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Review Article

A recapitulation of solar dryers in realm - evaluating geometry, modes, thermal energy storage, and applications in agricultural produce

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ABSTRACT

Waste of agricultural produce attributed poor post-harvest management practices. To resolve this problem now days solar drying system gained hegemony to preserve and process the agricultural produce. The study systematically analyses the experimentation conducted on different factors of solar dryer, including its geometry, modes, agricultural produce, heat storage materials, mathematical models, and validation through Finite Element Analysis (FEA) analysis, providing valuable insights for future study. In the reviewed literature, the desiccation of agricultural produce commonly occurs within the air temperature range of 28°C to 86°C. It was found that the most effective desiccation of agricultural produce in solar dryer cabinets takes place within the air temperature range of 50°C to 65°C, leads to reduce drying time. In the majority of studies aimed at improving the desiccation rate, air circulation is achieved through the use of blowers or fans, with velocities typically rang of 0.5 m/s to 2 m/s. Additionally, the air flow rates employed in these studies vary from 0.003 kg/s to 0.09 kg/s. However, further research and investment are needed to enhance solar drying technologies, exploring new geometries, intermittent air circulation, desiccants to reduce air humidity and make them available to more farmers across the world.

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INTRODUCTION

Food is an essential requirement for human beings to sustain their nourishment and ensure their survival. India holds a prominent position as one of the world's largest food-producing countries, however it's observed that wastage of food due to poor food preservation techniques is a serious concern. According to the Indian Council of Agricultural Research (ICAR), there is an estimated 35-40%

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loss of agricultural produce during the post-process harvest stage in India. Inadequate drying techniques contribute to post-process harvest losses of agricultural produce, which can range from 5 to 25% [1–4].

Moreover, efficient and sustainable food production and preservation techniques are demanding to cater ever-increasing global population need. An agricultural country like India, solar drying system has demonstrated to be a realistic and economically viable solution to dry fruits and vegetables [5,6]. Through an examination of previous literature, it has been noted that numerous researchers have explored the application of solar dryers for a wide range of agricultural produce such as, onion chips [7], potatoes [8,9], tomatoes [10–13], carrot [14–16], ginger [5,17–19], garlic [20–22], turmeric [19,23,24], chili [25–31], pepper [32], apple [33,34], mangoes [35–38], grapes [39], pineapple [40,41], wheat [42], corn [43], fish [44–46] and many more using different solar dryer geometries.

Open sun drying (OSD), a traditional method of preserving food, is associated with several drawbacks and disadvantages. Sun drying is accompanied by significant disadvantages, including food deteriorate by decomposition, insect, loss due to adverse climatic conditions like rain, moisture, dust and wind, as well as the risk of loss from bird droppings and animals [47]. Moreover, open sun drying demands substantial labor, consumes significant time and necessitates a considerable amount of space. Now days artificial mechanical drying methods have become more popular due its fast desiccation rate to address these challenges. Nevertheless, this approach is characterized by high energy consumption (approx. 60% energy) being utilized for heating and drying the food product. Consequently, this leads to increased operational costs for the setup [48].

Solar thermal energy has emerged as a promising renewable energy source for the desiccation of agricultural produce. The solar dryer becomes favorable and feasible solution due to the huge concern about use of conventional fossil fuels attributed atmospheric pollution for desiccating agricultural produce. Solar drying process not only use the freely available solar energy but also can help to decrease greenhouse gas emission eventually improve air quality. Therefore, solar drying stands out as the most effective green energy solution to mitigate the disadvantages inherent in artificial mechanical drying and open sun drying methods. Additionally, it enhances product quality, improves overall process efficiency, and contributes to environmental protection [49–52].

The literature provides a comprehensive investigation of the effectiveness of different solar dryer designs. The primary objective of this paper is to offer an extensive summary of the research highlight while emphasizing potential literature gaps for future investigations. To discuss the manuscript systematically and understand the various aspects of drying technology for preserving food it is better to draw a mind diagram as depicted in Figure 1. The analysis considers several aspects of the solar dryer, including its geometry, modes, agricultural products, heat storage materials, mathematical models, and validation via Finite Element Analysis (FEA). The findings of this study aid in designing innovative solar dryer shapes and developing them for diverse agricultural produce in future research endeavors.

GEOMETRY

In the past research, various types of shapes and geometries have been utilized to develop solar dryers to desiccate

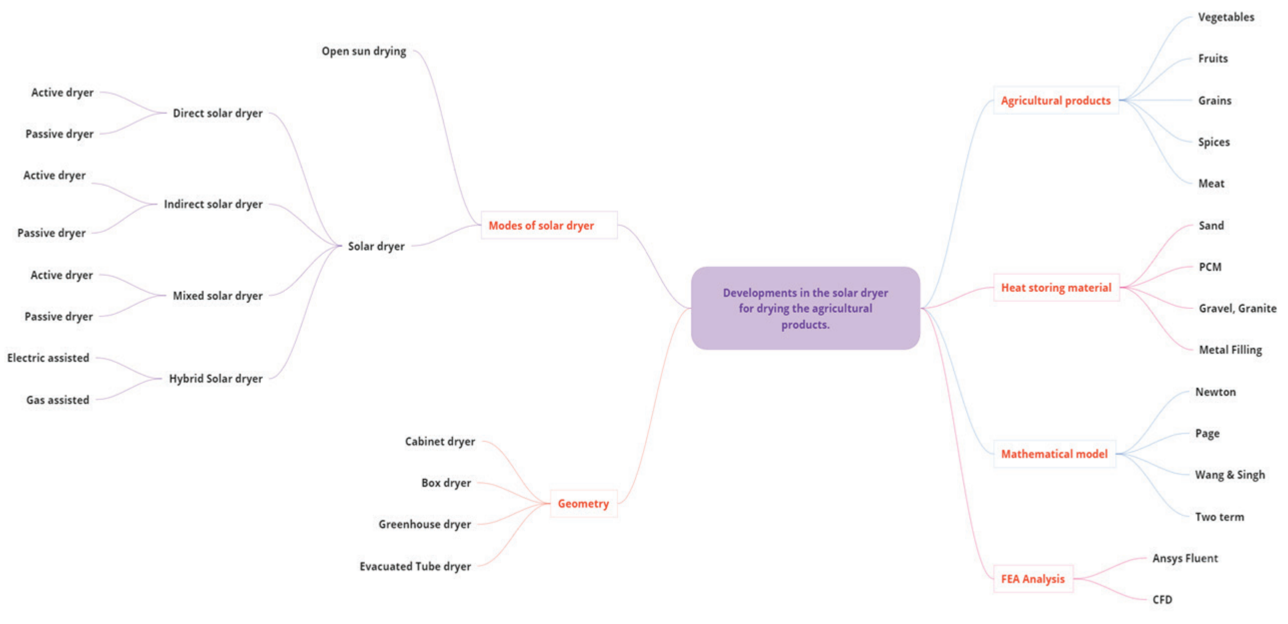

Figure 1. Literature review summary.

