ambient temperature, and humidity [50].The glass's participation in energy [19], [51] is estimated by,

 $Q\_{ic}=I\_{T}A\_{c}$ (1)

 $ Q\_{ac}=\dot{m}C\_{pa}(T\_{co }-T\_{ci })$ (2)

Qic is useful heat input, Qac is actual heat dispensed (W), IT is solar intensity (W/m2), $\dot{m} $is air flow rate (kg/s), Tci and Tco are the collector inlet and outlet air temperature (°C), and Ac = collector area (m2).

Collector efficiency (ηc) is estimated using the equation below [52]:

$η\_{c}=\frac{Q\_{ac}}{Q\_{ic}}= \frac{\dot{m}C\_{pa}(T\_{co }-T\_{ci })}{I\_{T}A\_{c}}$ (3)

* + 1. Drying Efficiency

A certain degree of moisture content, which varies for different fruits and vegetables, must be reduced for long-term preservation. The quantity of heat, Qd, required evaporating the product's water content from the surface and the core is calculated by:

 $Q\_{d}=m\_{a}C\_{pa}(T\_{co }-T\_{f })=m\_{w}L\_{w}$ (4)

Where Tf is the temperature at the chamber's exit in degrees Celsius, Lw is latent heat at a mean temperature of [(Tco+Tf)/2] in J/kg, and mw is the mass of water removed in kilograms.

Quantity of water extracted (mw) while drying is,

 $m\_{w}=\frac{m\_{i}(MC\_{a}-MC\_{f})}{100-MC\_{f}}$ (5)

Where mi is the product's initial mass (drying load) in kilograms, while MCi and MCf are the product's initial and final moisture contents.

The product's moisture content can be estimated using,

Moisture content, wet basis (wb),$ MC\_{i}=\frac{(m\_{i}-m\_{d})}{m\_{i}}$ (6)

Moisture content, wet basis (db),$ MC\_{i}=\frac{(m\_{i}-m\_{d})}{m\_{d}}$ (7)

Where md is the product's dried mass and mi is the product's initial mass before drying.

The power absorbed by the product (q) can be calculated using Equation (8) as:

 $q=\frac{m\_{a}C\_{p}(T\_{co}-T\_{i})}{t}$ (8)

The specific enthalpy of the air changes from hi to hco during heating in the collector, while the humidity ratio (ϕ) remains constant between ϕco and ϕf [11], [53].The mass of air required for moisture removal can be determined using Equation (9):

The specific enthalpy of the air rises from hi to hco during air heating in the collector, but the humidity ratio ϕi = ϕco stays constant. Drying air in the chamber absorbs moisture from the product, changing the humidity ratio from ϕco, and ϕf [11], [53].

The mass of air needed for the moisture removal process can be calculated using:

 $m=\frac{m\_{w}}{(ϕ\_{f}-ϕ\_{co})}$ (9)

The thermal power needed to heat the air from the absorber plate is given by Equation (10):

 $\dot{q}=m(h\_{co}-h\_{i})= ηA\_{c}I$ (10)

The drying efficiency (%) can be estimated as follows [11]:

For natural convection, drying efficiency (%),$η\_{d}=\frac{(m\_{w}h\_{fg})}{IA\_{c}}$ (11)

For forced convection[54], drying efficiency (%),$η\_{d}=\frac{(m\_{w}h\_{fg})}{(IA\_{c}+P\_{f })}$ (12)

Where hfg is the latent heat of vaporization (kJ/kg), Pf is the fan power

The power required to force air through the dryer can be determined by knowing the pressure drop (Δp) across the system and the efficiency of the blower/fan (ηf) ηf [55].

 $P\_{f }=\frac{\dot{(m\_{a}}∆p)}{(η\_{f}ρ\_{a })}$ (13)

In this equation, ṁa represents the mass flow rate of air, and ρa is the density of air.

