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Review Article

Recent advances in solar drying technologies: A Comprehensive review

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Abstract: Preservation of food and vegetable products is an age-old practice for the retention of flavor, appearance, and quality. From ancient times, driers for drying food grains work on direct sun rays, firewood, fossil fuels, and coals causing carbon release. These available methods are expensive, unreliable, and unhygienic; thereby the use of a solar dryer working on free and clean energy is better for higher value addition to food preservation. The objective of this exploration is to study the recent developments in the use of different types of solar dryers for drying foods, vegetables, seafood, etc. There exist many studies on the effects of the parameters such as temperature, relative humidity, and speed of air, turbulence effect, sun irradiation, and the latitude of the location in the solar drying process. The findings show that the climate conditions such as solar radiation and atmospheric air play an important role in the drying efficiency of the solar dryer. A phase change material stores thermal energy during the daytime and releases heat during the nighttime. This process improves thermal efficiency and reduces heat loss during the drying period. On the one hand, a hybrid dryer integrated with a solar panel produces electricity for the operation of a DC blower circulating hot air inside the drying chamber for better drying. In addition, a critical review has been performed on the usage of different absorbing plates increasing heat transfer rate, use of various phase change materials for heat storage, and analysis of CFD simulation.

Keywords: *CFD simulation, Food products, Phase change material, Solar drying, efficiency*

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Nomenclature	
A_c	Area of solar collector, [m^2]
C_p	Specific heat, [kJ/kg/K]
I	Instantaneous flux on a tilted surface, [W/m^2]
M_{fm}	Final moisture content of food products, [%]
M_{im}	Initial moisture content of food products, [%]
m_a	Mass flow rate of dry air, [kg/s]
m_{if}	Initial weight of food products, [kg]
m_{wr}	Mass of water to be removed from food products, [kg]
T_i	Inlet temperature of collector, [^{0}C]
T_o	Outlet temperature of collector, [^{o}C]
δ	Declination angle in degree, [deg]
η_c	Instantaneous collector efficiency, [%]
ω_s	Sunshine hour angle, [deg]
ϕ	Latitude angle of the location, [deg]
θ	Zenith angle, [deg]
T_a	Atmospheric temperature, [^{0}C]
T_c	Collector outlet temperature, [^{0}C]
T_d	Drying chamber temperature, [^{0}C]

1. INTRODUCTION

India demands an increase in clean energy generation for attaining a better quality of life. Clean energy technology is considered an alternative solution due to erratic electric supply and issues with centralized grid-based power. Many social enterprises are focusing their efforts to address this issue of energy solutions. Solar drying technology is based on clean energy technology, which is aimed to dry food products. This is a hygienic method and a quick process of drying as compared to open sun drying.

Solar dryers are classified in many ways according to hot air circulation, exposure to solar irradiation, and temperature range. Based on the hot air circulation, dryers may be natural convection and forced convection types. According to the temperature range, dryers may operate under high temperatures (fossil fuel as a heating source) and low temperatures (solar energy as a heating source). Dryers may be direct type, indirect type, mixed-mode type, and hybrid type depending on the exposure to solar irradiation. In the direct type operation, the food product is directly open to sunlight and the drying chamber is made up of good heat-conducting material. In the indirect type, the dryer consists of a solar flat plate collector and a drying chamber. The heat generated from the solar collector is circulated through the drying chamber instead of being direct exposure to solar radiation. In the mixed-mode type, the dryer is a combination of both direct exposure of solar intensity to the drying chamber as well as preheated air from a solar collector that will be useful for the drying process. The hybrid type is the recently developed dryer that can be used day and night. The advantages and disadvantages of various types of solar dryers have been discussed in Table 1.

Table 1. Advantages and disadvantages of different types of solar dryers [1].

Dryer type	Advantages	Disadvantages
Direct solar dryer	Simple design, small and low cost	Very slow rate operation
	Provide good drying quality compared to the open sun drying	Low drying capacity per unit area
	Both collections of solar energy and drying of the product take place in a single unit	Direct exposure of the material to solar radiation through a transparent wall
	Operation depends on solar energy and airflow	Only for drying a small quantity of material
Indirect solar dryer	The drying rate is high and product quality is good	More complex design
	The dried product can be stored for long times	More expensive
	Need smaller surface area and increased productivity	Maintenance cost is higher compared to direct type
	The flexibility of the dryer to accept similar seasonal crops	
Mixed-mode dryer	Collection of solar energy in both flat plate collector and drying unit.	Complex design and construction
	The product is dried simultaneously by both hot air from the solar collector and by direct solar radiation	High cost
	Faster drying with controlled drying temperature	
Hybrid Solar Dryer	Better control of drying	More complex system
	Continuous operation day and night	More expensive
	Reduce the chances of product damage	
Natural convection type	No external blower used for circulation of heated air.	Airflow is not sufficient during nighttime and adverse weather conditions
	Less maintenance and cost-effective	Deterioration of food products occurs
Forced convection type	Proper and sufficient amount of hot air circulation is happened by using an external blower.	More maintenance cost
	Drying rate and drying efficiency increase as compared to natural convection dryers.	

Rabha et al., [2] developed a forced convection tunnel solar dryer where ghost chili pepper and sliced ginger were successfully dried within the temperature range of 42-61°C and 37-57°C respectively. They calculated the parameters like overall thermal efficiency, specific energy consumption, and exergy efficiency. Chauhan et al., [3] developed a PV-integrated greenhouse solar dryer testing under no-load conditions. Heydari et al., [4] applied an energy/exergy analysis of a hybrid-type air heater integrated with a solar dryer. The performance evaluation was performed by taking heating fluids like air, Carbon-dioxide, and Nitrogen. The output temperature and second law efficiency were maximum by taking working fluid as Carbon-dioxide while thermal efficiency is maximum by considering air as working fluid. Elkhadraoui et al., [5] experimentally studied a mixed-mode type greenhouse solar dryer for a drying red pepper and grape in a forced convection mode. They performed a comparative study in two media consisting of open-air sun drying and in-chamber drying. Zoukit et al., [6] developed a multivariable modeled hybrid gas solar dryer to predict drying chamber temperature in two operating modes.