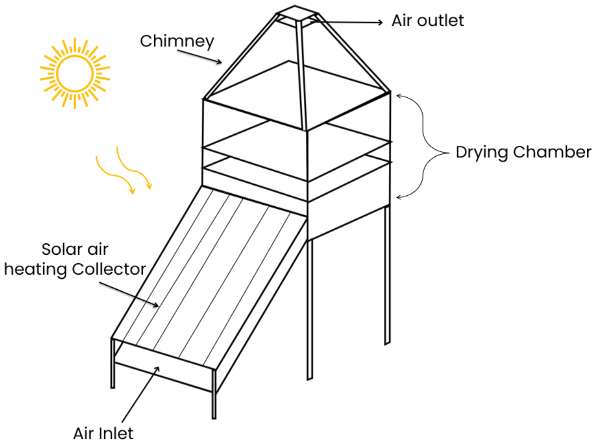

Figure 2. Natural convection cabinet solar dryer.

agricultural produce. The solar dryer's shape is crucial for maximizing the capture of sunlight and enhance its overall performance. Cabinet [53, 54], natural rack dryer [55], Geodesic dome [56], and solar greenhouse tunnel type [57] are among the commonly used shapes in solar dryers by various researcher. During this session, a comprehensive discussion is presented, explaining the various geometries that have been used in the solar dryers by different authors.

Cabinet Solar Dryer

Researchers led by Pangavhane et al. [58] developed a solar dryer for drying grapes using natural convection. The dryer consisted of a solar air heater and a drying chamber, as depicted in Figure 2. The performance of the developed solar dryer was assessed by comparing it with shade drying and open sun drying methods. The results showed that the grapes were successfully dried in the solar dryer, taking only 4 days and yielding higher quality raisins. In contrast, shade drying required 15 and open sun drying required 7 days. The average air temperature at the dryer inlet ranged from 51.9°C to 64.6°C over the 5-day period, in the same time the solar radiation varied between 605 and 673 W/m^2. The solar air collector's daily mean efficiency ranged from 48% to 56% during these days. Additionally, the desiccating time reduced by 43% in solar dryer compared to the open sun drying.

Kokate et al. [59] conducted a trial on indirect cabinet solar dryer specifically for drying onion and garlic as illustrated in Figure 3. The researchers compared the experimental results obtained from this dryer with those from an open solar dryer (OSD). The drying times for 1 kg of onion was 36 hours and 300 gm of garlic was 188 hours to dry in the dryer. The solar dryer cabinet reached a maximum temperature of 47.6°C at 2 pm. Over the course of 24 hours of experimentation, the moisture content of the onion samples decreased to 25%, while the moisture content of the garlic samples decreased to 60%. In contrast, the OSD maintained moisture contents of 67% and 63% for onion and garlic, respectively .

Solar Greenhouse Tunnel Dryer

Ragul Kumar et al. [60] developed natural convection large scale solar greenhouse dryer for their research project as shown in Figure 4. The dimensions of the greenhouse were 10 meters x 4 meters x 3 meters (length x width x height) at field level. The performance of the solar

Figure 3. Indirect cabinet solar dryer [From Kokate et al. [59], with permission from Elsevier].

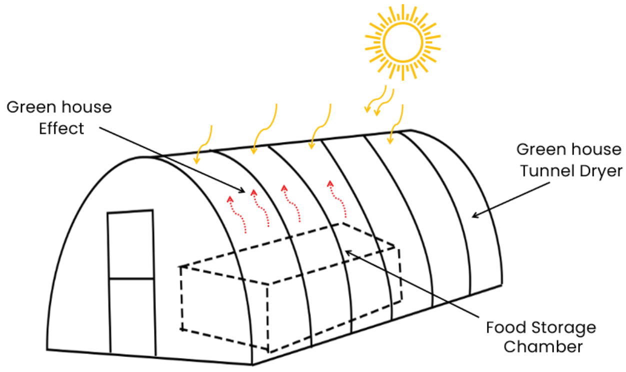

Figure 4. Solar greenhouse drier for desiccating of red chilli.

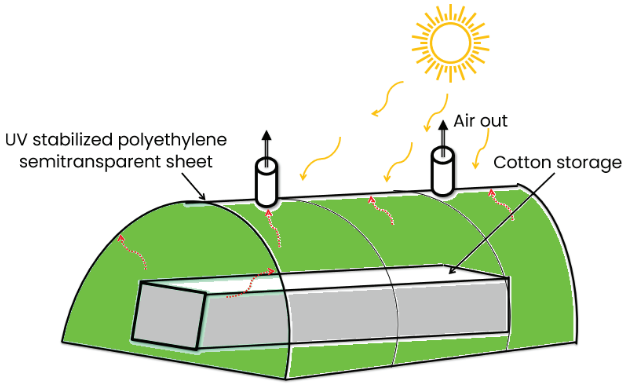

Figure 6. Solar tunnel poly-house dryer for desiccation of cotton.

dryer was assessed by drying red chilli, which exhibited a decrease in moisture content from 79% (w.b.) to approximately 10% (w.b.) within 55 hours, in comparison to the 124 hours required for open-sun drying. This indicates a 56% reduction in drying time. The highest recorded temperature inside the dryer was 64°C. The greenhouse effect resulted in a temperature difference of 10-28°C in the dryer. These findings indicate the efficacy of the developed solar greenhouse dryer in reducing the desiccating time for red chilli.

In this research paper, M. S. Seveda presents a study focused on the investigation of a passive solar tunnel dryer specifically for desiccating dibasic calcium phosphate. The dryer is depicted in Figure 5. The designed system consists of a solar collector with a surface area of 134.74 m^2, while the floor space of the dryer measures 78.75 m^2. During a two-day testing period, wet dibasic calcium phosphate with a load of 1500 kg was expected to dry from 62.87% to 10.62% (dry basis). The temperature difference between the interior of the solar tunnel and the ambient air was noted 18–21°C. In the summer season, the maximum temperature in the dryer under no-load & full load conditions were observed to be 63.1°C & 60°C at 15:00 h, while the minimum temperature was 29.4°C & 30.1°C observed at 8:00 h, respectively. These findings demonstrate the effectiveness of the designed passive solar tunnel dryer for drying dibasic calcium phosphate, highlighting its potential for application in various agricultural produce [61].

