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**Review Article**

# A Review on Recent Advancements in Indirect Solar Drying of Agricultural Products

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ABSTRACT

Preserving food from harvest to consumer level is a challenge in the agriculture sector. Drying is a crucial post-harvest technique that lowers moisture to levels suitable for storage. Solar drying is a traditional renewable energy drying process. Different solar drying methods have been developed to speed up the drying process and maintain the product's nutritious content. Indirect solar drying is one of the efficient drying methods that has better control over the drying temperature. Indirect solar drying has developed into a desirable, effective, and environmentally responsible drying technique when combined with solar collectors and thermal storage. Flat plates, evacuated tubes, and concentrated solar collectors are used in indirect solar dryers along with direct air heating or thermal storage systems. This study aims to review the improvement in the drying rate with different air heating mechanisms. Flat plate collectors with liquid working fluid are employed to heat the air, whereas in evacuated tube collectors, the air is directly heated passing through the tubes. Working fluids, air temperature, air velocity, and solar radiation are important dryer parameters affecting the drying rate. The paper also discusses the usage of heat storage devices for continuous drying operations. The drying time is greatly reduced through integration with latent and sensible storage technologies. Products that have been dried using indirect solar dryer and appropriate drying models are tabulated. Aspects of indirect solar drying and challenges in drying time reduction are also reported.

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## 1. INTRODUCTION

The quality of agricultural products deteriorates rapidly because of improper storage after post-harvest. Cold storage and drying are the commonly used post-harvest techniques for food preservation without compromising their nutritional value. Drying is a traditional technique to increase the shelf life of agricultural products. The drying process completes in two major steps: first is water transfer from the inside of the material to the surface; second, water diffusion to the atmosphere from the surface of the material (Belessiotis & Delyannis, 2011). Solar drying is an easier and more effective way of food preservation that has been used since ancient times. Solar drying methods can be divided into two major groups: open sun natural drying and forced energy drying. In the open sun, drying products are directly exposed to solar radiation. Direct exposure of the product to solar radiation reduces the color and nutritional value of the dried product (Getahun et al., 2021). Forced energy drying is carried out with hot air in a drying chamber. The use of fossil fuels to heat the air creates a problem of environmental pollution. The solar dryer is a great alternative to overcome the limitations of traditional drying methods. It is an efficient technology to fulfill the increasing demand for quality and long-life healthy food (Kusmiyati & Fudholi, 2021; Singh & Gaur, 2022; Zareiforoush et al., 2022). Researchers have developed solar dryers to avoid uncontrolled drying, exposure to direct sunlight, infection by insects, and exposure of foodstuff to rain and dust. Indirect solar drying ensures safe moisture levels and superior microbiological and nutritional values (Tabassum et al., 2019).

Solar dryers are designed based on local climatic conditions for drying specific products. Most agricultural products require a temperature range of 50-80 °C to get better quality of the product (Nukulwar & Tungikar, 2020; Prakash et al., 2016). The classification of solar dryers is presented in Figure 1. Solar dryers are categorized into three main groups: direct, indirect, and mixed-mode solar dryers. In the direct solar dryer, the substance to be dehydrated is exposed to sunlight coming from a transparent cover placed over it. Cabinet dryer and greenhouse solar dryer come under the direct solar dryer. When direct solar dryers are combined with solar air heaters, it falls under mixed-mode dryers. A variety of designs and performance evaluation methodologies of mixed mode, natural circulation, forced circulation, and greenhouse type of solar dryers are available in the literature (Girase et al., 2020). The higher temperature inside the greenhouse solar dryer increases the drying rate of the product significantly. Nowadays, photovoltaic-ventilated greenhouse solar dryers

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are becoming popular for large-scale agricultural product drying (Vengsungnle et al., 2020). Tiwari and Tiwari studied a greenhouse solar drying system integrated with a semi-transparent photovoltaic module. Experiments were conducted for drying grapes (Tiwari & Tiwari, 2018). The crop cannot be dried during off-sun hours in the greenhouse dryer. To improve the efficiency of the greenhouse dryer and to provide heat continuously throughout the drying, it could be integrated with a thermal storage system (Ahmad et al., 2021).

The second type of solar dryer is the indirect solar dryer. It consists of a solar collector, heat exchanger, and drying chamber. In an indirect solar dryer, the hot air heated at the collector is at the drying chamber. Indirect solar dryers usually consist of forced convection mode. Various researchers have used a DC fan and blower that operates on the PV system (Matavel et al., 2021). The quality of the product dried in an indirect solar dryer is improved because of better control over the drying temperature and the absence of direct exposure to sunlight (Pirasteh et al., 2014). Of all the solar drying techniques, indirect solar drying has proven to be the dominant and efficient drying method to maintain dried products clean and hygienic (Duffie & Beckman, 2013; Lingayat et al., 2020). Many experimental, numerical, and mathematical modeling studies have been carried out to evaluate the performance of the indirect solar dryer. The drying rate of the agricultural crop is enhanced by raising the air temperature to a considerably high value. The product dried inside the dryer is protected from birds, animals, and humans (Rahman et al., 2017). However, the cost of the development of indirect solar drying technology for agricultural applications is a major determining factor (Udomkun et al., 2020).

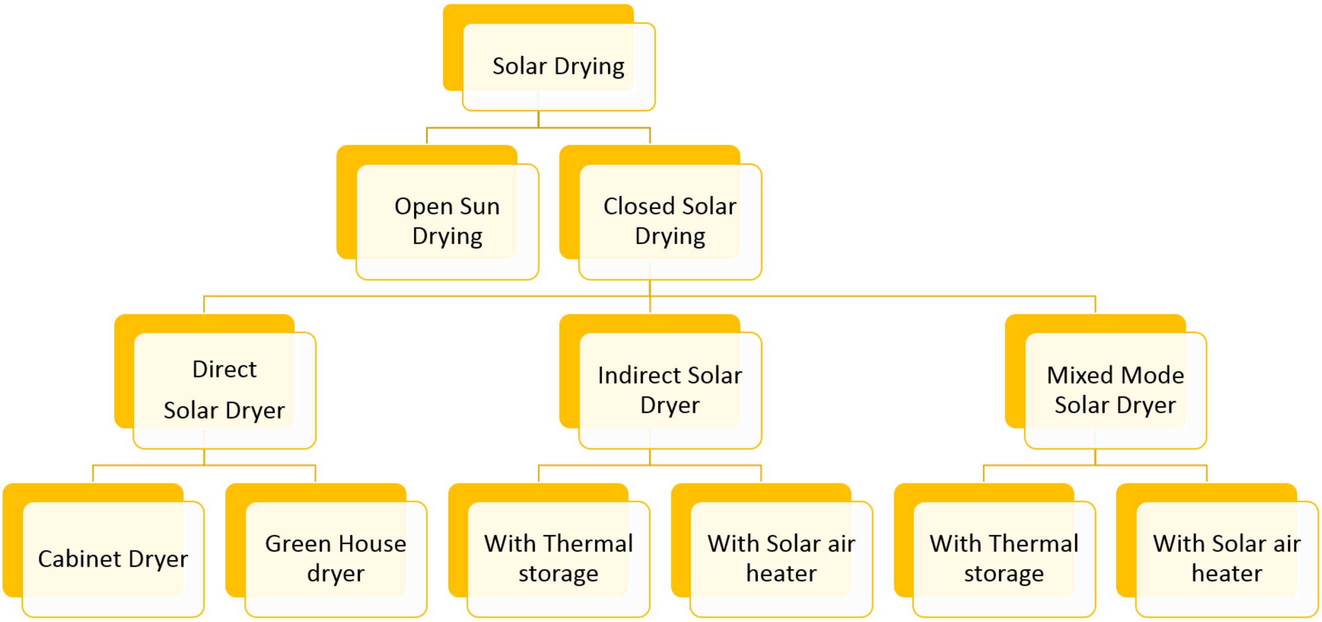

**Figure 1.** Classification of solar dryer system

The main purpose of the indirect solar dryer is to maintain the quality and color of the product to be dried and protect the environment by reducing the emission of hazardous gases. The indirect-type solar dryer has several advantages over direct and mixed-mode dryers for drying fruits and agricultural products (Jangde et al., 2021; Khallaf & El-Sebaii, 2022). Researchers have employed non-contracted and concentrated solar collectors in indirect solar drying. A recent development in indirect solar drying comprises thermal storage systems to ensure drying even during periods of no sunlight. Review studies on solar dryers reported in the literature focus on the type of dryer, operating parameters, product dried, and cost reduction. No study has yet addressed the air heating mechanisms and the role of the collector and thermal fluid in maintaining the drying temperature at an optimum level. In the current study, an effort has been made to review the dryers integrated with flat plate collectors, evacuated tube collectors, and solar concentrators with and without a thermal storage system. A flat plate collector with a glass cover is the most widely used solar collector in indirect solar drying. Various researchers have reported that effective utilization of solar energy and selection of appropriate thermal storage systems significantly reduce the drying time. Integration of the solar collector with the drying unit is a challenging task as it faces high installation costs and storage of excess thermal energy harnessed during peak sun hours. This study helps researchers select suitable solar collectors and thermal storage systems to increase the drying rate.

Section 1 presents the introduction of the solar dryer and the need for the review study. Section 2 describes the solar dryers integrated with the flat plate collector, evacuated tube collector, solar concentrator, thermal storage systems, and auxiliary devices. Section 3 presents the mathematical models used to dry products in indirect solar dryers. Section 4 presents the various aspects of the solar dryer.