Suresh et al., [7] worked on the forced convection solar dryers under different mass flow rates for drying mint leaves. The dryer consisted of galvanized iron tubes, as absorber sheet and collector efficiency were determined under different mass flow rates. A portable solar drying system with solar panels was developed for drying chili and spinach by Reddy [8]. It had a drying area of 3 m^2 and two DC fans operated by a 10 W powered PV panel. The PV panel efficiency increases by circulating air on the backside. Cano et al., [9] evaluated the maximum evaporation rate in an indirect solar dryer. The parameters such as temperature, specific humidity of airflow inside the drying chamber, and aspect ratio were introduced to calculate the evaporation rate. Sebaii et al., [10] performed extensive experiments on indirect solar dryers using 4 different techniques such as without using phase change material, with the use of phase change material (Paraffin wax), 11 mathematical models, and 4 parameter logistic models. Padmanaban et al., [11] made a performance study on a desiccant-integrated packed bed solar dryer for drying copra. The initial and final moisture content, drying rate, maximum extraction rate, and dryer efficiency are evaluated for drying copra and are compared with conventional dryers. The desiccant and phase change material-packed solar air heater has reduced relative humidity. Tedesco et al., [12] analyzed a passive indirect type solar dryer consisting mainly of a solar collector, dehydrating chamber, and chimney used for dehydrating apples. The coefficient of performance was obtained as 87%, mass reduction of 89% with a 32.78 MJ of energy delivered to the system. Haytem et al., [13]conducted extensive experiments on paper deals for drying apple peels as organic waste from food processing industries under different drying temperature ranges and two different mass flow rate conditions (150 m^3/h and 300 m^3/h). It was found that the drying efficiency increases with the rise in temperature and mass flow rate. Reddy et al., [14] performed an energy/exergy analysis of the indirect type of solar dryer under forced and natural convection for drying green chili. The useful heat outputs, average energy efficiency, average-drying efficiency, and specific energy consumption were estimated for both types of solar dryers.

A study on an agricultural solar dryer was performed by Tarigan [15] using biomass burner and thermal storage. He made a simulation study by using CFD on a collector getting an average temperature in the drying chamber of 56°C, which was sufficient to dry agricultural products. Sonthikun [16] performed a CFD analysis on a hybrid type of biomass dryer used for drying rubber sheets. The CFD simulation was conducted for proper circulation of air inside the drying chamber and moisture content was reduced from 34.26 to 0.34%. Yadav et al., [17] simulated an indirect type of solar dryer consisting of a set of concentric tubes having an outer plastic tube with paraffin wax and inner copper fined tube for airflow. The outlet temperature reached a maximum value of T = 68.62°C, which was sufficient for drying purposes that could be used during the nighttime. Erdem et al., [18] did both experimental and simulation studies of hybrid PVT solar dryers with and without fin. Thermal efficiency was obtained by integrating fins on the absorbing plate and PV panel. Matavel et al., [19] realized an experimental evaluation of a passive indirect solar dryer for drying amaranth and maize grains. Thermal efficiency, aroma, texture, and color in the case of an indirect dryer were improved compared to an open solar drying system.

In Section 1, various types of solar dryers have been discussed with their advantages and disadvantages. Section 2 discusses the drying principles and technology applied to different types of solar dryers. Also, it discusses the use of auxiliary components to enhance the drying rate and the use of different phase-changing materials in a hybrid solar dryer. In this section, various performance indicators such as drying rate, drying efficiency, coefficient of performance, specific energy consumption, payback period, and moisture ratio have been discussed with formulations. In Section 3, the installation of a solar drying system, the use of many measuring instruments, and photovoltaic systems for the drying process has been elaborately discussed. In Section 4, an extensive discussion has been made on various factors and parameters affecting solar drying efficiency, different operating conditions and geometric factors, and CFD simulation study for solar drying systems.

2. MATERIALS AND METHODS

2.1. Methods and Technology Used for Various Types of Solar Drying Systems

An indirect type solar dryer having a proper dimension of air collector, drying chamber, and three numbers of treys (wire mesh type constructed with wooden frames) has been used for drying cocoa beans. The parameters like moisture content desorption isotherms and thermo physical properties such as thermal conductivity, thermal diffusivity, and shrinkage were calculated by taking 17^0 tilting angles of the collector [20]. A comparative study on solar dryers separately integrated with natural convection forced convection, and heat pump has been carried out for drying mushrooms. The natural convection type consists of a glazed glass collector, a drying chamber, a chimney, and glass wool acting as an insulator. Airflow inside the drying chamber depended on wind velocity. The forced convection type consists of two blowers operated by a solar panel to regulate airflow through the collector and drying chamber. Heat pump solar dryer mainly consists of the expansion valve, condenser, evaporator and compressor, and refrigerant [21]. Mathematical formulation, modeling, and simulation have been done on natural convection mixed-mode solar dryer for drying chili. Various input parameters such as meteorological data, material properties, thermal properties, and thermal losses have been considered for conducting the simulation [22]. A tilted solar tunnel-type dryer with half portion consisting of a flat plate collector and the other half with a drying chamber has been developed for drying beef. A solar panel is used to power the two fans and glass wool is provided to reduce heat loss [23]. The solar air heater tilted with 30^0 facing due south consists of a finned type absorber, which is black painted. Different sensors or actuators such as temperature sensor, hygrometer sensor, air velocity measurement sensor, and anemometer, pyrometer, and pressure sensor have been provided to regulate the temperature of the air, relative humidity, the velocity of the exhaust fan, and ambient pressure [24].