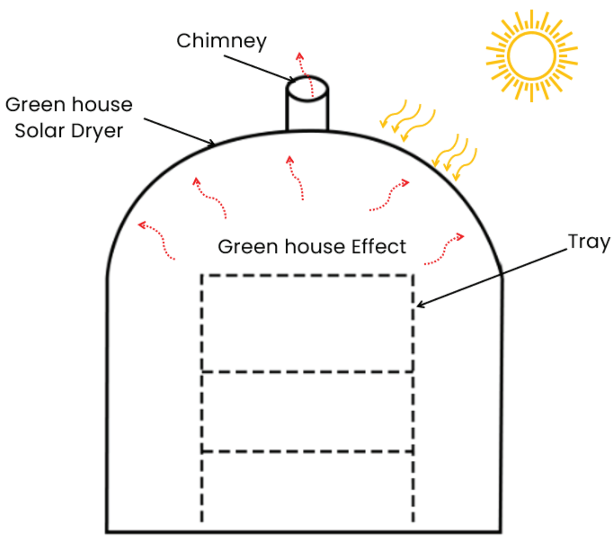

Figure 5. 2D view of passive solar tunnel dryer.

For drying surgical cotton Rathore et al. [62] specifically designed and tested an industrial-scale poly house walk-in type solar tunnel dryer based on natural convection. The dryer, depicted in Figure 6, can dry cotton from 600 kg to 390 kg where cotton moisture content of 40% (wet basis) turns to 5% (wet basis) in approximately 8 hours. The difference between the average air temperature inside the tunnel and ambient air temperature was found to be 18-20°C. On a typical day, under no load conditions and full load conditions, the maximum temperature inside the solar tunnel dryer was observed to be 54.6°C and 53.8°C at 1:30 PM and 2:00 PM, respectively.

In this research study, the performance of tent house solar dryer works on mixed-mode natural convection was developed and tested byVerma et al. [63]. The 1.12 m^2 solar flat plate collector area was specifically designed for the drying of potato slices in the dryer. The utilization of the polycarbonate sheet used in the tent facilitated direct irradiance heat transfer from the sun to dryer, ultimately leading to improved dryer performance as illustrated in Figure 7. The investigation shows that drying of potato slices from 85.25% initial moisture content to 14.75% during solar natural convection drying, in contrast open sun drying took 6 h longer duration to attain the same level. The maximum dryer efficiency was recorded to be 26.62% for 2.5 mm thick potato and 21.61% for 5.0 mm thick potato slices. These results highlight the potential of tent house solar dryer works on mixed-mode natural convection for efficient drying of various agricultural produce.

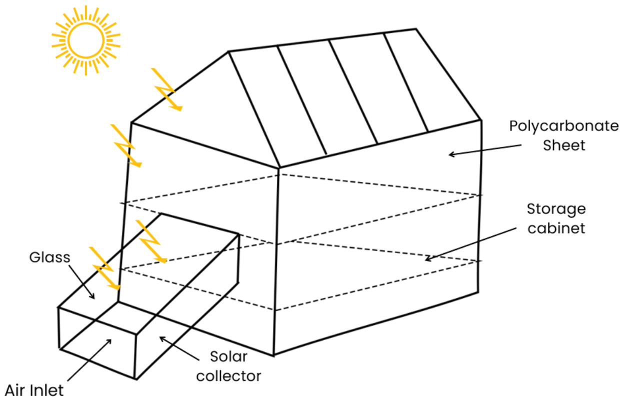

Figure 7. Tent house mixed-mode solar dryer.

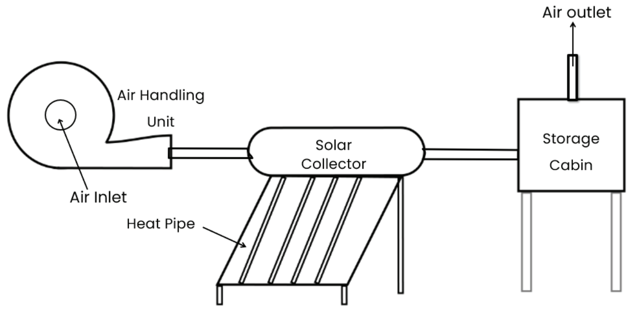

Figure 8. Evacuated tube collector solar dryer with heat energy storage.

Evacuated Tube Collector Solar Dryer

Mathew et al. [64] developed evacuated tube heat pipe collector, forced convection solar dryer integrated with thermal energy storage material as shown in Figure 8 for drying carrots and tomatoes. To enhance the drying duration as the thermal energy storage material Therminol 55 was used. The trials were conducted with five different individual mass flow of air 0.003 kg/s - 0.02 kg/s, as well as a combined mass flow rate of two air (0.015 kg/s and 0.0065 kg/s) also tested. The maximum air outlet temperature from the collector recorded was 118 °C. By utilizing the combined mass flow rate the average air outlet collector temperature was 67 °C, while in single mass flow rate air temperature decreased to 56 °C leads to reduce the drying time by 2 h.

Dutta et al. [65] conducted a study on the evacuated tube indirect solar dryer. The test was carried out with (ETDP) and without (ETD) phase change material as illustrated in Figure 9. The drying characteristics and quality of pre-treated turmeric slices for three different samples (control, peeled, and cured samples) were investigated. In ETD and ETDP test results recorded 9 h and 11 h duration to achieve final moisture content for different pre-treated turmeric samples, respectively. The set up ran at no load condition and noted the average temperature of drying chamber was 69.4°C and 60.9°C in ETD and ETDP, respectively. The results highlighted that ETDP retained maximum quality, whereas it was noted that drying time reduces in ETD.

Jahromi et al. [66], conducted experimental trials on the thermal-economic analysis of solar dryer work in indirect mode to dry Jerusalem artichoke (Helianthus Tuberosus L.). Dryer comprises evacuated tube collector connected to thermal storage consist of phase change materials, as illustrated in Figure 10. The activation energy increases by utilization of phase change materials to 33.4 kJ/mol during desiccation, eventually resulting in an improvement in the solar system efficiency by 1.5 -7.8 %. The optimum flow rate of air was determined at 0.09 kg/s based on considerations regarding quality, exergetic and economic aspects, of the dryer assisted with PCM. For three different flow rates of air 0.025, 0.05, and 0.09 kg/s the drying duration was recorded as 960, 930, and 900 minutes without PCM while with PCM the drying duration was reduced to 870, 840, and 810 minutes, respectively for the same airflow rates.

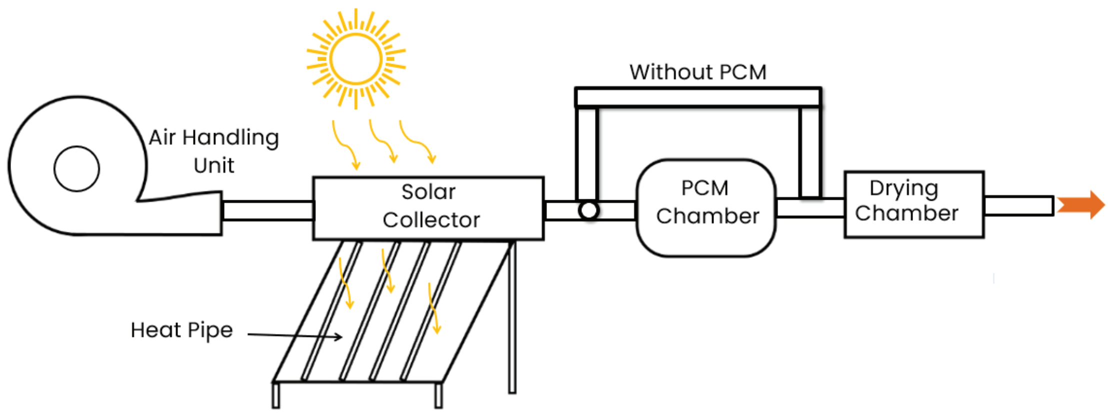

Figure 9. Forced circulation evacuated tube collector solar dryer.