The moisture removal rate (MRR) represents the quantity of moisture eliminated from the product within a specific time period. It can be determined by measuring the change in mass of the product before and after the drying process, along with the duration of drying required to achieve the desired moisture level. The relationship for calculating the MRR is provided as follows [52]:

 $MRR= \frac{initial mass-final mass}{drying time}$ (14)

The specific moisture extraction rate (SMER), which is the ratio of the mass of moisture removed in kilograms to the total energy supplied, can also be used to assess the drying performance. $SMER=\frac{mass of moisture removed(kg)}{total energy supplied}$ (15)

The second law of thermodynamics, known as exergy, asserts that a flow of matter, heat, or work can generate the maximum possible work when it reaches equilibrium with a reference environment. Exergy analysis is a valuable tool for analyzing, optimizing, and improving the energy efficiency of a process [46]. By conducting an exergy analysis, a more comprehensive understanding of the available useful energy at various system components, as well as the energy lost due to irreversibilities, can be obtained. The equations (17) and (18) provide the exergy inflow and outflow of the drying chamber, respectively, as described in reference [52].

 $Exin=m^{'}aCpa\left(To-Ta\right)-Tam'aCpaln\frac{To}{Ta}$ (16)

 $Exout=m^{'}aCpa\left(T-Ta\right)-Tam'aCpaln\frac{T}{Ta}$ (17)

Where: Ta is ambient air temperature T is temperature of air leaving the drying chamber

The exergy efficiency is a measure of how effectively the available exergy is utilized for the drying of a product. This efficiency value provides insight into the system's ability to convert available exergy into useful work for the drying process.

 $ηex=\frac{Exin-Exout}{Exin}$ (18)

1. Thermal energy storage (TES)

Solar dryers utilize solar heat to dry various foods and agricultural products. However, their main limitation is the discontinuous drying process in the absence of sunlight. To address this issue, various technologies have been implemented, such as heat recovery mechanisms, integrating curtains and photovoltaic (PV) systems in solar tunnel dryers, modifying collector designs, incorporating sun-tracking mechanisms, and utilizing thermal energy storage (TES) systems [56]. These systems improve energy system efficiency by stabilizing energy supply and enhancing reliability, reducing the time gap or uncertainty between energy supply and demand. In many impoverished nations, inadequate thermal energy systems and TES lead to substantial food and grain losses, particularly during the harvest season. Additionally, the shrinkage process during drying reduces the volume of food and agricultural products, resulting in lower shipping costs [57].

Sensible heat, latent heat, and thermochemical processes are three ways that thermal energy storage (TES) materials can store energy. Heating or cooling a liquid or solid medium, such as water, sand, molten salts, or rocks, constitute sensible heat storage. Phase change materials (PCM) that switch between the solid and liquid states are used for latent heat storage. Chemical reactions are used in thermochemical storage (TCS) to store and release thermal energy [58]. Due to the complexity of chemical reactions involved and its limitations, such as chemical instability and being unable to stop the process, chemical energy storage is the most difficult of all technologies. The most common type of energy storage is sensible heat storage since it is straightforward and inexpensive. However, it suffers from inadequate storage capacity, requiring larger systems. Latent heat storage (LHS) is advantageous as it allows for increased heat storage without triggering chemical reactions. For LHS systems, a high power capacity is essential for both energy charging and discharging [59]. Comparing latent heat storage (LHS) to sensible heat storage (SHS), LHS has several advantages over SHS, including maintaining a nearly constant average temperature during energy absorption and diffusion, higher energy densities in phase change storages, 5–14 times more latent heat storage than sensible heat per unit volume, and a significant thermal storage capacity per unit mass and volume for small temperature differences [57]. Extensive research has been carried out on indirect-type solar dryers combined with thermal energy storage (TES) units, biogas units, fossil fuel heaters, and electric heaters. However, the use of electric heaters, fossil fuels, and biogas-based burners can lead to higher operational costs and environmental impact. Consequently, there is a growing interest in assessing previous studies on different thermal storage systems integrated with indirect solar dryers operated in natural convection (NC) and forced convection (FC) modes. The objective is to identify sustainable and efficient solutions for solar drying processes, with a focus on minimizing environmental harm and ensuring cost-effectiveness.