## 2. DEVELOMPENT OF INDIRECT SOLAR DRYER

Based on the recent trend in the development of indirect solar dryers, these are categorized into two major groups. The first is a dryer without thermal storage and the second is with thermal storage.

### 2.1. Integration with solar collector

A solar collector is the main device in the indirect type of solar drying. Solar collectors are employed to harness solar energy and heat the working fluid. Flat plate collectors and evacuated tube collectors are commonly used solar collectors in indirect solar drying. Recently, some researchers have used concentrated solar collectors to heat air (Malwad & Tungikar, 2020).

### 2.1.1. Flate plate collector

A flat plate collector heats the air to a low to moderate temperature. Solar dryers with flat plate collectors with natural and forced convection systems are proven to be suitable for drying various products. Koua et al. designed and constructed an indirect solar dryer. Dryer consists of a solar air collector system and a drying chamber in which rectangular trays are arranged in the tree structure. Wooden trays of size 95 cm × 106 cm are separated by 15 cm from each other. Solar air collector system has dimensions of 89 cm × 225 cm, which produces thermal energy for drying cocoa beans. Shrinkage, density, porosity, heat, and mass transfer coefficients of cocoa beans were measured during the indirect solar drying process. The experimental result showed that the cocoa beans had a final porosity approaching 25 %. Water removed during the drying process was replaced by gas. The heat and mass transfer coefficients increased from 1.92 × 104 to 8.08 × 102 W/m$^2$K and from 1.88 × 107 to 7.88 × 105 m/s, respectively (Koua et al., 2019). Zoukit et al. (Zoukit et al., 2019) developed a tunnel-type indirect solar dryer and established static and dynamic characteristics under different weather conditions. An experimental setup is shown in Figure 2. The Takagi-Sugeno fuzzy (TSF) model was implemented to predict the temperature distribution in the drying chamber. This study is highly informative to know the energy available inside the drying chamber under different environmental conditions.

**Figure 2.** The experimental rig (Zoukit et al., 2019)

Demissie et al. (Demissie et al., 2019) analyzed the temperature distribution inside the dying chamber of a solar dyer. The Computational Fluid Dynamics (CFD) model was employed to predict flow and temperature at different positions of the trays. The difference between experimental and numerical results was found to be less than 2 %. This study gave insight into the temperature distribution in the drying chamber. Bhor et al. (Bhor et al., 2010) studied the performance of solar tunnel dryers for fish drying. Experiments were conducted on drying salted and unsalted fish and compared with open sun drying. The maximum temperature obtained in the drying chamber was 53.5 °C. Moisture content reduced in the upper and lower parts of the tray was 19.29 % and 19.63 % (d.b.), respectively, within 35 hours. Fish drying time was reduced by 5 hours in comparison with open sun drying. Friedman's test evaluation demonstrates retention of color and texture and improved the overall quality of the dried fish. Sallam et al. (Sallam et al., 2015) compared the performance of direct and indirect solar dryers having the same dimensions in natural and forced convection modes. Transparent polyethylene film was used to cover the direct solar dryer, while the indirect solar dryer was covered with black polyethylene film. Each dryer consists of six perforated galvanized steel trays with the dimension of 1.00 × 0.90 × 0.04 m, and spacing between them was maintained at 0.12 m. Experiments were conducted under the same atmospheric conditions to analyze the performance of both dryers. The average moisture removal rates of 70.0-75.4 % and 85.5-86.8 % were observed for natural and forced convection, respectively. Experimental results showed a better drying rate in the forced convection mode. Kilanko et al. (Kilanko et al., 2019) evaluated the performance of a novel natural convection solar dryer. Aluminum foil was used as an insulator in the dryer compartment. The collector is made of galvanized sheet and glass mounted on the top of the dryer. The setup was used for drying pepper. Experiments were conducted for drying 200 g of pepper which was weighed periodically to measure weight loss. During the experimental study, lower temperatures and humidity in the drying chamber were observed within the early morning hours. However, after 10 am, the temperature of the chamber reached higher than the ambient. The average moisture content of 81.3 % w.b. was removed from the pepper during the experiments. The average efficiency of 28.4 % was achieved with the removal of 81.3 % w.b. moisture content. Montero et al. (Montero et al., 2010) constructed a hybrid solar dryer and analyzed the drying kinetics of various agro industrial by-products in different operation modes. Air heated by the flat plate collector heating system passed into a cabin-type drying chamber. The dryer comprises a galvanized iron chimney that allows easy removal of moisture from the drying chamber. The dryer consists of two trays. 2 kg olive pomade was loaded in each tray and experiments were carried out. The result showed 15 % to 50 % reductions in drying time based on the convection mode. In the forced convection mode, air speed inside the collector of 4 m/s and the average mass flow of 0.224 kg/s were maintained. Banout et al. (Banout et al., 2010) compared the effect of direct and indirect solar drying on the essential oil quality of Sacha culantro (Eryngium foetidum L). A direct solar dryer having drying chamber dimensions 1200 mm wide, 1600 mm length, and 600 mm height was employed. Natural circulation indirect solar dryer has a cylindrical drying chamber with 500 mm diameter and 1100 mm height. The drying chamber is connected to a solar collector to take hot air. A solar drying test was conducted and the main constituent of the Sacha culantro essential oil was determined. The indirect solar drying method was found to be better, given that a dried product had excellent chemical composition and better appearance.

Deshmukh et al. (Deshmukh et al., 2014) investigated the performance of a dryer for drying ginger. A natural circulation solar dryer with three trays was developed in the study. The drying chamber was coated and thermally insulated with asbestos sheets to reduce heat loss. The air was heated during its flow through the solar collector and then passed into the drying chamber to remove moisture. A vent was provided at the top to facilitate the removal of moist air. During the test, the average temperature inside the drying chamber reached 57 °C. The average drying time required for drying gibber was observed to be 8 hrs, which was much less than open sun drying. Sunil et al. (Sunil et al., 2014) investigated the performance of an indirect solar dryer for drying fenugreek leaves in the natural convection mode. The developed indirect solar drying system consists of double-glazed flat plate solar collectors of 0.60 $m^2$. The drying chamber has two plywood trays of dimensions 60 mm × 30 mm × 60 mm. The drying temperature at the collector outlet was observed to be in the range of 49.45 to 77 °C. Drying time of the fenugreek leaves was reduced to 5-6 hours from 13 hours in open sun drying.

Flores-Prieto et al. (Flores-Prieto et al., 2014) developed an indirect solar dryer prototype integrated with a flat plate solar water collector. An intermediate heat exchanger was installed which is connected to the thermal storage and drying chamber. A flat plate cross flow-type heat exchanger was installed to prevent the mixing of water and air. Wet air from the drying chamber was removed via electric fans. Solar dryer was tested for 32 wet molds of the ceramic at the air velocity of 90 $m^3$/hr in a drying chamber. Moisture content was reduced by 27 % to 1 % in 9 days, which has 73 % of the drying time of the plaster molds. ELkhadraoui et al. (ELkhadraoui et al., 2015) carried out an experimental analysis of a solar greenhouse dryer. The forced convection drying system consisted of a flat plate solar collector and a chapel-shaped greenhouse. Two centrifugal fans were provided to exhaust moist air from the greenhouse. Drying tests were carried out on red pepper and Sultana grape. Experimental results were compared with the open sun drying method. The drying times of red pepper and grape were reduced to 7 and 17 hrs, respectively. Economic analysis revealed a very small payback period. The payback period was found to be 1.6 years, which is quite shorter than the life of the dryer.

Gulandaz et al. (Gulandaz et al., 2015) evaluated the performance of a mixed-mode solar dryer for drying paddy seeds. The modified solar drying system had a flat plate solar collector with tracking adjustment. The drying unit had four compartments: each compartment comprises two trays made of a wooden frame. The drying chamber was placed below the solar collector. The temperature inside the drying chamber was recorded to be in the range of 39.35 to 49.9 °C. The germination viability of the seeds dried in a solar dryer was 97.5 %.

Hegde et al. (Hegde et al., 2015) designed and constructed a low-cost indirect solar dryer. Solar collectors with two different configurations were employed to heat the air required for drying. In the first configuration, air flows between the glass cover and absorber plate and in the second configuration, air flows between the absorber plate and bottom insulation of the flat plate solar collector. The second configuration provides about 2.5 °C higher drying temperatures in comparison with the first configuration. The efficiency rate of 27.5 % was achieved in the top flow configuration, whereas the efficiency in the bottom flow configuration was found to be 38.21 %. Banana dried at 1 m/s was found best in color, taste, and shape.

Shrivastava & Kumar (Shrivastava & Kumar, 2016) developed an indirect drying unit that consisted of a drying chamber, V corrugated double pass solar air heater, and an air-supplying unit. The drying chamber comprised three stainless steel wire mesh trays. A DC fan provided in the air supply unit supplies ambient air to the solar air heater. Then, the heated air was supplied to the drying chamber through the duct, as shown in Figure 3. Experiments were performed by keeping 2 kg of fresh fenugreek in each tray. The average value of the convective heat transfer coefficient for natural and forced convection modes varied from 2.90 to 6.91 $W/m^{2}{}^\circ C$ on the first day and 0.45 to 0.79 $W/m^{2}{}^\circ C$ on the second day of drying.