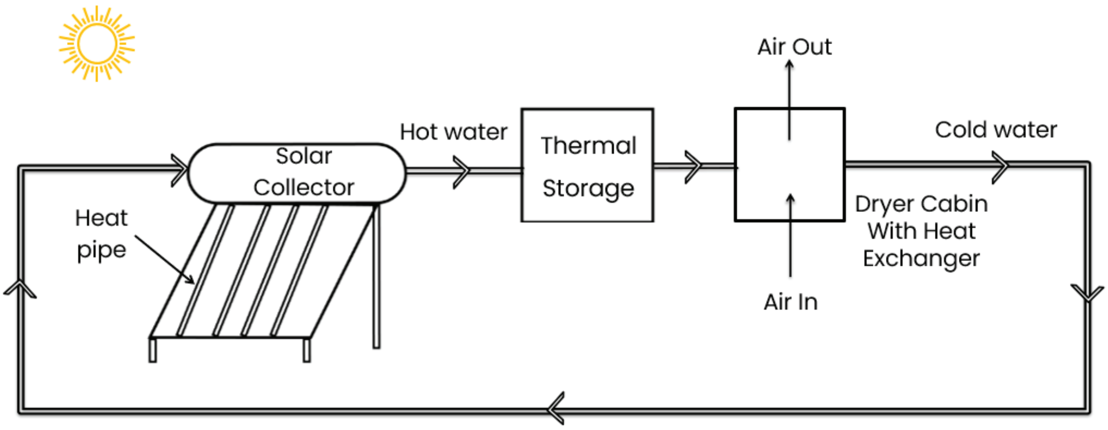

Figure 10. Schematic diagram of evacuated solar dryer with PCM.

The ANSYS Workbench software (Fluent subprogram 17.2) was utilized to simulate the heat storage material PCM and temperature profile during thermal energy charging and discharging has been discussed in detailed in the study.

In this research article, Shringi et al. [67] utilized indirect solar dryer had heat pipe collector connected to heat storage and dehumidifier unit as illustrated in Figure 11. The dryer system was tested at approximately 65°C drying air temperature. The Midilli et al. model was best fitted for the experimental results among different five kinetics models for garlic cloves. With and without recirculation of air into drying chamber, the efficiency of drying process varied from 43.06 to 83.73% and 3.98 to 14.95%, respectively. Furthermore, the results highlighted the exergy efficiency of the drying process ranged from 5.01 to 55.30% and 67.06 to 88.24% with and without recirculation of air respectively.

In this study, Wang et al. [68] tested an active indirect solar dryer with heating unit for drying mango slices, as shown in Figure 12. The dryer comprises of heat pipe solar air collector with an exposed surface area of 5.24 m^2. The dryer achieved thermal efficiency in the range from 30.9% to 33.8% by attaining the specific moisture extraction rate (SMER) was 1.67 (kg water/kW·h) at 52°C air cabinet temperature. The solar dryer performance was evaluated by drying 24 kg of sliced mango at four temperatures 40, 44, 48, and 52°C. The dryer took approximately 13 h to dry mango slice from an initial moisture content (MC) of 3.42 (kg water/kg dry matter) (d.b.) to final MC of 0.25 (kg water/kg dry matter) (d.b.).

Despite many solar dryers have been investigated by the researcher in the history, there is still considerable scope for different geometry to be tested as a solar dryer. Future research could focus on optimizing the geometrical dimension of solar dryers to enhance their efficiency and effectiveness in desiccating agricultural produce. By exploring new shapes and configurations, researchers may be able

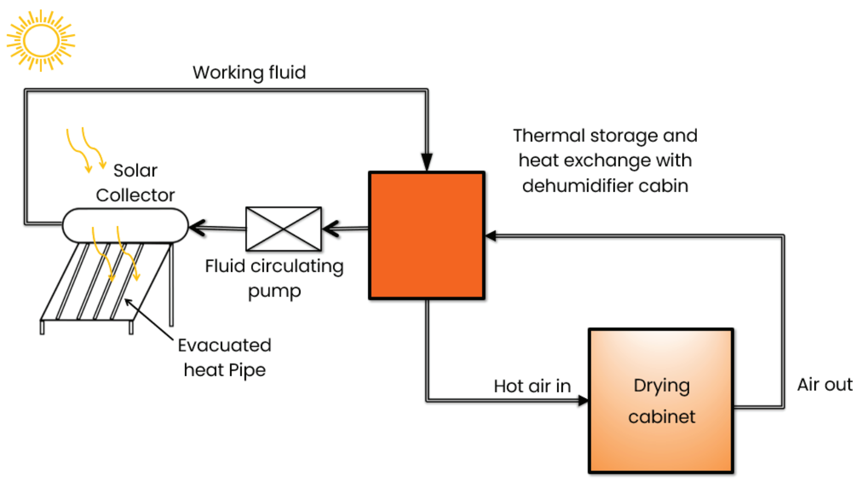

Figure 11. Evacuated-tube heat-pipe collector with a heat storage and dehumidifier unit solar dryer.

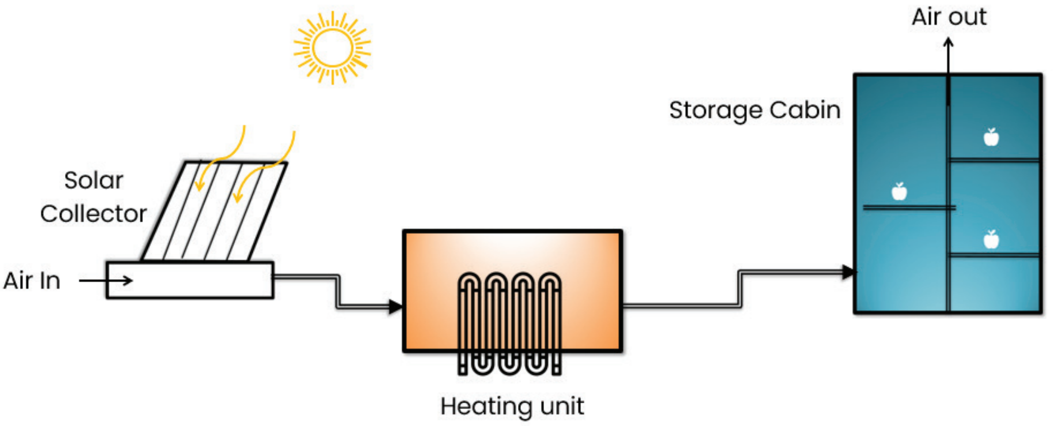

Figure 12. Schematic diagram of an active indirect solar dryer.

to develop solar dryers that can achieve even greater performance by utilizing more solar thermal energy leads to reduce the drying time of agricultural produce.