* 1. **Sensible heat storage units (SHS)**

The materials are heated in sensible heat storage units (SHS) in order to store additional solar energy. The specific heat capacity, mass, and temperature difference of the material are only a few variables that affect how much energy SHS can store. High density, great thermal conductivity, high specific heat, and long-term stability are all desired properties for SHS materials. Brick, NaCl, cast iron, cast steel, rock, sand, and concrete are materials that are frequently utilized in SHS units [60]. The use of sensible heat storage in indirect sun dryers has been the subject of several studies that considered design, kinds, and qualities. Equation 19 can be used to figure out how much sensible heat is held in a substance.

 $Q=m\_{m}C\_{p}(T\_{f }-T\_{i})=ρC\_{p}V(T\_{f }-T\_{i})$ (19)

Where Q is the heat stored, mm is the mass of the material, Cp is the specific heat of the material, Ti is the initial temperature, ρCp is the volumetric heat capacity of the solid material, V is the volume, and Tf is the final temperature.

Overall, sensible heat storage systems are essential for improving the effectiveness and performance of sun drying systems, enabling efficient energy storage, and shortening the drying time for a variety of agricultural products. Kareem et al. [61] tested the drying of Roselle (Hibiscus sabdariffa) in order to study the characteristics of multi-pass SAC. The mechanism was helped in storing SH by granite. Estimates showed that a number of efficiencies, including collector efficiency (64.08%), moisture pickup efficiency (67%), drying efficiency (36.22%), and system optical efficiency (70.53%), varied. The system consumed 21 hours less time than OSD. The anticipated payback period was 2.14 years.

Cherry tomato dryers with integrated heat storage systems were created by Nabnean et al. [62]. 100 kg of tomatoes were dried over the course of four days at a temperature range of 30 to 65 °C. Insects, dust, and rain were all protected against by the system while the clothes were drying. Achieving efficiencies between 21% and 69%, the solar air collector (SAC) in this system. A triple-pass indirect-type forced convection solar dryer was constructed and tested in Vijayan's study [63]. With an average of 45%, the solar collector's thermal efficiency ranged from 12% to 66%. In the solar dryer, the pickup efficiency for drying potato slices ranged from 2.5% to 62.9%, with an average of 29.9%. The energy efficiency ranged from 2.8% to 87.02% throughout the day, with an average of 53.57%.

Dorouzi et al. [64] designed a solar dryer for drying tomato slices, which utilized a liquid desiccant system. This innovative dryer was self-sufficient in terms of electricity, eliminating the need for grid dependence. It operated at a drying temperature range of 60-65 °C and maintained a relative humidity (RH) of 28% during the desiccant regeneration process.

Tekasakul et al. [65] investigated the use of sensible heat storage for drying rubber sheets. They conducted experiments with heat storage devices placed at heights of 50, 100, and 150 cm. When used at various heights, the thermal efficiency of the heat storage devices ranged from 33% to 28%. Rubber sheets dried over a 100 cm heat storage surface in 78 hours, with a 6.71% thermal efficiency for the drying system.

Dryers equipped with sensible heat storage systems offer advantages such as accelerated drying processes and improved product quality. The thermal energy storage (TES) system allows drying to continue even when there is no sunlight available. Without TES systems, uneven drying rates can occur in integrated thermal solar dryers (ITSDs) due to the lack of solar radiation after sunset. TES systems are crucial for crop drying applications to ensure consistent and efficient drying. Mathematical models can be used to determine the required amount of TES material based on the desired temperature inside the drying chamber and the mass of the material to be dried.