**Figure 3.** Photographic view of drying of fenugreek a in forced convection indirect solar dryer (Shrivastava & Kumar, 2016)

Ergün et al. developed an indirect solar dryer in which even drying temperature was maintained. A drying temperature of 40 °C was maintained though solar radiations received by the solar collector varying continuously over the day. An artificial neural network model was implemented to maintain the outlet air temperature constant. Purnomo & Indarti (Ergün et al., 2017) investigated the drying kinetics of sambungnyawa leaves in a modified indirect solar dryer. Modifications were done to increase the service time of the dryer. A wind ventilator was provided at the top of the modified dryer to create negative air pressure and increase the airflow in the drying chamber. Mathematical modeling presented by Verma proved to be the best equation. Experimental results showed double production rate of Simplicia with an improved dryer.

Zaredar et al. (Zaredar et al., 2018) constructed a cabinet-type indirect solar dryer. Castillo Téllez et al. (Castillo Téllez et al., 2018) presented an experimental study of solar drying of stevia leaves in an indirect solar dryer operating in natural and forced convection modes. A drying chamber is where hot air was delivered from the array of flat plate solar collectors. The temperature of the air entering the drying chamber reached a maximum value of 57 °C at average solar irradiance of 930 $W/m^2$.

Mahapatra and Tripathy (Mahapatra & Tripathy, 2018) compared the performance of direct, indirect, and mixed-mode solar dryers in the natural convection mode. The indirect solar dryer has a drying chamber and flat plate collector covered with a glass cover for effective air heating, as shown in Figure 4. Experiments were performed to dry 0.005 m thick slices of carrot. The mathematical model of Wang and Singh was found better than direct and mixed-mode solar dryers. Indirect solar dryers were found to be more efficient than direct and mixed-mode solar dryers. Drying times were found to be 40.91 % and 7 % longer than those in direct and mixed-mode solar dryers, respectively.

**Figure 4.** Indirect solar dryer for drying carrot slices (Mahapatra & Tripathy, 2018)

Ullah et al. (Ullah et al., 2018) studied the drying behavior of asparagus (Asparagus Officinalis L.) in an indirect natural convection solar dryer with a flat plate solar collector. Drying tests were conducted in different months for drying 78 and 48 Asparagus samples. A maximum moisture removal rate of 8.6 % was obtained in July. Lakshmi et al. (Lakshmi et al., 2019) conducted a comparative performance analysis of mixed mode and indirect parallel flow solar dryers. Abi Mathew and Thangavel (Abi Mathew & Thangavel, 2019) dried anti-diabetic medicinal products in an indirect natural convection solar dryer. Flat plate collector efficiency and dryer efficiency were found to be 15 % and 7 %, respectively. Ash content in the product dried in the dryer was observed to be lower because it was not contaminated by surrounding dust particles.

Haque et al. (Haque et al., 2019) developed solar dryers based on local requirements and expectations to dry agricultural products. A collector covered by the plastic sheet was seamlessly integrated into the drying chamber. The temperature in the drying chamber was observed to be 15 °C higher than the ambient temperature. Average collector and drying efficiency was 21 %, and 10.73 % respectively at average solar radiation 648 W/m$^2$. Simo-Tagne et al. (Simo-Tagne et al., 2019) developed a mathematical model to predict the drying behavior of wood in an indirect solar dryer. Results of the numerical and experimental analysis showed a noticeable reduction in the drying time for wood.

A solar dryer developed by Goud et al. (Goud et al., 2019) consists of a V-shaped corrugated absorber plate, as shown in Figure 5. One end of the absorber plate was connected to the drying chamber and another to the trapezoidal duct. DC fans fitted to the duct were powered by a PV panel. Experiments were conducted to determine the drying kinetics of the product and estimate the thermal performance dryer. The collector and drying efficiencies were achieved in the range of 74.13-78.30 % and 9.15-26.06 %, respectively. We managed to make better improvement in the forced convection mode than in the natural convection mode.

The Physico-chemical and sensory properties of wild berries, wild canola, and wild bell dried in indirect dryers showed significant improvement over those dried in the open sun. Indirect solar drying is a low-cost and effective option to increase the shelf life of perishable agricultural products (Kumar Aggarwal Yashwant Singh Parmar & Sharma Yashwant Singh Parmar, 2019).

**Figure 5.** Indirect-type solar dryer with V corrugated absorber surface coupled with the trapezoidal duct (Goud et al., 2019)

The drying temperature is the crucial parameter in deciding the performance of the dryer and the quality of the product dried. Uniform temperatures in the drying process significantly reduce the drying time of the product. Nasri (Nasri, 2020) developed a solar chimney dryer for drying bananas and peaches. The novel design of the indirect chimney solar dryer is presented in Figure 6. The chimney acts as a drying chamber that comprises trays to dry the product. The bottom end of the chimney is connected to a solar collector to pass the hot air through it. The maximum temperature inside the chimney increased to 67.5 °C.

Etim et al. (Etim et al., 2020) observed that air inlet area, shape, and quantity of products dried significantly affected the drying efficiency of the indirect and direct solar dryers. Das and Akpinar (Das & Akpinar, 2020) integrated an automatic tracking solar air collector with the two-cabinet indirect solar dryer. Drying efficiency was calculated at three different fan speeds to determine the effect of airflow rate on the drying performance. Maximum drying efficiency was obtained at a fan speed of 1690 rpm. Mutabilwa and Nwaigwe (Mutabilwa & Nwaigwe, 2020) developed a forced convection indirect solar dryer integrated with a double-pass flat plate solar collector as depicted in Figure 7. Drying temperature and airflow inside the dryer were predicted using the CFD model. A dryer achieved a maximum temperature of 72 °C with operational efficiency of 72.5 %.