Solar Dryer Working Modes

Solar dryers mainly have two main types indirect and direct solar dryers based on the way sun rays are utilized for drying the food products. In the storage cabinet sun rays directly make contact with the food products in case of direct solar dryer. However, the direct exposure of UV light to the food products may degrade the color and nutrient values. To diminish these issues, the direct exposure of UV light to the food product should be avoided which is possible by using indirect solar dryer. Indirect solar dryer collector air expose to sun irradiance eventually increases the air temperature which is used to dry the food products in the cabinet. If in the solar dryer buoyancy force circulates air due to density difference, known as a passive solar dryer, or by fan force circulation, referred to as an active solar dryer are two types based on air circulation. However,

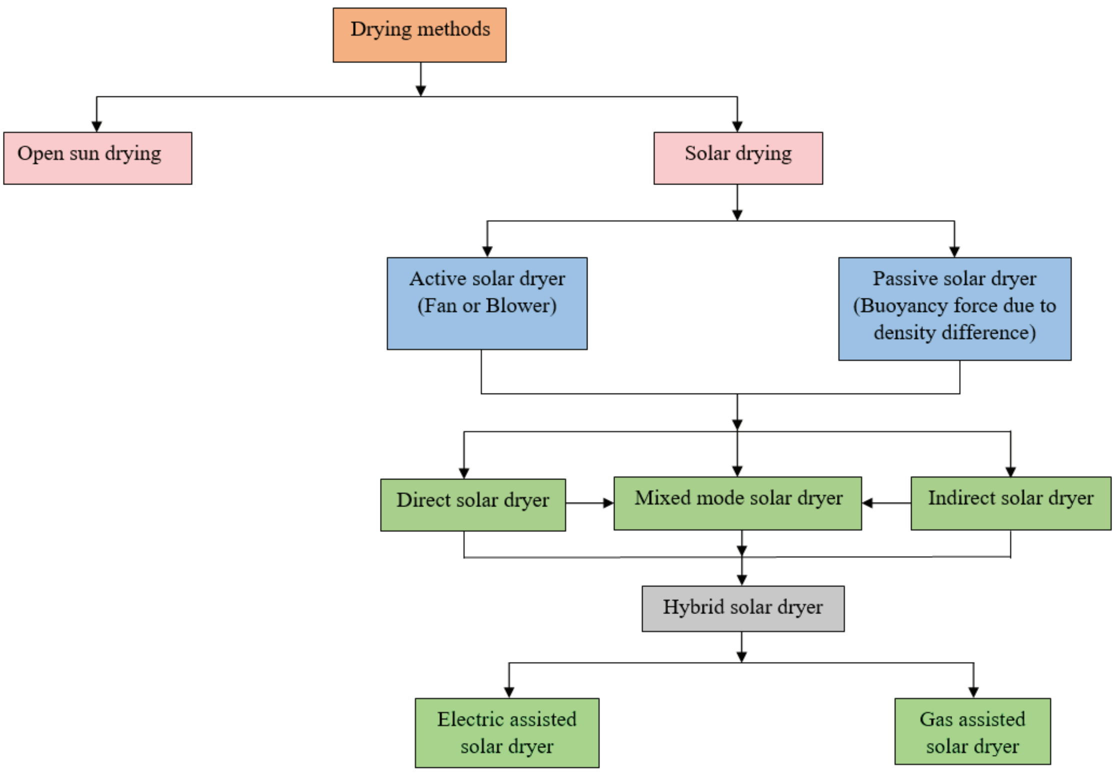

Figure 13. Solar dryer classification.

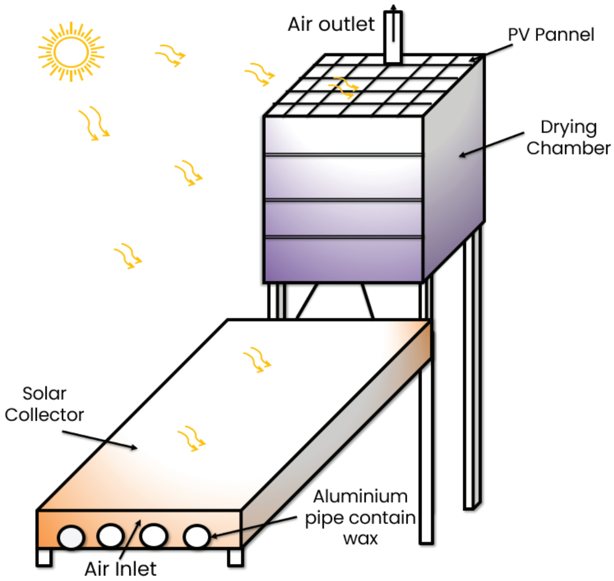

Figure 14. Schematic diagram of passive cabinet solar dryer.

the desiccation process is halted at night, which demands additional heating methods to dry the food products. Hybrid solar dryer, which employs electric heater or burning of gas at night to dry the food products, is one of the solution [48, 49]. The different types of solar dryer modes are explained in detail in the accompanying Figure 13. The upcoming section discusses the different modes of dryers used by various authors and the performance attained in their corresponding solar dryers.

In the present study, Bhavsar et al. [69] extracted ginger powder by desiccating 2000gm fresh ginger. To attain this, the trials conducted on a cabinet solar dryer works on natural mode, both with (Atlas wax SF 42 in aluminum pipe) and without heat energy storage material as depicted in Figure 14. During the trial solar dryer system recorded a higher efficiency of 48%. It was observed that the 80 % moisture content in 2000 gm fresh ginger decreased to 8% with and 9% without the utilization of heat energy storage material within 18 h. Moreover, the inclusion of heat energy storage material extends drying time up to 3 h after sunset.

An active solar tunnel greenhouse dryer comprising two tunnels connected in series, each facing an area of 4 m^2, was used to desiccate amla candy, as shown in Figure 15. A batch of 40 kg of amla loaded into the tunnel followed by pretreatment blanching in hot water. During the trial for 36 h on amla candy initial moisture content of 80% (w.b.) reduced to 18% (w.b.) in tunnel greenhouse dryer while 33% (w.b.) in open sun drying. This demonstrated that proposed active solar tunnel dryer showed the decrease in desiccating time. Patil et al. [70] evaluated six thin layer mathematical models to describe the drying behavior of amla candy. The Modified Page model was best suited and trace the experimental data. The payback period for the developed active solar dryer was approximately 17 months, hence it is the economical feasible solution.