2.2. Design Aspect of Additional Components of Various Solar Dryers

A forced convection type of greenhouse solar dryer is designed for drying grapes. The collector is tilted at 37^0 facing south. The drying chamber integrated with two centrifugal fans is used for removing moist air from the chamber [25]. The solar dryer consists of a concrete base, a polycarbonate front, and a back wall and the roof consists of a transparent glass plate. The back wall is connected with a mirror to concentrate solar radiation. A copper pipe is connected to a solar collector dissipating heat through fins provided on the surface of the pipe [26]. A solar dryer integrated with a fan powered by a PV panel is developed for drying tomatoes as indicated in Fig. 1**.** A sun-tracking system is used for rotating the collector as per the position of the sun. Anemometer and solar meter are used to measure the velocity of fan and sun radiation [27].

An air collector of the drying system is connected to the outdoor 5-ton AC condenser. The inlet of the collector is connected with a conical duct where heated air is trapped from the outdoor of the condenser, while the outlet of the collector is connected to the drying chamber through a pipe. Thermocouples and pyrometers are provided to measure the temperature and irradiation data at regular intervals for drying grapes as shown in Fig. 2 [28].

Fresh plant such as chamomile is dried in the drying chamber and moisture content such as wet basis and dry basis are calculated. A radial fan is used to circulate drying air in the drying chamber and a water tank is used for heat storage purposes. A heat exchanger consisting of a collector with a copper coil is provided to circulate heat during the nighttime. The reflectors are also provided with the collector as presented in Fig. 3[29].

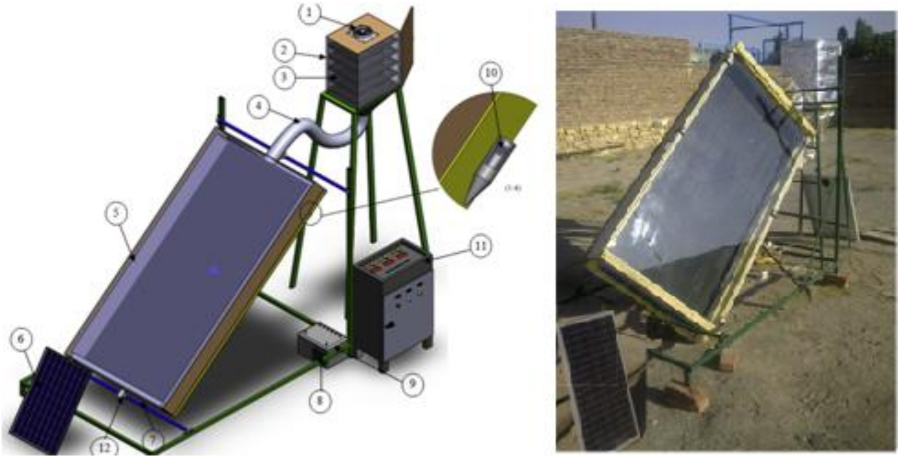


Figure 1. PV integrated solar dryer using sun tracking system from Ref. [27]: 1) Blower, 2) Drying chamber, 3) Trays, 4) Air tube, 5) Solar collector, 6) Solar Panel, 7) Air inlet, 8) Charge controller, 9) Battery, 10) Sun tracking sensor, 11) Control panel, 12) Mechanical pivot.

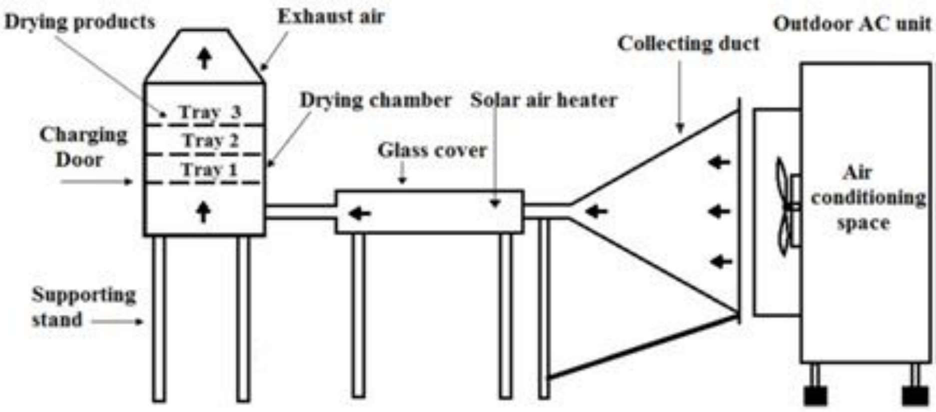


Figure 2. Schematic diagram of the experimental set-up of solar dryer integrated with split air conditioner from Ref. [28].

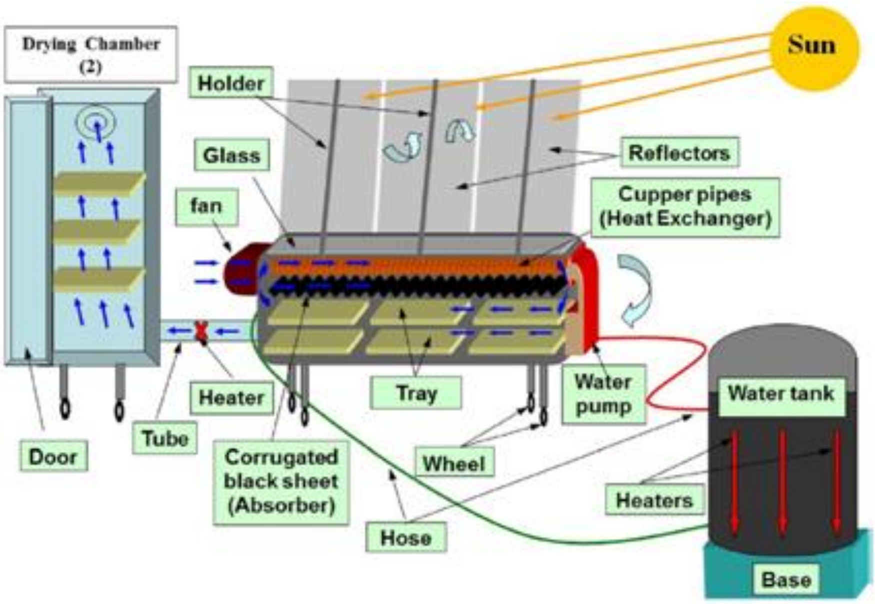


Figure 3. Schematic diagram of a hybrid type of solar dryer from Ref. [29].