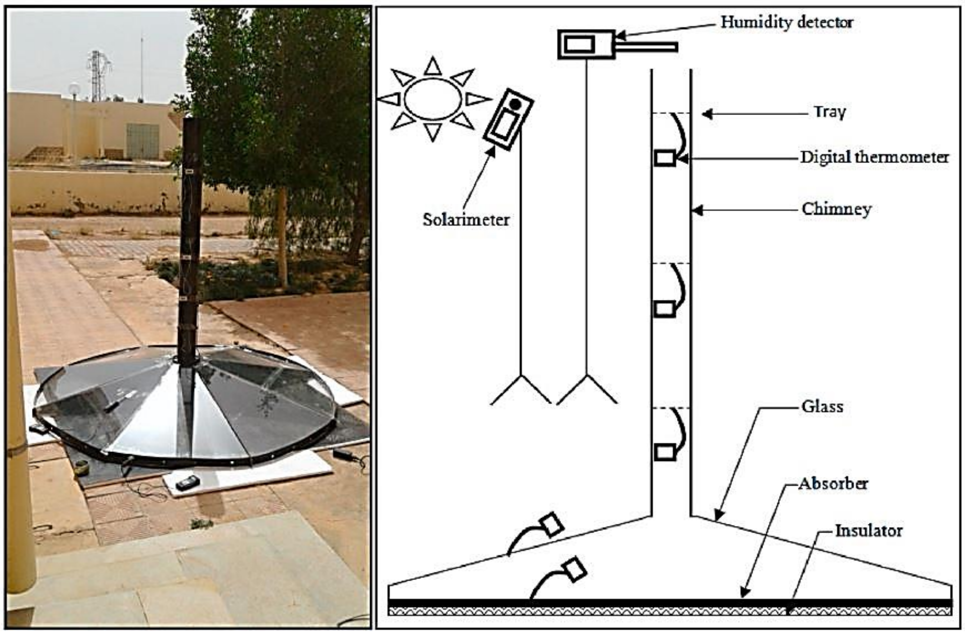

**Figure 6.** Solar chimney dryer (Nasri, 2020)

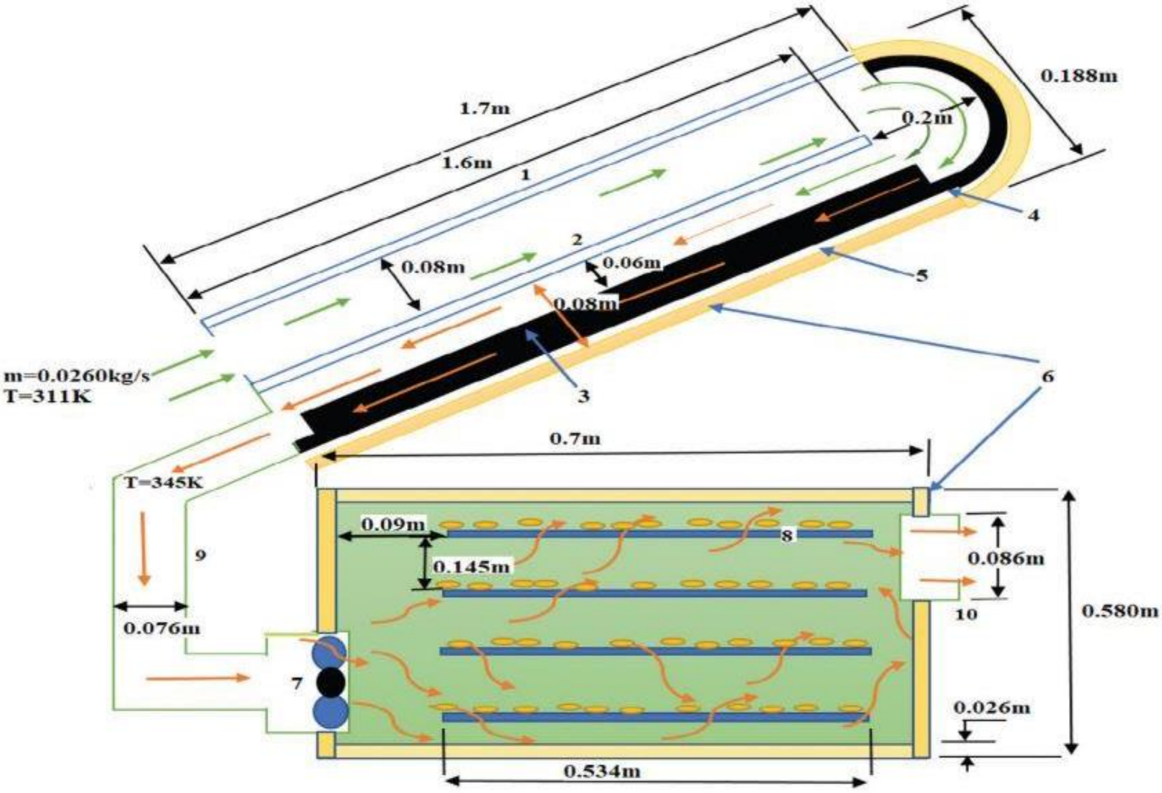

**Figure 7.** Schematic of DPSC banana solar dryer (Mutabilwa & Nwaigwe, 2020)

Lingayat et al. (Lingayat et al., 2020) reported exergy and energy efficiency of indirect solar dryers at 21.57 % and 17.73 %, respectively. Sharma, Srivastava, and Singh (Sharma et al., 2021) constructed low-cost solar dyers from locally available material for drying agricultural products. The maximum temperature obtained under natural and forced convection was 72 °C and 203 °C, respectively.

An innovative indirect solar dryer with an auxiliary heating system was investigated by Hssaini et al. (Hssaini et al., 2021) for drying figs. The drying system consists of a solar air collector, an auxiliary heater, a drying chamber, and a circulating fan. Figure 8 shows the components of the dryer. A control unit was provided to regulate the temperature inside the drying chamber. Experiments were performed at 60, 70, and 80 °C temperatures, and air flow rates were maintained at 150 and 300 $m^3/h$. The results showed that energy consumption increased with speed and drying temperature.

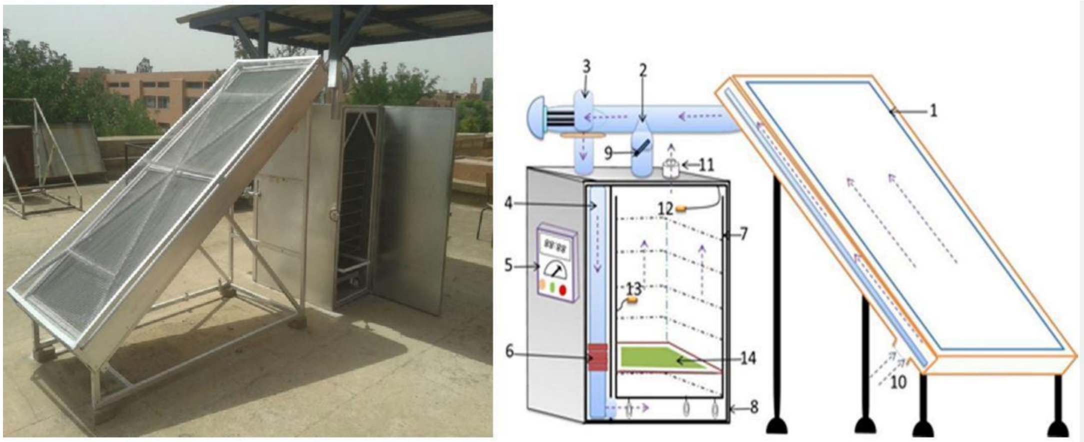

**Figure 8.** Experimental setup and schematic diagram of the indirect solar dryer (Hssaini et al., 2021)

Geete et al. (Geete et al., 2021) studied the effect of solar collector roughness on the performance of the dryer. Experiments were conducted with Grade 150 and Grade 300 surfaces to analyze the effect on collector efficiency and cabinet temperature. The results showed a maximum collector temperature of 74 °C and a cabinet temperature of 66 °C with a grade 300 surface. Maximum energy efficiency of 35.98 % was achieved with a rough surface.

Lingayat et al. (Lingayat et al., 2021) performed drying experiments on tomatoes and brinjal to study the drying kinetics using the indirect solar dryer. Solar air collector with V-shape absorber plate was used for air heating. Hot air passed from the upper opening of the collector into the drying chamber. The results of the drying experiment revealed an average temperature of 56.45 °C at the collector outlet and the chamber temperature of 57.27 °C during the drying of the product. The drying efficiency of the system was 31.4 % and 25.16 % during tomato and brinjal drying, respectively. Zriba et al. (Zriba et al., 2021) carried out an experimental and numerical study to predict the drying kinetics and drying time of tomatoes. Dimensions of the drying chamber were optimized from the numerical study.

Goud et al. (Goud et al., 2021) experimentally investigated the drying behavior of green chili and okra in an indirect solar dryer. Experimentations were carried out to compare the drying time and quality of the dried product with open sun drying. It was found that the average drying ratio of green chili to okra was 0.4303 and 0.9788 kg/h, respectively. Abdelnour et al. (Abdenouri et al., 2022) developed a fuzzy logic controller to restrict the temperature inside the drying chamber in the drying process. Performance evaluation for the fuzzy logic controller revealed that dryer performance was recovered in less than 8 minutes after the temperature variation. Gupta et al. (Gupta et al., 2022) concluded that drying green tea in a photovoltaic-thermal (PVT) collector-based solar dryer was an excellent choice to maintain quality.

Galago and Chandramohan (Gilago & Chandramohan, 2022) compared the performance of natural and forced convection indirect solar dryers for drying ivy gourds, as shown in Figure 9. Results of an experimental study revealed that the forced convection mode was better than the natural convection mode. Average specific energy consumption rates were 1.549 and 1.144 kW-h/kg and the specific moisture extraction rates were 0.645 and 0.875 kg/kW-h, respectively, in the natural forced mode.

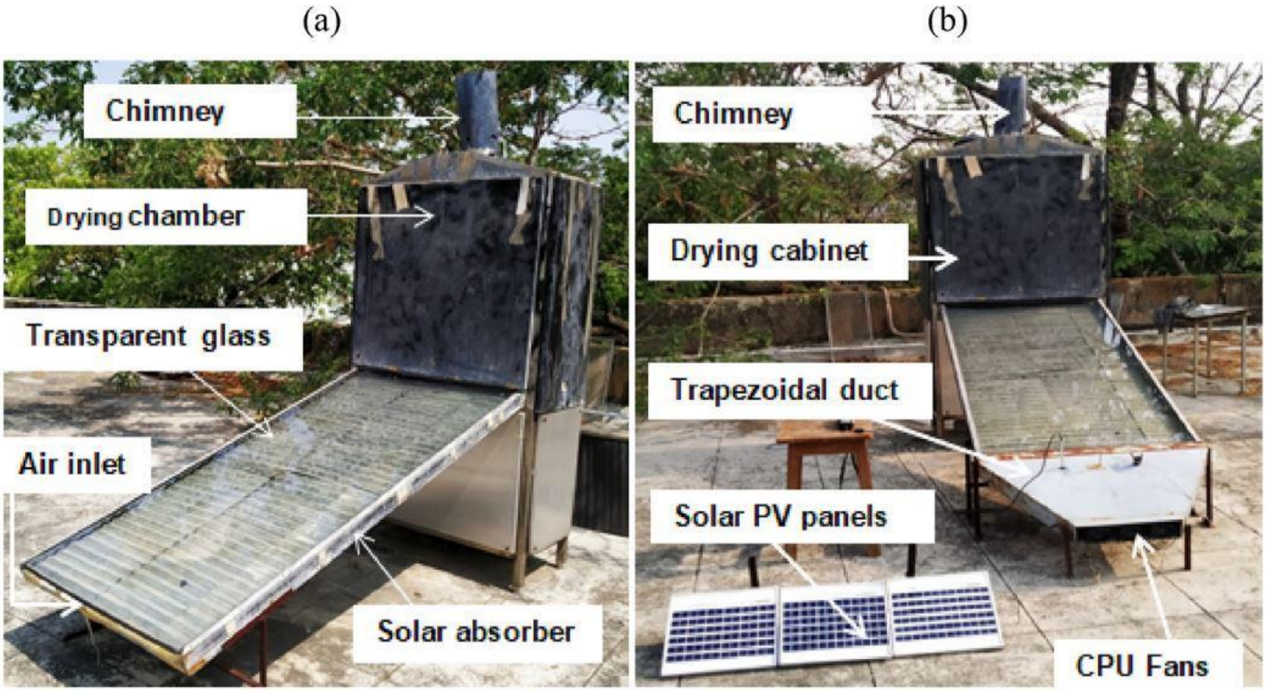

**Figure 9.** Indirect-type solar dryer: (a) natural and (b) forced convection modes (Gilago & Chandramohan, 2022)

### 2.1.2. Evacuated tube collector

Researchers have also shown interest in the use of evacuated tube solar collectors based solar dryers for drying industrial and agricultural products. However, limited studies are available on the solar dryer with an evacuated tube solar collector. Misha et al. (Misha et al., 2016) evaluated the drying performance of solar-assisted industrial-scale solid desiccant dryers. The schematic of the experimental setup is shown in Figure 10. Solar collector heats the water in the tube and, then, hot water passes through a heat exchanger to heat the air. Experiments were carried out to dry oil palm fronds. Drying time was reduced by 64 %, 44 %, and 33 % for products in the first, second, and third columns of the developed solar dryer, respectively. Drying efficiency was achieved 19 % with 65 % solar energy utilization. Nabnean et al. (Nabnean et al., 2016) presented a performance analysis of an indirect solar dryer integrated with a water-type solar collector. New design consists of a solar collector, a storage tank, a cross-flow heat exchanger, and a drying chamber. Three full-scale experiments were conducted to dry cherry tomatoes from 8.00 am to 6.00 pm. The moisture content of the cherry tomatoes was reduced from 62 % (wb) to 15 % (wb) within 4 days at an average air temperature of 50 ºC during drying.