The Mixed Solar Dryer (MSD) operated on direct and indirect mode was investigated and results compared to that of the Indirect Solar Dryer mode (ISD) by Erick César et al. [71] as depicted in Figure 16. In MSD, solar radiation allowed to pass through drying chamber and collector through transparent polycarbonate, while in case of ISD

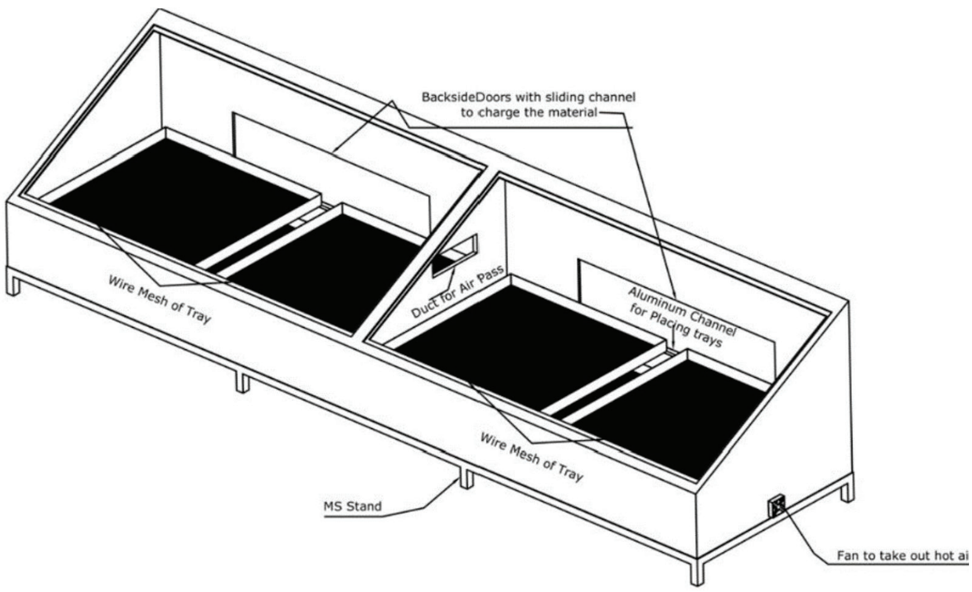

Figure 15. Schematic view of active solar tunnel greenhouse dryer [From Patil and Gawande [70], with permission from John Wiley and Sons].

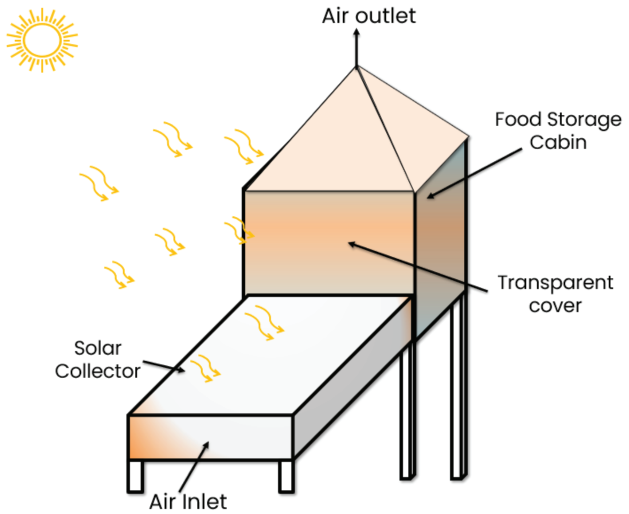

Figure 16. 3D view of mixed type solar dryer.

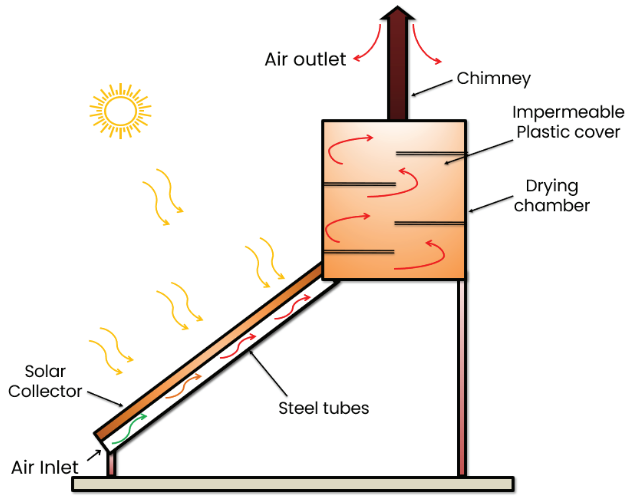

Figure 17. An indirect passive solar dryer modified by metallic tube with greenhouse plastic enclosing the dryer cabinet.

mode the drying chamber can be covered. In MSD temperature was recorded between 65°C to 70°C, while in ISD it was between 55°C to 60°C. The results demonstrated that desiccating tomatoes took 26 h in ISD and 17 h in MSD.

In an effort to enhance the collection of solar heat flux leads to enhance drying rate, an indirect passive dryer works on hybrid mode (HIP) was designed and developed, as shown in Figure 17, by Ssemwanga et al. [72]. The collector of the dryer is made up of a metallic plate while the cabinet constructed from greenhouse plastic materials. The trial was taken on hybrid indirect passive dryer (HIP), Open Sun Drying (OSD) method and a previously designed active-mode dryer assisted with Electric heater operated on solar photovoltaic cell (SPE). In the study, peeled pineapple and mango samples of different cultivars with thicknesses of 10 mm, 6 mm, and 3 mm were used for trials. From the results, it was noted that in SPE the pineapple and mango cultivars dried fast (10 h) while in HIP dryer and traditional OSD method took longer time (18 h and 30 h, respectively).

A liquefied petroleum gas (LPG) assisted hybrid solar dryer was utilized to examine the drying process of lime as Illustrated in Figure 18. Suherman et al. [73] studied the effect of temperature on the desiccation process at different five temperatures (40°C, 50°C, 60°C, 70°C, and 80°C). Results showed that the desiccating rate at 80°C was quickest for lime, with a completion time of 5 h, and slowest at 40°C, with a completion time of 24 h. Hence, the solar dryer system efficiency was increased with temperature, with the highest efficiency observed at 80°C. The correlation