* 1. **Latent heat storage units (LHS)**

Through the phase change process of phase change materials (PCMs), latent heat storage units (LHS) are employed to store solar energy. Temperature control and energy storage are made possible by PCMs' ability to absorb and release heat throughout the melting and freezing stages. Based on the PCMs' thermo physical, kinetic, chemical, economic, and environmental properties. According to their composition, PCMs can be divided into three groups: organic, inorganic, and eutectic. For example, organic PCMs based on paraffin and inorganic PCMs containing metallic or salt-hydrate components are further subclasses [66]. Equation (20) can be used to determine how much heat is stored in an LHS material.

 $Q=m\_{m}C\_{ps}(T\_{m }-T\_{i})+L+C\_{pl}V(T\_{f }-T\_{m})$ (20)

where, Q represents the heat stored in the LHS material (J), mm is the mass of the material (kg), Cps is the specific heat capacity of the solid material (J kg^(-1) K^(-1)), Ti is the initial temperature of the material (°C), L is the latent heat of fusion (J kg^(-1)),Tm is the melting point temperature of the material (°C), Tf is the final temperature of the material (°C).

Gilago et al. [67] examined the efficiency of passive and active convection indirect solar drying systems for drying carrot slices utilizing paraffin wax as a heat storage medium in a current study on dryers with latent heat storage. In order to enhance the mass flow rate, they first developed passive indirect sun dryers (type I), which they later upgraded by adding solar-powered fans to create a type II active setup. Comparing the type-I system to the type-II system, the type-II system showed gains in real heat supply, activation energy, and specific energy consumption, with average values being 11.8%, 12.2%, and 20.7% better, respectively. The collector efficiency for type-II was also higher than type-I, with average values of 67.8% and 59.7%, respectively. Drying efficiency showed significant improvements, with average values of 14.2% and 11.1% for type-II and type-I, respectively, representing improvements of 27.93% and 13.6%, respectively. In a study by Gilago et al. [68], two setups of a forced convection indirect sun dryer for drying pineapples were compared. Setup-1 did not include thermal energy storage (TES) system, while Setup-2 incorporated a TES system. In comparison to Setup-2 (66.97% and 10.84%), Setup-1 had somewhat greater collection and drying efficiencies (67.04% and 7.23%, respectively). In terms of activation energy and targeted energy utilization, Setup-2 performed better. For Setup-1, the dryer and collector had average energy efficiencies of 2.33% and 34.66%, respectively, and 2.12% and 57.07% for Setup-2. Setup-2 also exhibited enhanced CO2 emissions mitigation and credit. The efficiency of passive and active indirect type sundryers (PITSD and AITSD) with thermal energy storage units was assessed using drying ivy gourd slices in a different study by Gilago and Chandramohan [69]. Compared to AITSD, PITSD had an average collector efficiency of 69.87% and a drying efficiency of 15.2%. PITSD attained an average collector efficiency of 66.7% and a drying efficiency of 13.15 percent.

Ebrahimi et al. [70] investigated the impact of phase change materials (PCMs) positioned inside a flat plate collector (FPC) on its thermal performance and overall drying efficiency. The use of a collector with a PCM at the end section reduced the drying time of the slices by approximately 21.87%. The position of the PCM led to a thermal efficiency improvement of 5.02% to 10.13%. The overall efficiency varied from 21.92% to 25.72% depending on the PCM position. Mathew and Thangavel [71]designed and evaluated a novel evacuated tube heat pipe solar dryer with integrated thermal energy storage. The average energy and exergy efficiency of the solar collector ranged from 10% to 30% and 1.9% to 5.6%, respectively. The combined mass flow rate approach increased the collector output temperature to 67°C and shortened the drying time by 2 hours. Singh and Mall [72], used a paraffin wax layer as a thermal energy storage medium in an NC solar dryer for drying banana slices. The thermal efficiency of the dryer was 2.9%, and the banana slices were dried from 73.2% (w.b) to 20% (w.b) in 18 hours. Ebrahimi et al. [70]conducted a study to examine the impact of phase change materials (PCMs) placed inside a flat plate collector (FPC) on its thermal performance and overall drying efficiency. By incorporating a PCM at the end section of the collector, the drying time for the slices was reduced by approximately 21.87%. The position of the PCM also resulted in a thermal efficiency improvement ranging from 5.02% to 10.13%. The overall efficiency of the system varied between 21.92% and 25.72%, depending on the placement of the PCM. Mathew and Thangavel [71]developed and evaluated a novel evacuated tube heat pipe solar dryer with integrated thermal energy storage. The average energy and exergy efficiency of the solar collector ranged from 10% to 30% and 1.9% to 5.6%, respectively. By employing a combined mass flow rate approach, the collector output temperature was increased to 67°C, leading to a reduction of 2 hours in the drying time.