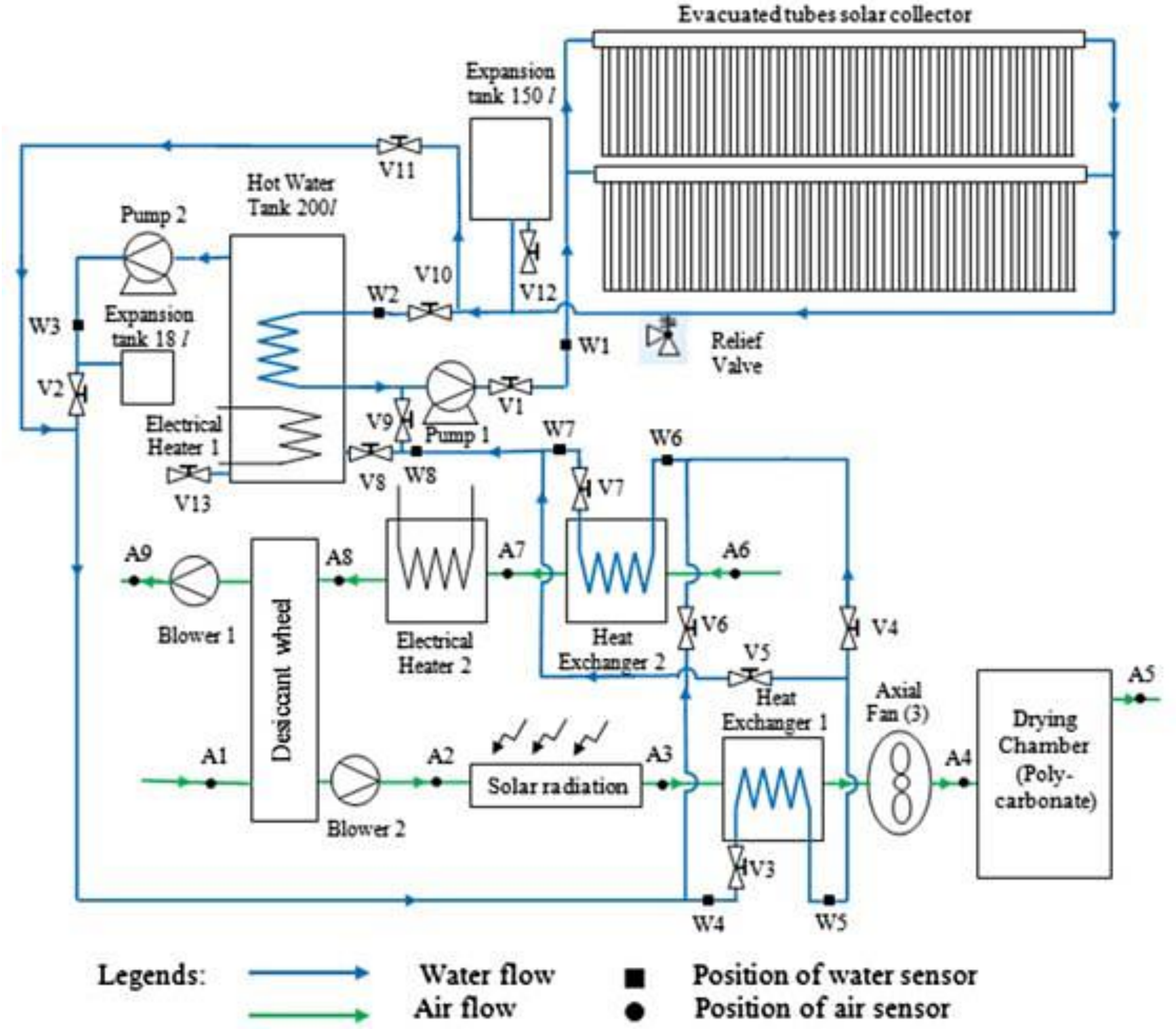

**Figure 10.** Schematic diagram of the advanced solar drying system with an evacuated tube (Misha et al., 2016)

Daghigh and Shafieian (Daghigh & Shafieian, 2016b) designed a double-function solar drying system with a heat pipe solar collector. The evacuated tube heat pipe was used to heat water and employed as a secondary working fluid. A hot water insulated storage tank was provided between the solar collector and heat exchanger. Energy and exergy analysis was carried out to evaluate the performance of the heating-drying system. In another study, Daghigh and Shafieian (Daghigh & Shafieian, 2016a) developed a solar dryer integrated with a heat pipe evacuated tube solar collector. A heat recovery system was employed to enhance the performance of the drying system. Water was used as working fluid and its heat was delivered to the blown air through a heat exchanger.

Wang et al. (Wang et al., 2018) evaluated the performance of indirect forced convection solar dryers at different drying air temperatures. Air was heated using an evacuated tube solar air collector and passed into the drying chamber from two inlet ports. An auxiliary electric heater and an automatic control system were provided to maintain constant temperature airflow inside the drying chamber. Experiments were conducted for drying 24 kg of sliced mango to analyze the performance of the dryer and drying kinetics. Experimental results showed 30.9 % to 33.8 % variation in the average drying efficiency. Page's model was found accurate to predict the moisture removal rate for mango slices.

Arun Sandeep et al. (Arunsandeep et al., 2018) developed a numerical model to predict the drying time in the indirect solar dryer at different air temperatures and moisture levels. Heat and mass transfer equations with finite difference methods were solved using computer code in MATLAB. The developed drying model is applicable only to spherical shape products. The authors report a good agreement between numerical and experimental results.

### 2.1.3. Solar concentrator

Liu et al. (Liu et al., 2014) employed a parabolic trough concentrator to supply the heat for tobacco drying. Air was circulated through the V-shape metallic cavity receiver. Improvement in efficiency was found by increasing the opening width of the absorber. Naemsai, Jareanjit, and Thongkaew (Naemsai et al., 2019) investigated the performance of solar dryers with heat recovery and no heat recovery systems. The developed greenhouse dryer consists of two rooms. The drying product was kept in the evaporator room, whereas heating was carried out in the condenser room. Implementation of a heat recovery system reduced the drying time by 2 hours with an efficiency rate of 33.2 %. Some studies on indirect solar drying have found that the rate of moisture removal increased due to external reflectors, which focus on solar radiation on a transparent glass cover provided at the top of the drying chamber (Kabeel et al., 2022).

## 2.2. Integration with thermal storage

Researchers have worked to maintain drying during off-sun hours uniform and constant. Thus, indirect solar dryers are integrated with the thermal storage unit and auxiliary devices to supply hot air continuously. Thermal energy is stored in the form of sensible and latent heat. Sensible heat has lower thermal energy density than latent heat (Saikia et al., 2022). A literature study on the indirect solar dryer with thermal storage focuses on thermal storage material, drying time, and temperature attained in the drying chamber.

Integration of solar dryers with biogas, heat pump, and thermal storage materials eliminates the impact of varied climatic and uncontrolled environmental conditions on drying characteristics. It also allows the maintenance of a wide drying temperature which is suitable for heat-sensitive products (Jha & Tripathy, 2021). Thermal storage materials are incorporated into solar drying systems to supply constant temperature (Natarajan et al., 2022). Thermal energy accumulators can maintain the temperature of 10-25 °C above the ambient temperature. Phase change material such as paraffin wax significantly increases the drying cost and efficiency of small-scale dryers (Patel et al., 2020). Komolafe et al. (Komolafe et al., 2019) investigated the performance of solar dryers under natural and forced convection modes integrated with the thermal storage system. The experimental setup is shown in Figure 11. Gravel was used to store the heat collected from the solar collector. Experiments were conducted on a 4 kg solar drying system to determine the diffusivity of moisture, activation energy, and mathematical modeling of drying locust beans. Among the eleven thin layer-drying models, the Lewis model was found to be best for describing the drying characteristics of locust beans.