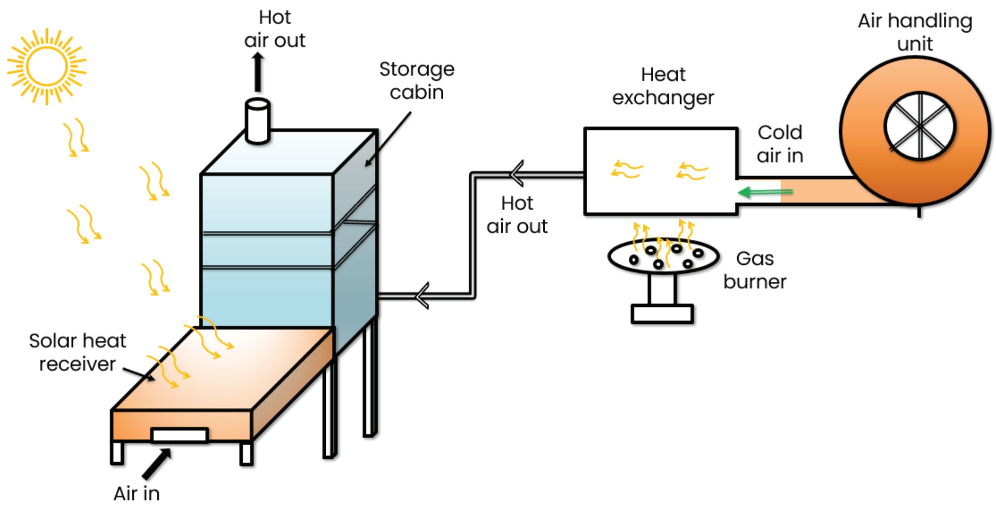

Figure 18. Liquefied petroleum gas (LPG) assisted hybrid solar dryer.

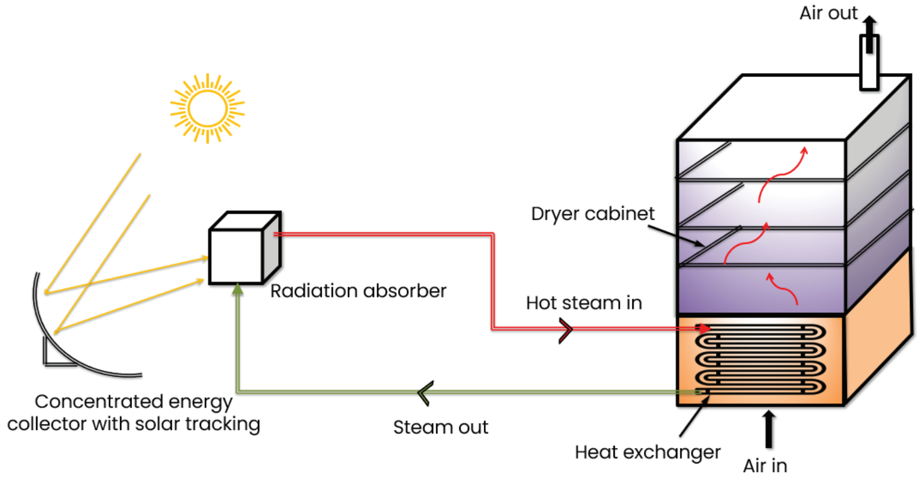

Figure 19. Scheffler cabinet solar dryer system.

between temperature and drying efficiency was attributed to the increased heat as well as mass transfer, which leads to enhance moisture evaporation from the lime.

Nukulwar et al. [74] investigated and observed the drying kinetics of turmeric rhizomes utilizing a solar cabinet dryer (SCD) with two configurations: one in which the SCD was connected to steam generated by a Scheffler system, and another in which it was not connected to steam, as depicted in Figure 19. On Pre-treatment of blanching of turmeric rhizomes shown in a shorter duration of 26 minutes at 705 w/m^2 solar radiation, eventually enhance the desiccation. During trial on SCD with and without steam recorded 1.62 % and 49.76% solar dryer efficiency with moisture content reduced to 15% from 77% in 39 h and 51h respectively, while 108h took in open sun drying method for same reduction in moisture content. The greenhouse effect is able to maintain 55°C in SCD without steam. It was noted that the drying rate in the SCD with was higher than without steam at 2%/h and 1.2 %/h respectively.

To dry a fish, tent-type solar dryer operates on mixed mode was utilized by Mehta et al. [75], as illustrated in Figure 20. In passive mode under no-load conditions air outlet temperature for collector was recorded at 86°C as a maximum, while no-load performance index (NLPI) was evaluated 2.11 at 600 W/m^2 average solar intensity. The fish was desiccated by utilizing tent-type solar dryer operating on mixed mode and open sun drying method loosen the moisture content to 10 % from 89% within 18 h and 38 h respectively. Lewis drying kinetics model traced the experimental data very well.

Hegde et al. [76] fabricated and tested an indirect flat collector active solar dryer also investigate the drying kinetics of bananas, as depicted in Figure 21. Trial was conducted to analyses the effect of velocities (0.5 m/s, 1 m/s, and 2

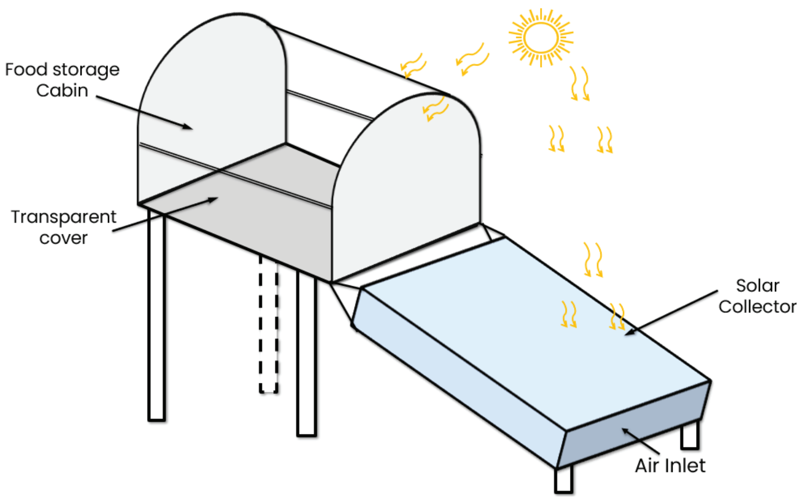

Figure 20. Tent-type solar dryer operates on mixed mode to dry a fish.

Figure 21. Indirect active solar dryer[From Hegde et al. [76], Open access].

m/s) on performance of solar dryer. The experiment was conducted using two methods of flow: top flow (between the glass and the absorber plate and between the absorber plate) and bottom flow (the insulation). The result indicated that the bottom flow had a higher chamber temperature and efficiency, with a 38.21% increase in temperature and 2.5°C higher temperature compared to top flow. The results showed that the banana quality in terms of shape, color, and taste was good at a velocity of 1 m/s, instead of 0.5 m/s and 2 m/s velocity.

The study by Eltawil et al. [77] proposed a solar photovoltaic powered solar tunnel dryer (STD) operates on mixed mode for desiccating potato chips as shown in Figure 22. This research attempted to evaluate the impact of different pre-treatments on the drying potato process. The results showed that the desiccating rate of blanched potato slices was significantly higher as compared to the unblanched samples. The dehydration process was carried out by utilizing both mixed-mode with black thermal curtain and without black thermal curtain. The appearance and color of the potato chips were found to be superior when the black thermal curtain and pre-treatment of sodium meta-bi-sulphite solution were used as compared to treatments without thermal curtains. The highest drying efficiency at flow rate of air 0.0786 kg/s was 34.29 % with thermal curtain, while a lower efficiency was recorded 28.49 % without the thermal curtain.