Singh and Mall [72] utilized a paraffin wax layer as a thermal energy storage medium in a natural convection (NC) solar dryer for drying banana slices. The thermal efficiency of the dryer was measured to be 2.9%, and the banana slices were dried from an initial moisture content of 73.2% (w.b) to a final moisture content of 20% (w.b) within a drying time of 18 hours. Vásquez, Reyes, and Pailahueque [73] conducted a thermodynamic analysis of solar dryers and highlighted the advantages of latent heat storage (LHS) dryers. LHS dryers maintain a nearly constant drying air temperature, even after sunset or during weak solar energy conditions. They are particularly suitable for drying medicinal plants with volatile oil content.

 As a result of shortening the drying process' processing time, it significantly contributes to energy conservation and improves system functionality. Low melting temperatures should be present in the LH storage material of choice. Paraffin wax is frequently chosen as an LH storage medium due to its inexpensive cost, convenient availability, and limited melting temperature.

* 1. **Both combination of latent and sensible heat thermal storage**

Combining sensible and latent heat thermal energy storage systems allows for flexibility in using a range of energy sources, including solar heat, waste heat, heat pumps, and off-peak power. By combining sensible heat storage (SHS) and latent heat storage (LHS), this system takes advantage of both of their advantages while addressing some of their drawbacks. By using concrete as the sensible storage medium, passive thermal energy storage units with enhanced thermal conductivity and wider contact areas, such as tubular heat exchangers, are commonly employed. Hybrid materials that integrate latent and sensible heat storage materials can effectively combine the benefits of both techniques and mitigate concerns associated with SHS and LHS systems [74].

In an experimental investigation by Bhardwaj et al. [75], Valerian rhizomes were dried using an integrated air-based indirect sun dryer (AITSD) with thermal energy storage (TES). With an average drying rate of 0.051 kg/h, the solar air heater achieved energy and exergy efficiencies of 26.10% and 0.81%, respectively. The drying process's total efficiency (TE) and specific energy consumption (SEC) were recorded as 11.33 kWh/kg and 10.53%, respectively. Sensible heat storage (SHS), phase change material (PCM), and direct sunshine were used in an experimental examination of an indirect solar dryer for drying chilies in the Western Himalayas by Bhardwaj et al. [76]. When compared to solar drying without heat storage and direct sunshine, the drying time was lowered by 78.12% and 86.00%, respectively. The study also found that chilies dried in the solar dryer with SHS, PCM, and direct sunshine included increased quantities of capsaicin, carotene, thiamin, and vitamin C.

Atalay [77] evaluated two thermal energy storage technologies, packed bed thermal energy storage (PBTES) and phase change material (PCM), in terms of energy usage and economics. Pebble stones and paraffin wax with a melting point of 55-60 °C were used as the storage media. The maximum thermal energy storage during the charging phase was found to be 49.52 MJ for PCM and 52.59 MJ for PBTES. Lemon slices were dried using the stored energy, and the average drying time was 6.27 hours for PBTES and 6.23 hours for PCM. The energy efficiencies of PBTES and PCM were 68.2% and 68.55%, respectively, while PBTES had a lower initial investment cost than PCM by 10.47%.Combining sensible and latent heat thermal energy storage systems in indirect solar dryers helps compensate for daily variations in solar radiation intensity. Latent heat storage is generally more efficient than sensible heat storage for solar drying applications due to its ability to store and release large amounts of energy within a small temperature range. Simulation models should be used to assess the short- and long-term performance of drying systems with and without storage media, enabling estimation of drying curves and financial benefits before implementing solar drying systems on a larger scale. Atalay [77] compared two thermal energy storage technologies, packed bed thermal energy storage (PBTES) and phase change material (PCM), in terms of energy usage and economics. Pebble stones and paraffin wax with a melting point of 55-60 °C were employed as the storage media. Lemon slices were dried using the stored energy, and the average drying time was 6.27 hours for PBTES and 6.23 hours for PCM. The energy efficiencies of PBTES and PCM were 68.2% and 68.55%, respectively.