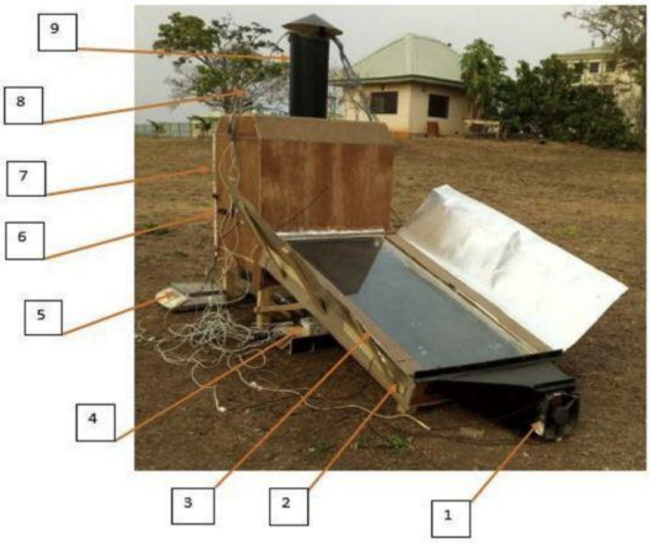

**Figure 11.** Experimental setup of the forced convection solar drying system indicating the position of the temperature and humidity sensors, 1. Blower, 2. Solar collector, 3. Reflector, 4. Data acquisition system, 5. Weighing balance, 6. Thermostat, 7. Drying chamber, 8. Temperature and humidity sensors, and 9. Chimney (Komolafe et al., 2019)

Prakash, Kumar, and Laguri (Prakash et al., 2016) developed a novel greenhouse dryer integrated with thermal energy storage. Thermal storage was applied on the ground in three different ways. In the first case, the ground was kept bare. In the second case, the ground floor was covered with PVC while in the third, the floor was coated with black color. Energy, exergy, and environmental analysis of the dryer was carried out under less than three floor conditions throughout a year. From the experimental results, it was found that a PVC-covered floor was better because of its high thermal storage capacity. The payback period of the dryer was only 1.11 years in the active mode condition.

Ndukwu et al. (Ndukwu et al., 2017) conducted an energy and exergy analysis of solar dryers combined with thermal storage. The thermal storage potential of sodium sulfate decahydrate and sodium chloride was evaluated for dry red chilies. The result revealed that moisture content was reduced from 72.27 % to 7.6 and 10.1 with sodium sulfate decahydrate and sodium chloride, respectively. The average drying efficiency of 18.79 % was achieved with a carbon emission of 602 tonnes per year.

Yadav et al. (Yadav et al., 2018) performed numerical analysis on thermal storage devices in indirect solar drying. The device consisted of two concentric tubes in which the central tube was a copper tube and the outer tube was a plastic tube. The gap between the concentric tubes was filled with paraffin wax and air passed through the inner copper tube. Computational fluid dynamics analysis was carried out to estimate heat loss due to exposure to the air. The analysis results show that drying can be done up to 10.00 pm without the use of an auxiliary heat source.

Chaouch et al. (Chaouch et al., 2018) aimed to reduce the drying time in an indirect solar dryer by integrating it with sensible heat storage. The setup is shown in Figure 12. The drying behavior of camel meat was studied under different environmental conditions. The average thermal efficiency of the solar collector during the thermal charging of pebbles decreased. However, efficiency time after the sunset increased to 70 minutes with an increase in the mass of pebbles from 15 to 50 kg. Indirect drying thermal efficiency reached 18.34 % and 15.72 % in July and November, respectively.

**Figure 12.** The solar dryer: Setup front view (Chaouch et al., 2018)

Tarigan (Tarigan, 2018) carried out a numerical analysis of solar collectors and drying chambers for drying agricultural products. The dryer was provided with a backup biomass burner and thermal storage. The analysis results did not show a significant difference in the temperature of the outlet air by increasing the number of glass covers from one to two. The CFD simulation of the drying chamber showed the average drying air temperature at 56 °C.

Essalhi et al. (Essalhi et al., 2018) developed an indirect solar dryer with thermal storage to keep the drying chamber temperature more than the ambient temperature during off-sunshine hours. As a result of drying, the humidity in the grapes decreased from 79.8 % (w.b.) to 20.2 % (w.b.) in 120 hours. Thermal storage systems significantly reduced daily drying time.

Shamekhi-Amiri et al. (Shamekhi-Amiri et al., 2018) investigated the drying behavior of lemon balm leaves in an indirect solar dryer with a double glass cover solar air collector. First, air flows through the gap between the two glass covers and, then, into the second glass cover and black plate packed with wire meshes. Hot air ranging from 38 °C to 68 °C enters the drying chamber. Increasing the air flow rate from 0.006125 $m^3/s$ to 0.01734 $m^3/s$ showed a 20 % improvement in the collector thermal efficiency.

Mall and Singh (Mall & Singh, 2018) carried out a comparative analysis of indirect and mixed-mode solar dryers shown in Figure 13. In an indirect solar dryer, the drying chamber was connected in series to a solar air collector in which the phase change material was stored. The moisture content of the coriander leaves was reduced from 88.02 % to 9.68 % in 3 hours and 3 hours 15 minutes in the indirect and mixed mode solar dryers, respectively. The overall drying efficiency of indirect solar dryers was found higher than that of mixed-mode solar dryers. Bhendwade and Dube (Bhendwade & Dube, 2018) reported that following the application of thermal storage materials in solar collectors, their efficiency increased from 40.29 % to 60.40 %.

**Figure 13.** Indirect and mixed mode solar dryers with phase change material (Singh & Mall, 2018)

Kondareddy et al. (Kondareddy et al., 2019) evaluated the performance of the solar dryer integrated with the phase change material. The experimental setup is shown in Figure 14. A developed forced convection drying system consists of two solar collectors and a drying chamber. The secondary collector contains phase change material paraffin wax as thermal storage material. Experimental results showed a 12 % increase in collector efficiency because of thermal storage. Annual drying hours increased by 65 % and the quality of the dried product was found to be excellent. The payback period of the dryer was calculated as 2.56 years, which is significantly less than the life (20 years) of the dryer.

Ndukwu et al. (Ndukwu et al., 2020) developed an indirect solar dryer integrated with a flat plate collector and biomass furnace. In the experimental setup presented in Figure 15, a flat plate collector covered with glass consists of black-painted granite rock pebbles, which act as heat storage material. Flue gases coming from the furnace pass through the copper tubes provided in the drying chamber. Drying time for plantain slices was reduced by 10-21 hrs, compared to drying under the open sun. The thermal efficiency of the solar collector was 21.89 %. Moisture content was reduced from 66 % w.b to 15 % w.b of plantain slices with the average drying efficiency of 14.64 %.