The roof type of greenhouse solar dryer is designed for drying bitter guard in natural and forced convection methods. The roof is oriented at an angle of 23.5° as per the latitude of the location. A DC fan powered by a solar module circulates heated air inside the drying chamber and stainless steel wire mesh trays are provided for placing the food products [30]. A solar tunnel dryer is designed to dry the potato slices. The DC fan powered by a PV panel circulates the heated air. The dryer is made up of a Plexiglas sheet and the roof of the slope is tilted by 30° [31]. A hybrid type of solar greenhouse dryer is developed for both drying and water heating purpose. The solar dryer consists of mainly a water storage tank and a water circulation system. The solar hot water collector consists of an absorbing tube, a transparent cover having 5 mm thickness, and 10 mm thickness insulation foam, and it is tilted 14° facing due south [32].

A solar tunnel dryer installed at a location (10° N, 77° E) is used for drying fruits, and vegetables with a cover collector material such as UV polythene 200 microns [33]. The fluidized bed dryer consisting of mainly two collectors (connected in series) and integrated with a biomass furnace is used to dry paddy. The collectors mainly consist of a finned absorbing plate made up of Aluminum material and a biomass furnace for the combustion chamber and heat exchanger [34]. Three solar tunnel-type greenhouse dryers are used to dry peppermint leaves by forced convection mode. The fan is connected to a thermostat to keep the drying chamber at a constant temperature [35]. A dryer made with an evacuated type collector and heat exchanger is used for the heat recovery process. The hot water from the water tank enters the heat exchanger and the heated air is supplied to the drying chamber via a blower provided at the outlet of the heat exchanger [36]. An experimental set-up of a solar dryer has been installed in Thailand for drying 100 kg of cherry tomatoes. Hot water from the collector passes through the cross-flow type of heat exchanger and heated air is circulated inside the drying chamber through the blower [37].

2.3. Materials Used for Thermal Energy Storage Device

An energy storage device is provided in a solar drying system when there is a very low intensity of solar radiation and continuous operation of drying. There is a significant improvement in drying efficiency and drying rate by using energy storage material. Any phase change material is used as a heat storage material for the drying process during sunset time. Its use increases the thermal efficiency of the solar drying chamber and the quality of food products. Generally, paraffin wax is considered a good phase change material.

A solar dryer is fabricated for drying cocoa beans with a proper dimension of the drying chamber and solar collector (mainly consists of an absorber made up of galvanized stainless steel sheet). The thermal storage is placed at the bottom of the drying chamber, which contains two types of desiccant like $CaCl_2$, and a molecular sieve is placed on a container made up of steel. It is operated in both day and night mode and parameters like specific energy consumption, and moisture contents are calculated. It is observed that with the use of desiccant-type thermal storage, the drying efficiency and specific energy consumption increase, and the drying time decreases [38]. Twenty evacuated tubes are integrated with the collector and Therminol 55 is used as a thermal energy storage material for drying tomatoes. Polyurethane foam is provided as insulation. The header unit of the solar dryer consists of a condenser, thermal storage, and air passage. It has been observed that introducing new thermal energy storage maintains a uniform outlet collector temperature even if there is a fluctuation in solar radiation [39]. A solar kiln is used for drying wood, which consists of 4 principal components such as solar air collector, drying chamber, phase change material, and cylindrical parabolic collector as shown in Fig. 4. Incoming heated air from the solar air collector is passed through the drying chamber for the drying wood stack placed in it. Again, exhausting hot air from the drying chamber is passed through the thermal storage integrated between the drying chamber and solar air collector for recycling purposes. The thermal storage device is further used during the night time and is integrated with a parabolic collector which concentrates more solar radiation [40].

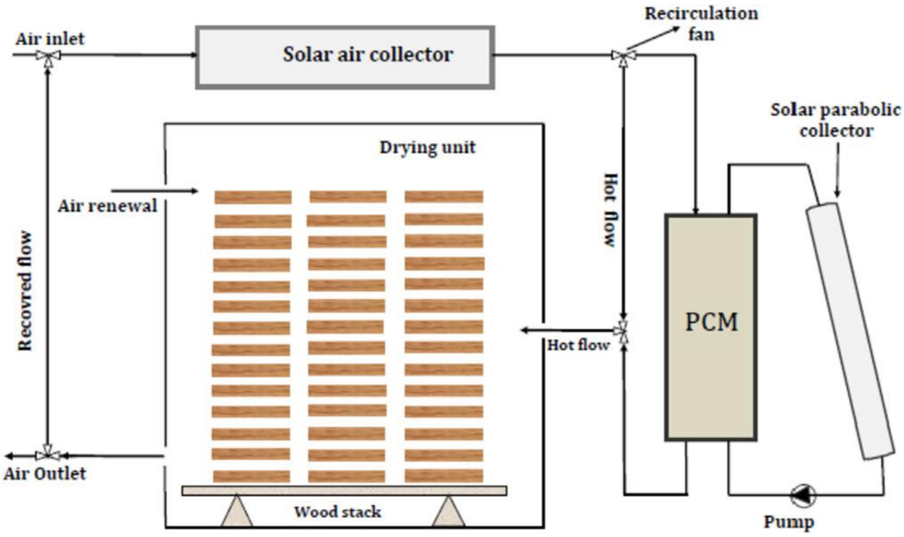


Figure 4. Schematic diagram of solar kiln integrated with PCM and parabolic collector from Ref. [40].