Integrating sensible and latent heat thermal energy storage systems in indirect solar dryers helps compensate for daily variations in solar radiation intensity. Latent heat storage is generally more efficient than sensible heat storage for solar drying applications due to its capacity to store and release large amounts of energy within a narrow temperature range. To assess the performance of drying systems with and without storage media, it is recommended to utilize simulation models. This approach enables the estimation of drying curves and financial benefits, facilitating the evaluation of solar drying systems before implementing them on a larger scale.

1. Challenges and future research

Several challenges and areas for future research have been identified in the field of solar drying. The efficiency of current solar dryers ranges from 2.5% to 54%, indicating moderate performance. One of the main limitations is their inability to function effectively during periods of insufficient or no solar energy, such as cloudy weather or at night. This makes solar dryers less suitable for extensive and industrial applications. To achieve higher performance with lower operating costs, there is a need for upgraded solar dryer designs. Here are some key areas for future research identified from the literature review:

* Optimization of indirect-type solar dryers to reduce equipment and operating costs while maintaining product quality.
* Investigation into the use of reflecting panels or lenses to focus sunlight into a smaller space, increasing the amount of solar energy absorbed by the absorber plate and increasing the temperature of the final product.
* Investigation of thermal drying using renewable energy sources other than solar energy to reduce pollution emissions.
* Development of methods to achieve regulated drying parameters, such as higher drying temperatures and lower relative humidity, while minimizing energy input consumption.
* Reduction of pressure drops in the drying chamber to enhance airflow over the products being dried, such as fruits, vegetables, and agricultural produce.
* Determination of the optimal value and position of latent heat thermal storage to improve the performance of solar cabinet dryers.
* Running computer simulations to determine the short- and long-term effectiveness of drying systems with and without storage media, calculating drying curves, and assessing the financial advantages of solar-drying agricultural goods.

By addressing these research areas, advancements can be made in enhancing the efficiency, effectiveness, and cost-effectiveness of solar drying technologies for various applications.

1. Conclusion

In this review, the focus was on indirect-type solar dryers (ITSDs), covering their designs, construction details, thermal energy storage, and performance evaluations. The following key points were summarized from the review:

* ITSDs are crucial equipment for mitigating post-harvest losses of agricultural produce, particularly in rural areas of developing countries.
* ITSDs can be categorized as passive solar dryers (natural convection) or active solar dryers (forced convection). Passive solar dryers are simpler and less expensive to construct but lack control over drying rate compared to active solar dryers.
* Forced convection ITSDs, incorporating double-pass or triple-pass collectors and reflectors, have demonstrated better performance, leading to improved drying quality and overall efficiency.
* Enhancements in ITSD performance efficiency can be achieved through improvements in solar absorber designs, configurations, and materials.
* Integration of thermal storage systems and the use of different thermos fluids show promise in enhancing the performance of ITSDs.
* The combination of solar dryers and thermal energy storage reduces the overall drying process time. Sensible heat storage materials can maintain the interior temperature of the dryer higher than the ambient temperature for an average of 2 to 6 hours, while latent heat storage materials can maintain it for 1.5 to 10 hours.
* The interior temperature of the solar dryer with sensible heat storage is typically 6 to 10°C higher than the ambient temperature, while with latent heat storage, it is 8 to 20°C higher. Latent heat storage systems are preferable as they provide a constant heat supply throughout the drying process.

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