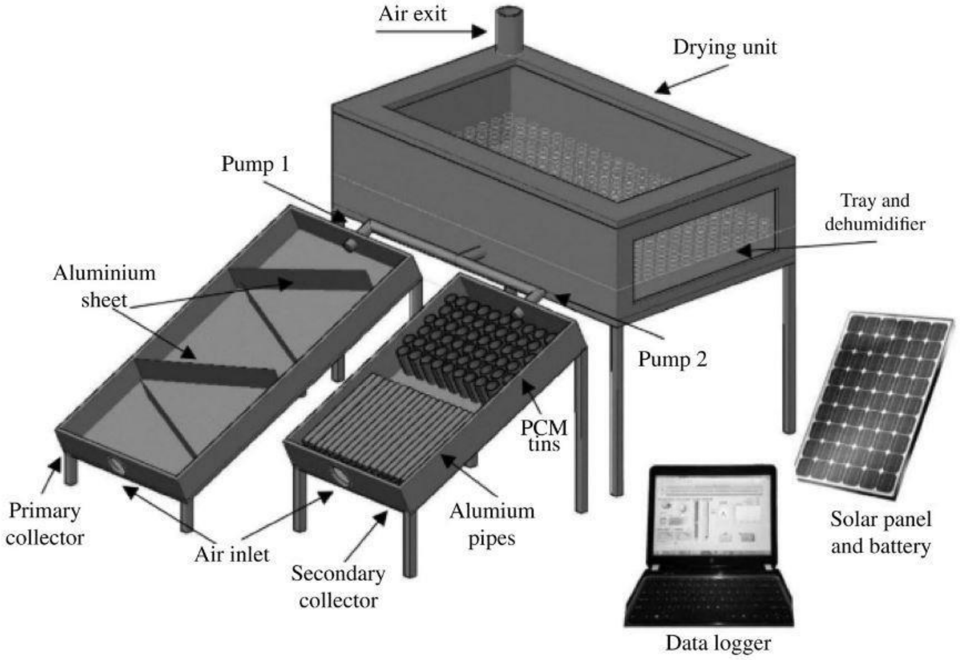

**Figure 14.** Experimental setup of solar dryer integrated with thermal storage (Kondareddy et al., 2019)

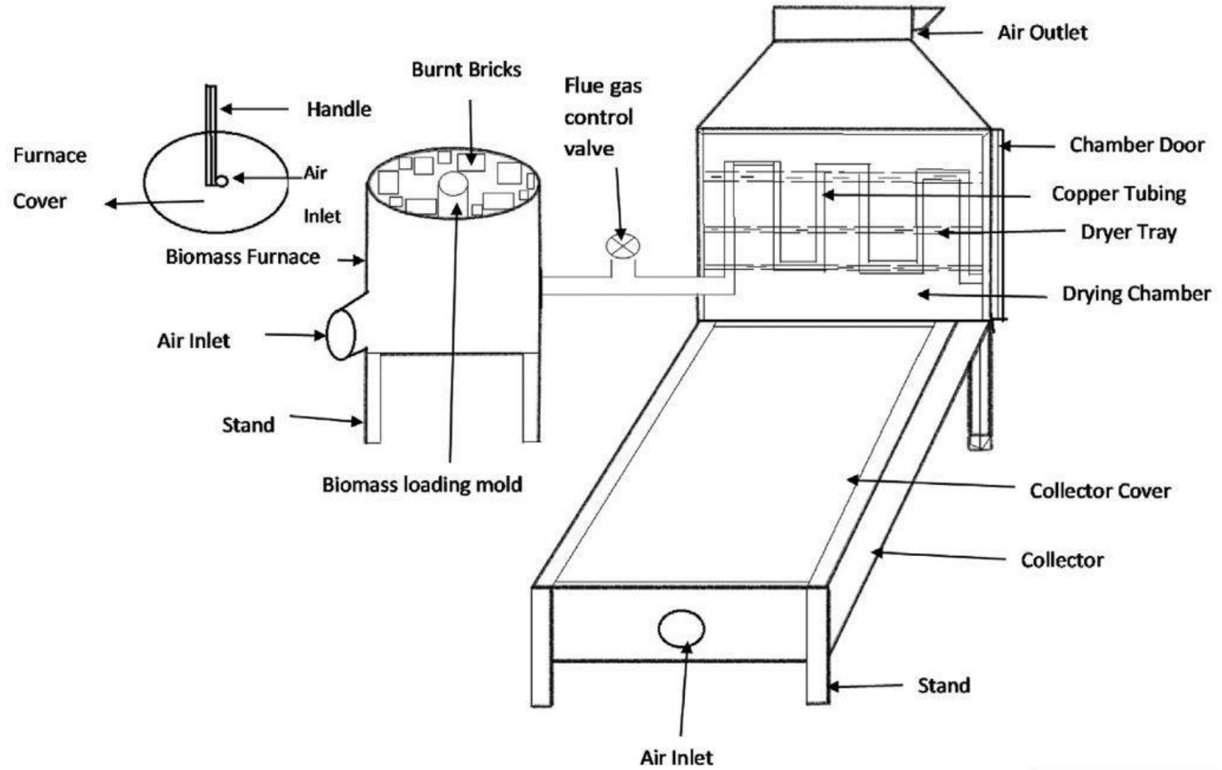

**Figure 15.** Schematic view of the prototype of the indirect solar dryer with biomass furnace (Ndukwu et al., 2020)

Singh and Mall designed (Singh & Mall, 2020) tested the performance of an indirect-type solar dryer with phase change material. Paraffin wax was used as thermal storage material to maintain the continuous supply of energy for drying banana slices. The drying time was reduced by 5 hours due to the release of latent and sensitive heat from the phase change material after sunset. Lamrani and Draoui (Lamrani & Draoui, 2021) carried out a numerical study to investigate the thermal performance of the indirect solar dryer integrated with a packed bed thermal energy storage system. Thermal storage backup reduced the drying time of wood and the payback period by about 15 % and 33 %, respectively. Thermal storage makes the solar drying system a techno-economically feasible and attractive technology.

Subramaniam, Sugumaran, and Athikesavan (Subramaniam et al., 2022) developed a solar dryer coupled with thermal storage shown in Figure 16. Water and waste oil are used as active working mediums and $Al_2O_3$ Nanofluids are used as thermal storage materials. For the dryer with thermal storage, the energy output was maximum at a flow rate of 0.035 l/sec compared to the flow rates of 0.045 and 0.065 l/sec.

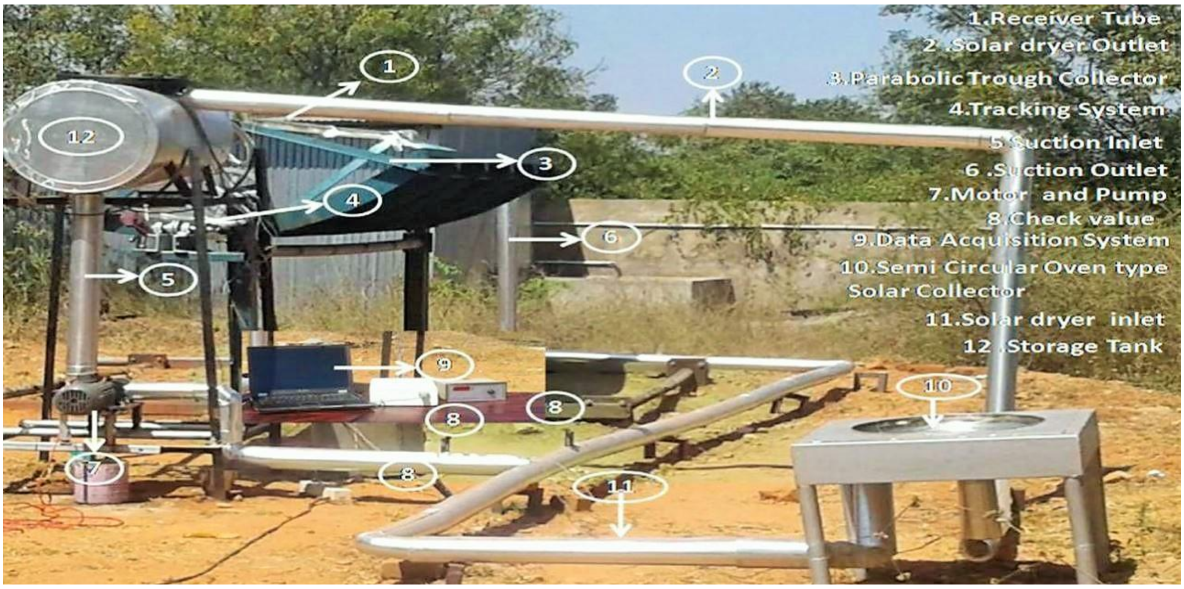

**Figure 16.** Solar dryer coupled with thermal storage (Subramaniam et al., 2022)

The use of the phase change material in solar dryers reduced drying time and increased the effectiveness of drying (Radhakrishnan Govindan et al., 2022). Nanoparticle-enhanced thermal fluids and paraffin wax inside the solar collector coupled with the drying chamber enhanced the drying performance of the dryer (Barghi Jahromi et al., 2022).

## 2.3. With auxiliary devices

Sekyere et al. (Sekyere et al., 2016) constructed a natural convection solar dryer with a backup heater for drying agricultural products. Experiments were conducted for drying pineapples under four different drying scenarios. The product was dried continuously with solar radiation during the day and by a heater during the night, hybrid drying, drying with a heater only, and drying during the day with the use of solar energy only. The maximum moisture pickup efficiency was found at 32 % with a continuous drying scenario. Nguimdo and Noumena (Nguimdo & Noumegnie, 2020) developed a hybrid indirect solar dryer with an automatic control device, which controls the temperature in the drying chamber. An electric heater was provided as a backup heating system. No load tests were conducted to perceive the maximum temperature rise in the drying chamber. The maximum temperature attained in the dryer was 39.9 °C and 47.10 °C in loaded and no loaded conditions respectively. The drying rate obtained was 46.7 % faster than conventional drying.

Suherman et al. (Suherman et al., 2020) developed a hybrid solar drying system that comprised a drying chamber, flat plate solar collector, and auxiliary LPG heater. Hot air enters the drying chamber from the upper side of the collector and blower and burner units through the pipe provided to the left side of the drying chamber. The purpose of the LPG heater is to support the drying process during off-sun hours. Maximum drying effectively factor at 6.4 was found at 60 °C temperature.

## 3. APPLICATIONS

Solar dryers are used to assist the conventional drying system to reduce their consumption. Indirect solar dryers are the most suitable for drying fruits, vegetables, and medicinal plants that prevent the product from contamination. Table 1 illustrates the product dried and a suitable mathematical model to study the drying kinetics of the product.

**Table 1.** Product dried in indirect solar dryer and drying model

| Author | Country | Category | Fruit | Drying model |
|---|---|---|---|---|
| Wang et al. (Wang et al., 2018) | China | Fruit | Mango | Page's model |
| Sekyere, Forson, and Adam (Sekyere et al., 2016) | Ghana | | Pineapples | NA |
| Lingayat, Chandramohan, and Raju (Lingayat et al., 2020) | India | | Banana | NA |
| Singh and Mall 2020 (Singh & Mall, 2020) | India | | Banana slices | Modified Henderson and Pabismodel |
| Radhakrishnan Govindan et al. 2022 (Radhakrishnan Govindan et al., 2022) | India | | Coconuts | NA |
| Kondareddy et al. 2019 (Kondareddy et al., 2019) | India | | Elephant apple | NA |
| Kumar Aggarwal Yashwant Singh Parmar and Sharma Yashwant Singh Parmar 2019 (Kumar Aggarwal Yashwant Singh Parmar & Sharma Yashwant Singh Parmar, 2019) | India | | Wild berries, wild anola and wild bell | NA |