Energy/Exergy analysis of the indirect type solar dryer has been studied using a phase change material for drying Momordica Charantia. This consists of a fan powered by a solar PV system and a solar collector integrated with a corrugated absorbing plate, thermal energy storage, and glass plate. Thermal energy storage uses paraffin wax and four thin Aluminum strips to increase the thermal conductivity. The maximum thermal efficiency will be achieved for an indirect solar dryer with thermal energy storage having a fin inserted. The payback time is 1.42 years and it is environmental sustainability and has less CO_2 emission [41]. A mixed-mode type mainly consists of two solar air heaters, a drying chamber, and a shell and tube type of heat exchanger developed for drying black turmeric slices. Here the heat exchanger acts as a thermal storage device and consists of tubes whose inner surface is Copper and the outer surface is filled with paraffin wax. Experimentally it was found that the drying time for open sun drying is 46.5 hours while for mixed-mode forced convection solar dryer integrated with Paraffin wax is 18.5 hours. Also, the efficiency of the solar air heater and overall solar dryer was found as 25.6% and 12% respectively [42].

A natural convection solar dryer having a flat plate collector has been used for drying chilly. The collector has an absorber (1mm thickness made up of stained steel and black coated) with the dryer tilted at an angle of 35.5° facing due south. $Na_2SO_4.10H_2O$ and NaCl are used as phase change material placed in the upper plenum of the drying chamber during off-sunshine hours. The exergy efficiency of drying using $Na_2SO_4.10H_2O$ through off sunshine hour is 81.19% and the exergy efficiency during the sunshine hour is 96.09% [43]. The multi-pass solar air heater collector is provided to dry Roselle with a loading capacity between 75.2 and 81.3 kg and the weight of a specified sample is measured using digital balance at regular intervals during the drying process. The data logger is connected to the weather pole station to provide weather conditions for the whole day. The porous matrix is used as a thermal storage device for night purposes. The drying rate, drying efficiency, and moisture pick-up efficiency have been improved as compared to open sun drying. The payback period is 2.14 years. [44].The major disadvantage of the solar dryer is that it can be useable and effective during sunny hours and not effective during cloudy weather.

2.4. Mathematical Modeling

A complete theoretical and mathematical modeling consideration for the design of a solar-based dryer is given. The drying requirements like the initial weight of food products, and initial and final moisture content, collector outlet, drying chamber, atmospheric temperature are used to determine the mass of water to be removed, instantaneous collector efficiency, zenith angle using Eqs. 1-3 as presented below [45]. The mass of water to be removed from food products (m_{wT}), instantaneous collector efficiency (η_C), and zenith angle (θ) are calculated using Equations 1-3.

$$m_{WT} = m_i \left(\frac{M_{im} - M_{fm}}{1 - M_{fm}} \right) \quad (1)$$

$$\eta_c = m_a C_P \left(\frac{T_o - T_i}{A_c \times I} \right) \quad (2)$$

$$cos\theta = sin\phi sin\delta + cos\phi cos\delta cos\omega_s \quad (3)$$

Where ω_S is called the sunshine hour angle, which is defined as the angular displacement of the sun east or west of the local meridian due to the rotation of the earth on its axis at 15° per hour with the morning being negative and afternoon being positive. Performance indicators such as drying efficiency, drying rate, heat utilization factor, coefficient of performance, moisture content on a dry basis, and moisture ratio have been presented below using Eqs. 4-9 [3]. Similarly, specific energy consumption and payback period have been discussed below using Equations 10-11 [46].

Drying efficiency ($\eta_{thermal}$) is a measure of the overall effectiveness of the drying system. It generally depends on the mass of water evaporated, latent heat of evaporation, the surface area of the collector, and Instantaneous flux incident on a tilted surface. It is defined as the ratio of energy required to evaporate moisture from food products by supplementing heated air.

$$\eta_{thermal} = \frac{m_{WT} \times L}{A_C \times I} \quad (4)$$

The drying rate (*DR*) is defined as the time required for the mass of water to be removed from the food products.

$$DR = \frac{m_{WT}}{t} \quad (5)$$

Heat utilization factor (HUF) is calculated from the collector temperature (T_C), drying chamber temperature (T_d), and ambient temperature (T_a) using Eq. 6 as presented below:

$$HUF = \frac{T_c - T_d}{T_c - T_a} \quad (6)$$

The coefficient of performance (COP) is calculated using Eq. 7 as presented below:

$$COP = \frac{T_d - T_a}{T_c - T_a} \quad (7)$$

Moisture content on a dry basis (*M*) is calculated from the initial and final moisture contents by using Eq. 8.

$$M = \frac{M_{im} - M_{fm}}{M_{fm}} \quad (8)$$

Moisture ratio is defined as the ratio of the difference between instantaneous moisture content and equilibrium moisture content to the difference between moisture content on a dry basis and equilibrium moisture content under the condition of constant temperature and air humidity.

$$Moisture\ ratio,\ \ MR = \frac{M_I - M_E}{M - M_E} \tag{9}$$

Specific energy consumption (SEC) is defined as the total energy received during drying divided by the amount of water evaporated from the object.

$$SEC = \frac{Q_{net}}{m_{WT}} \tag{10}$$

The payback period (PBP) is an important economic parameter of a solar drying system. It is defined as the time needed to recover the initial investment for the project from the savings obtained during that period. It is calculated as explained below:

$$Payback\ period = \frac{C_{Total}}{M_{dry\ product} P_{dryproduct} - M_{fresh\ product} P_{freshproduct} - M_{dry\ product} X} \tag{11}$$

where, the total capital cost for the dryer is given by,

$$C_{Total} = total\ material\ cost + total\ labor\ cost\ for\ manufacturing \tag{12}$$

Above, the annual cost per unit of the dried product is called drying cost (*X*) and it is defined by *X*= Annual cost/amount of dried product per year. $M_{Dry\,product}$ is the annual production of dry product in kg, $M_{freshproduct}$ is the amount of fresh products in kg, $P_{dry\,product}$ is the price of dry product, and $P_{freshproduct}$ is the price of fresh product.