| | | | | |
|---|---|---|---|---|
| Hssaini et al. 2021 (Hssaini et al., 2021) | Morocco | | Figs | Modified Handerson and Pabis |
| Etim, Eke, and Simonyan 2020 (Etim et al., 2020) | Nigeria | | Banana | NA |
| Tarigan and Tekasakul 2005 (Tarigan & Tekasakul, 2005) | Nigeria | | Pepper | NA |
| Ndukwu et al. 2020 (Ndukwu et al., 2020) | Nigeria | | Plantain slices | NA |
| Essalhi et al. 2018 (Essalhi et al., 2018) | Morocco | | Grapes | Midilli et al. model |
| Nasri 2020 (Nasri, 2020) | Tunisia | | Banana and peach | Midilli and kucuk, Verma et al. |
| Das and Akpinar 2020 (Das & Akpinar, 2020) | Turkey | | Apple | Midilli et al. |
| Ergün et al. 2017 (Ergün et al., 2017) | Turkey | | Cranberry, medlar and cherry | NA |
| Aydin et al. 2021 (Aydin et al., 2021) | UK | | Apple, banana, chili pepper, and grapes | NA |
| Mutabilwa and Nwaigwe 2020 (Mutabilwa & Nwaigwe, 2020) | UK | | Banana | NA |
| Tiwari and Tiwari 2018 (Tiwari & Tiwari, 2018) | | | Grapes | NA |
| Ullah et al. 2018 (Ullah et al., 2018) | China | Herbal Medicine | Asparagus (Asparagus officinalis L.) | Modified Henderson and Pabis |
| Abi Mathew and Thangavel 2019 (Abi Mathew & Thangavel, 2019) | India | | Anti-diabetic medicinal products | NA |
| Lakshmi et al. 2019 (Lakshmi et al., 2019) | India | | Curcuma zedoaria | Verma model |
| Gupta et al. 2022 (Gupta et al., 2022) | India | | Green tea | NA |
| Purnomo and Indarti 2018 (Purnomo & Indarti, 2018) | Indonesia | | Sambungnyawa leaves | Verma equation |
| Shamekhi-Amiri et al. 2018 (Shamekhi-Amiri et al., 2018) | Iran | | Lemon balm leaves | Wang and Sing correlation |
| Castillo Téllez et al. 2018 (Castillo Téllez et al., 2018) | Mexico | | Stevia (Rebaudiana Bertoni) leaves | Weibull model |
| Tlatelpa-Becerro et al. 2020 (Tlatelpa-Becerro et al., 2020) | México | | Crataegus mexicana | NA |
| Matavel et al. 2021(Matavel et al. 2021) | Mozambique | | Amaranth leaves and maize grains | NA |
| Koua, Koffi, and Gbaha 2019 (Koua et al., 2019) | | Seed | Cocoa beans | Fick's diffusion model |
| Komolafe et al. 2019 (Komolafe et al., 2019) | Nigeria | | Locust beans | Lewis model |
| Koua, Koffi, and Gbaha 2019 (Koua et al., 2019) | Ivory Coast | | Cocoa beans | GAB model, |
| Nguimdo and Noumegnie 2020 (Nguimdo & Noumegnie, 2020) | Cameroon | Vegetable | Sliced tomatoes | NA |
| Sallam et al. 2015 (Sallam et al., 2015) | Egypt | | Mint | Verma et al. |
| Sunil, Varun, and Sharma 2014 (Sunil et al., 2014) | Hungary | | Fenugreek leaves | Wang and Singh |
| Gilago and Chandramohan 2022 (Gilago & Chandramohan, 2022) | India | | Ivy gourd | NA |
| Haque et al. 2019 (Haque et al., 2019) | India | | Bitter Gourd, Okra, RawMango | first-order kinetics |
| Goud et al. 2019 (Goud et al., 2019) | India | | Capsicum and okra | Modified Page |
| Mall and Singh 2018 (Mall & Singh, 2018) | India | | Coriander Leaves | Midilli et al. |
| Deshmukh et al. 2014 (Deshmukh et al., 2014) | India | | Ginger | Page model |
| (Goud et al. 2021 (Goud et al., 2021) | India | | Green chili and okra | Modified Page mode |
| Lingayat et al. 2021(Lingayat et al., 2021) | India | | Tomato and Brinjal | NA |
| Suherman et al. 2020 (Suherman et al., 2020) | Indonesia | | Cassava starch | NA |

| | | | | |
|---|---|---|---|---|
| Tarigan and Tekasakul 2005 (Tarigan & Tekasakul, 2005) | Nigeria | | Scotch bonnet peppers | NA |
| Naemsai, Jareanjit, and Thongkaew 2019 (Naemsai et al., 2019) | Thailand | | Chili | NA |
| Vengsungnle et al. 2020 (Vengsungnle et al., 2020) | Thailand | | Ganoderma | NA |
| Zriba, Guellouz, and Jemni 2021 (Zriba et al., 2021) | Tunisia | | Tomato | NA |
| Mahapatra and Tripathy 2018 (Mahapatra & Tripathy, 2018) | India | | Carrot slices | Wang and Singh's model |

## 4. ASPECTS OF SOLAR DRYER

Several advantages of solar dryers have been highlighted in the literature for drying various products. Solar drying is a cheap and safe drying technology that ensures the required product quality with lower environmental impact. Here, the political, economic, and environmental aspects of the indirect solar dryer are discussed.

### 4.1. Technology aspect

Energy consumption, evaporation rate, and thermal efficiency are the major indices in indirect solar drying. The amount of energy required to evaporate the moisture in the product to be dried is supplied through hot air. Indirect solar dryers are becoming technically sound because of the development of concentrating collectors and thermal storage devices. A wide range of temperatures in the drying chamber as per the product drying kinetics can be maintained because of the high-temperature thermal storage. Integration of the solar drying system with a thermal storage system reduces the drying time by 15 % compared to conventional indirect solar drying (Subramaniam et al., (2022). Hybrid drying technology reduces drying time and energy consumption. The development of industry-scale indirect solar dryers with high energy-saving characteristics is the main technological challenge (Khaing Hnin et al., 2019). Uniform temperature distribution in the drying chamber and invariable drying air velocity shortens the drying time. Dryer design and drying condition play an important role in achieving quality products.

### 4.2. Political aspects

Government policies on solar energy and protecting the environment significantly affect the development of solar thermal energy. World's total installed solar thermal energy capacity is increasing day by day. The government of India is also promoting solar thermal energy under the Ministry of New and Renewable Energy. This will spark great motivation and interest in utilizing solar energy for thermal applications such as drying and cooking. A developing country like India is making progress on the renewable energy sector. However, the increasing demand for energy for the purpose of thermal applications puts pressure on fossil fuels (Chandra et al., 2019). Solar energy is an important part of India's renewable energy expansion program. Solar energy plays a vital role in the energy capacity and energy security of India (Digambar Singh et al., 2019). Various governments have carried out research and development efforts as solar thermal energy is becoming a mainstream power source (Liu et al., 2016; Pranesh et al., 2019).

### 4.3. Economic aspects

Given the considerable variation in the number of daily dried products throughout the year, for the economic analysis of dryers, the price of dried products per unit weight is determined by taking into account the number of products dried in a year. Economic analysis can be done by considering the capacity of the dryer, installation cost, operating and maintenance cost, payback period, and life of the dryer. The payback period of an indirect solar dryer depends on the location and product to be dried. The operating cost of the solar dryer is lower than the dryers running on conventional fuels. Hasan & Langrish developed a robust life cycle performance evaluation method to overcome the limitation of the previous studies. The proposed method is effective for all dryers and products (Hasan & Langrish, 2016). The color and composition of the agricultural dried product depend on the drying parameters. The market value of the product dried using solar increased due to controlled drying parameters (Deng et al., 2021).

### 4.4. Environmental aspects

Consumption of fossil fuel is increasing drastically because it plays an essential role for enhancing the living standard. Energy demand in developing countries is increasing continuously, which causes a surge in greenhouse gas emission (Ravindra et al., 2019). Replacing fossil fuels and non-renewable energy sources reduces carbon dioxide emission and, subsequently, prevents global warming. Among all the renewable energy sources, solar energy is easily available and the most abundant energy source can be utilized to fulfill electrical and thermal energy demands. Solar thermal application such as solar drying is clean and hygienic for agricultural product processing and it meets national and international standards.

## 5. CONCLUSIONS AND FUTURE SCOPE

This study presented a review of solar collectors, thermal storage, and working fluid used to enhance the drying rate in indirect solar drying. The selection of solar collectors for drying depends on a number of parameters such as initial moisture content, the quantity of products dried, drying temperature, solar radiation, and heat transfer enhancement mechanism. Products dried in an indirect solar dryer were completely protected from any kind of contamination caused by environmental factors. It was demonstrated through a number of research studies on solar dryers that they were technically possible for widespread agricultural uses.

Forced convection solar dryers with glazed flat plate collectors had better control over the drying rate than natural convection solar dryers. The addition of a thermal storage material bed between the plate and glass cover increased the drying rate and efficiency. Solar dryers with evacuated tubes were efficient and had direct air heating mechanisms; however, maintenance and installation cost was greater than solar dryers coupled with flat plate collectors. Recent research on solar dryers focused on 24-hour drying cycles. Indirect solar dryers with heat storage facilitated drying during the hours when the sun is not shining, which is a significant step in reducing the drying time. Sensible and latent heat storage materials played a vital role in this regard.

Concentrating collectors with thermal storage have gained popularity in recent years. The coupling of concentrating collectors with indirect solar dryers requires further study. Considering the development of solar drying technology, solar concentrators and latent heat storage systems with indirect solar dryers may be used for high-temperature industrial drying applications in the future.

## 6. ACKNOWLEDGEMENT

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