3. EXPERIMENTAL PROCEDURE FOR THE SOLAR DRYING PROCESS

3.1. Installation Process and Use of Measuring Instruments

An experimental study has been conducted for drying tomatoes using two methods such as mixed type solar drying and indirect solar drying. The main components are a collector, a drying chamber covered with polycarbonate, and a chimney for exhausting moist air. Different measuring instruments such as temperature sensors, humidity sensors, an anemometer, and a moisture analyzer are used during the experiment for measuring different parameters. The weight of a tomato slice is measured at regular intervals by a weight-balanced machine [47]. Experimental setup of a mixed type of solar drying system consisting of copper oxide nanoparticle coated flat plate collector has been used for drying maize. Five numbers of thermocouples are connected at different locations of the experimental set-up for recording temperature. A hygrometer and an anemometer are also used to record relative humidity as well as the velocity of airflow [48]. 24 kg of sliced mangoes is placed inside an indirect type of preheated solar drying chamber. Initial and final moisture content is measured by a moisture analyzer. Four temperature sensors are provided for measuring the temperature at the inlet and outlet of the evacuated collector and drying chamber. An electric-consuming device such as a three-phase inverter fan and heating device is used [49]. An indirect mode forced convection type solar drying system consisting of a converging type solar drying chamber is used to dry lemon balm leaves. The collector is tilted at a 40°angle oriented towards the south as per the latitude of the location. Hygrometer, hot wire anemometer, digital balance weight machine, and thermocouples are used to measure relative humidity, wind velocity, the weight of the sample, and temperature at different points of the solar dryer respectively [50].

An experimental study has been carried out for heated air with fins attached to the air heater. The collector is connected to a centrifugal pump for circulating air and an absorbing plate (made up of copper having 1 mm thickness) is attached with seven numbers of copper fins. Paraffin wax is provided between the space of the base of the collector and the finned plate as presented in Fig. 5. Anemometer, pyrometer, and temperature sensors are connected for measuring the velocity of air, the intensity of solar light, and temperature at various points of the heater respectively. All the measured data are recorded Arduino-based [51]. A double-glazed solar air heater is installed with an angle of 30°. Phase change material as paraffin is provided below the absorbing plate. In this experimental study, the Aluminum powder is added to paraffin wax to improve the heat transfer coefficient [52]. The solar air heater is integrated with a baffle to increase the turbulence effect. Two numbers of transparent cover plates with a gap of 3.5 cm are provided to increase the transmittance. Paraffin is filed up below the absorbing plate and Styrofoam is provided for insulation purposes [53]. A solar dish concentrator with a cylindrical cavity receiver is used for drying mint. Pure thermal oil or Al_2O_3 acts as a solar working fluid [54].

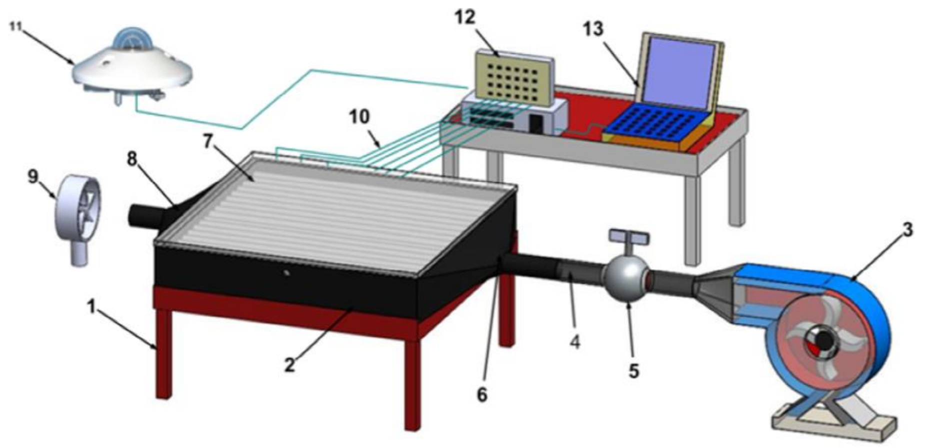


Figure 5. Schematic diagram of solar air heater with phase change material [51]: 1) Collector frame, 2) Collector, 3) Blower, 4) PVC connection pipe, 5) Gate valve, 6) Conical inlet section, 7) Glass cover, 8) Conical exit, 9) Anemometer, 10) Temperature sensors, 11) Pyranoameter, 12) Arduino board, 13) PC-lap.

A mixed type of solar dryer has been developed for drying tomatoes and is integrated with 15 temperature sensors, humidity sensors, a moisture analyzer, and a hot wire anemometer used to measure temperature, humidity, moisture, and wind velocity respectively [55].

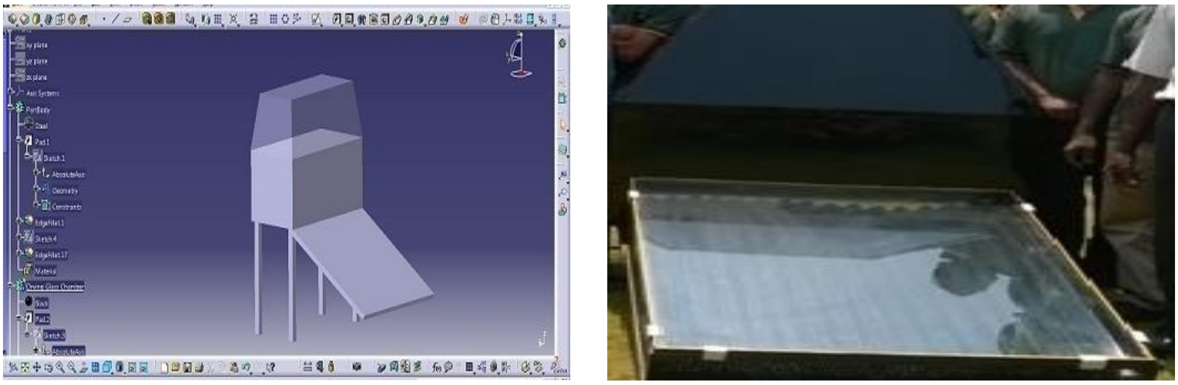
3.2. Use of Photovoltaic Systems for the Drying Process

An experimental set-up of a PV-integrated solar dryer has been developed for drying tomato slices. The experimental set-up consists of a collector, drying chamber, PV panel, DC motor, blower, battery, charge controller, and sun-tracking system. T-Type thermocouple, solarimeter, anemometer, and digital hygrometer are used to measure the temperature, solar radiation, airflow, and relative humidity of the solar dryer respectively [56]. A Mixed-mode and active-type dryer have components as absorbing plates and are made from Aluminum, Zinc, Silicon, and fiber-reinforced Polyester composites. Polystyrene is provided for insulation. The solar panel, battery, and charge controller are used to run the DC blower. Temperature sensors and an Aurdino microcontroller are used for monitoring data [57]. A direct-type dryer has been developed at Markondi village 30 km from the city of Berhampur, sponsored by Voluntary Integration for Education and Welfare of Society (VIEWS), a development organization working for the livelihood security of fisherwomen of south Odisha as presented in Fig. 6**.** Four DC blowers are operated by solar panels for proper circulation of warm air inside the drying chamber as well as for removing moist air [58].

(a) (b)

Figure 6. (a) Solar fish dryer for the livelihood security of fisherwomen of south Odisha from Ref. [58]. (b) Drying products from Ref. [58].

A solar dryer has been developed which was operated by the forced convection method as stated in Fig. 7 (a, b). The collector is tilted at a 20° angle facing due south as per the latitude of the location. The solar dryer is fabricated of Aluminum material and stainless wire mesh-type trays are provided. An exhaust fan is operated by a solar panel [59].



(a) (b)

Figure 7. (a) Design and (b) constructed units of a forced convection cabinet type of solar dryer [59].

A hybrid type of solar dryer has been developed for drying potatoes, tomatoes, ginger, etc. The solar panel, battery, and charge controller are connected electrically to run four numbers of DC blowers for proper circulation of heated air as well as for the exhaust process as mentioned in Fig.8 (a, b). Baffles are provided for increasing the turbulence effect. The dryer is used during the nighttime by using a heated coil. The setup is used during the nighttime by attaching an inverter and electric coil operated by a battery. The battery is charged during the daytime and is used for 24 hours of backup [45].

(a) (b)

Figure 8. A hybrid type of solar dryer used both (a) day and (b)night time from Ref. [45]:1) Blower, 2) Glass plate, 3) Baffle, 4) Drying chamber, 5) Solar panel, 6) Heating coil 7) Inverter, 8) Insulation

A solar dryer using V-shaped fins integrated with a solar panel has been used for the enhancement of efficiency. Compound parabolic concentrators are placed at the right and left sides of the 50 W solar panel to increase the absorption of solar radiation. Several fins are provided under the solar module for providing a cooling effect, thus increasing the air temperature circulated through it. The heated air is circulated through the second floor of the drying chamber by a 12 V DC fan through convective heat transfer [60].

4. RESULTS AND DISCUSSION

4.1. Factors and Parameters Affecting Solar Drying Efficiency

The thermal performance of a solar dryer depends on a lot of factors and techniques that affect solar drying efficiency. Various studies regarding factors and techniques which improve solar drying efficiency have been discussed below. It is found that factors like there is no significant change of solar radiation and temperature inside and outside of the greenhouse solar dryer as there is no cloudy weather. The Nusselt number, Prandtl number, Reynolds number, and amount of air exchange per hour with respect to time have been plotted for the greenhouse solar dryer with and without modification [61]. A shell and tube latent heat storage for a solar drying system with low commercial-grade Paraffin wax is considered a phase change material for drying food products when solar intensity is very low. Transient variation of phase change material is studied by considering various angular (such as 0°, 90°, and 180°) and axial positions, and the highest temperature is found at 180° position during the melting of phase change material. The temperature profile is plotted for phase change material at various heat transfer fluid inlet temperatures and a constant mass flow rate. It is observed that the average temperature is higher at 90°C of heat transfer fluid temperature [62]. A comparative study between heat pump conventional dryer, solar dryer, and heat pump-assisted type have been performed for drying bananas in four types of continental climate conditions. It is found that the heat pump-assisted type is efficient enough for drying food products. Variations of moisture content, moisture ratio, and coefficient of performance are maximum for heat pump-assisted solar dryers as compared to heat pump dryers and solar dryers during different climate conditions such as summer clear climate conditions, summer cloudy condition, winter clear climate condition and winter cloudy condition [63].

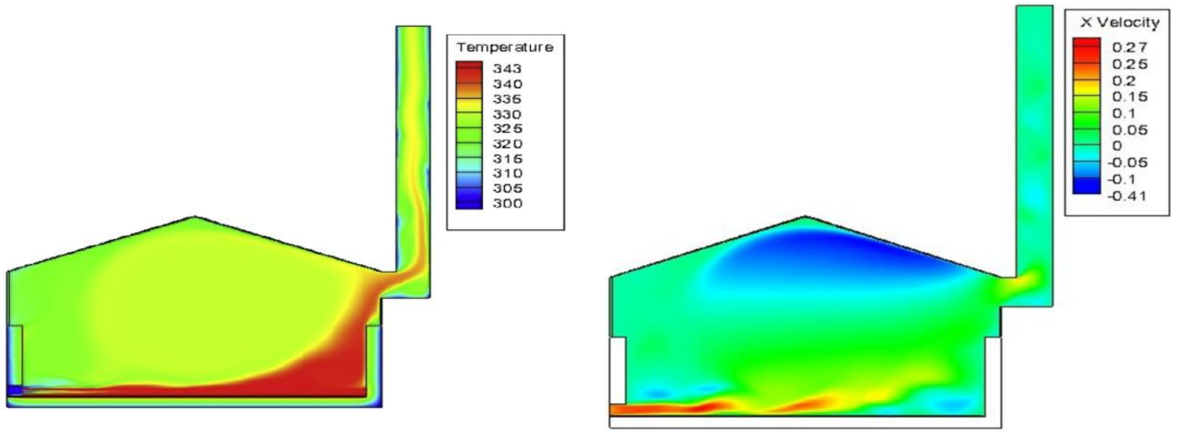
4.2. Operating Conditions and Geometric Factors

A fuzzy model (Takagi Sugeno) has been used to do the static and dynamic behavior of both natural and forced convection indirect-type solar dryers. For maintaining a suitable drying temperature range (40°C-50°C), a proper airflow value (0.027 kg/s) with continuous circulation is chosen [64]. Experimental study and comparative analysis for both open and closed modes of indirect type have been conducted. Different graphs have been plotted between atmospheric and drying chamber temperatures for a closed and open system of the solar dryer at different airflow rates. It is observed that the closed system type of solar dryer is more efficient as expelled air from the outlet of the drying chamber is further recirculated through the inlet of the collector [65]. An experimental study has been conducted on a mixed-mode forced convection type of solar dryer for drying turmeric. Uncertainty results for different parameters are found during the experimental study. The temperature at various points of the solar dryer is plotted against time at different solar radiation. Mathematical modeling for moisture ratio versus drying time is obtained by using RMSE and Chi-square distribution [66]. A comparison has been done for a mixed-mode type solar dryer. Similarly, drying efficiency, average drying rate, and collector efficiency are more while using thermal storage as compared to without using thermal storage [67].

A hybrid type of solar integrated with a dual-function flat plate collector is used for drying lemon slices. Experiments have been performed for analysis of ambient air temperature, drying chamber temperature as well as relative humidity and the average drying chamber temperature is 44°C. The moisture content in the case of open solar drying is higher than in a hybrid type of solar drying resulting in a more drying capacity [68]. An experimental study on the direct type of solar dryer consists of a parabolic roof structure made from polycarbonate for drying bananas. The moisture content of bananas is also reduced with the increase in temperature [69]. Natural convection direct-type solar dryer has been used for drying apples and it is found from the experimental analysis that 886.64 grams are reduced to 135.1 g of sliced apples. Similarly, the drying rate, amount of heat required for drying, latent heat of vaporization, etc. is also calculated [70]. A study on solar drying has been performed for the storage of seafood under forced convection. Horizontal and inclined solar radiation, temperature, relative humidity, and airflow rate are measured for time. The dry curve signifies the amount of moisture present within the food materials and the evaluation of the drying rate. Different Mathematical models describe the shape of drying kinetics such as the Chi-square method. The predicted and experimental moisture ratio is calculated using the logarithmic model and a plot is drawn between the predicted moisture ratio and drying rate [71].

4.3. Simulation Study for Solar Drying System

An experimental and simulation study has been carried out on a solar dryer for drying kiwifruits and mushrooms. The main components are a solar panel, drying chamber, and solar accumulator, which consist of a thermal storage device using paraffin wax. The simulation and modeling are carried out for different components of the solar dryer using MATLAB. From the simulated results, a plot is drawn between the average air temperature and efficiency and it is found that a higher airflow rate leads to higher efficiency. Similarly, simulation for the radiative heat transfer coefficient between the glass plate and absorbing plate has been carried out at varying temperatures at two different airflow rates (0.03 and 0.048 kg/s). Also, a similar simulation has been performed for the solar accumulator and drying chamber [72]. A simulation considering various parameters has been performed to increase the thermal efficiency of a direct type of solar dryer using a tubular heat exchanger as shown in Fig. 9 (a,b).



(a) *(b)*

Figure 9. CFD simulation of (a) air temperature and (b) x-component of air velocity distribution inside the drying chamber from Ref. [72].

It is observed that ambient temperature is highest when the intensity of solar radiation is 643 W/m^2 at 1 P.M. and the drying chamber temperature is increased up to 15°C as compared to ambient air temperature without using a heat exchanger. Experimentally it is found that the temperature of the air inside the solar dryer reaches up to 58°C and a constant temperature is maintained at 47°C after sunset while using a heat exchanger. Therefore, the thermal performance is improved. The simulation result is correlated to the experimental result while using CFD Fluent software [73].

Simulation of photovoltaic/thermal-based collectors has been studied for dry agricultural products. The maximum outlet air temperature generated is 50°C, which is enough to dry agricultural products. Both simulated and experimental data for open-circuit voltage and short-circuit current have been plotted versus time. It is observed that the maximum value is reached at 1 P.M. Similarly, variations of solar cell temperature, the temperature of the back surface of the solar cell, outlet air temperature, solar radiation, ambient air temperature, wind velocity, etc., have been plotted for time. Overall energy efficiency with various mass flow rates is also plotted for performance evaluation of the PV/T collector [74]. The thermal performance of an indirect forced convection solar dryer has been simulated using ANSYS fluent CFD software. Different simulation results such as velocity contour, maximum collector outlet temperature, and maximum absorbing plate temperature are obtained corresponding to different mass flow rates of air. At different mass flow rates and circulating maximum heated air the maximum absorbing plate and collector outlet temperature were obtained as76.02°C and 48.5°C. Temperature and pressure contour for four treys have been attained and temperature at the bottom plate was maximum while at the upper plate was lowest [75].

5. CONCLUSION

This paper presents the highlighted studies on solar drying systems. According to the literature, the performance of a solar dryer strictly depends on many parameters such as inside temperatures, relative humidity, solar radiation, and the speed of hot air. The baffle and finned-type absorbing plate integrated with the solar collector can be used to enhance the drying rate and thermal efficiency. Many phase change materials can be used for heat storage so that the dryer can continuously operate day and night. It is established from the literature that the hybrid type of dryer is more efficient and gives a better drying effect in comparison to other types of solar dryers. Still, more research is needed on the reduction of heat loss to build an energy-efficient and cost-effective solar drying system.

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