In this study a passive solar dryer with a backup heater work on mixed mode was evaluated to study pineapple drying characteristics by Sekyere et al. [78] in Ghana, as illustrated in Figure 23. The electric resistance heater was designed to incorporate an 1800W as a supplementary heat source. Pineapple slices of total weight 2262 g were used to analyses the drying rate in each mode of operation. The results had been shown that pineapple slices in the solar mode reduced the moisture content to 144% from 1049 % (db) in 23 h, while by utilizing backup heating mode in the dryer, it reduced to 106% from 924% in 19 h. The backup heating mode reduced the moisture content to 184% from

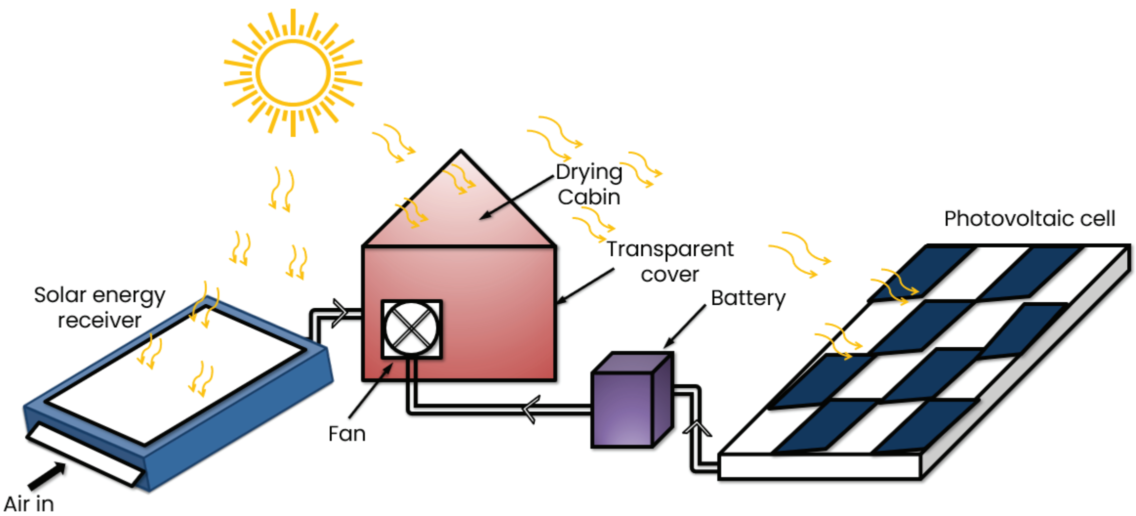

Figure 22. Mixed mode solar photovoltaic powered solar tunnel dryer (STD).

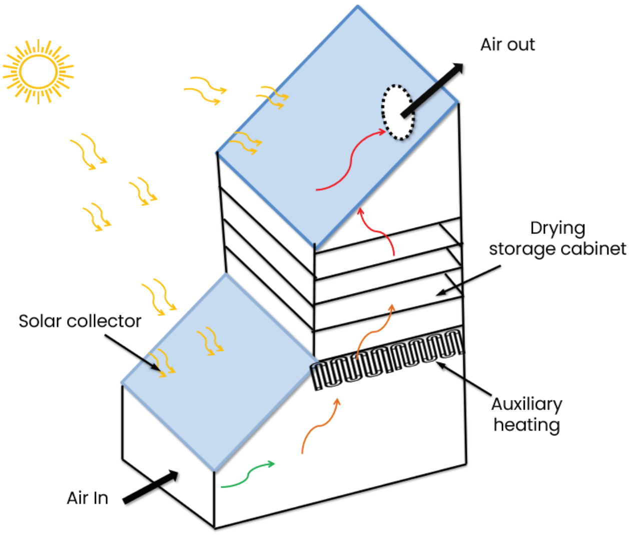

Figure 23. Schematic view of mixed mode passive solar dryer with a backup heater.

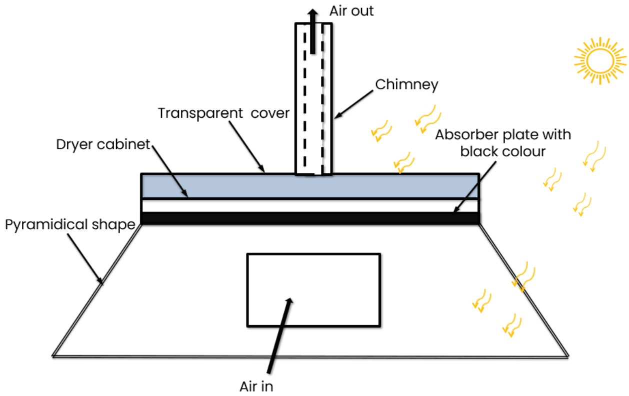

Figure 25. Schematic view of mixed mode passive pyramidical shape solar dryer.

1049% in 10 h, while the hybrid mode reduced the moisture content to 155% from 912% in 7 h.

Fudholi et al.[79] utilized an indirect active solar dryer assisted by the heater to desiccate red Malaysian chili with a total weight of 40 kg as depicted in Figure 24. The desiccating process removed moisture content of red chili to 10% (w.b.) from 80% (w.b.) within 33 h, resulting in a reduction in weight from 40 kg to 8 kg, while open sun drying took 65 h to achieve similar results. The drying time is reduced to 49 %in solar dryer compare to open sun drying. For flow rate of an air 0.07 kg/s and 420 W/m^2 solar radiation with 0.19 kg/kWh specific moisture extraction rate (SMER) the efficiency of drying system and collector was determined 13 % and 28% respectively. By studying various mathematical models, it was observed that the Page model well traced the experimental data. The trail readings showed that average drying chamber relative humidity, average drying chamber air temperature and average solar radiation during the 5-day (33 h) experiment varied from approximately 30% (ranged from 18% to 74%), 45°C (ranged from 28 to 55°C) and 420 W/m^2 (ranged from 104 to 820 W/m^2), respectively. The average collector efficiency determined 28 % (ranged from 11% to 74%), at a flow rate of air 0.07kg/s.

For processing horticultural crops, Ayua et al. [80] developed and tested a passive pyramidical shape solar dryer operates on mixed mode as shown in Figure 25 and direct mode solar dryer results compared with it. The working temperature range of solar dryer that operating on mixed mode was 72°C (high) and 40°C (low). The maximum ambient temperatures at different sections of the mixed-mode dryer from bottom to top were 42°C, 63°C and 67°C while maximum temperature attained 72°C. The drying time was recorded 270±6 min for spider plant, while the longest time noted 3867±31 min for African bird's eye chili in the dryer.

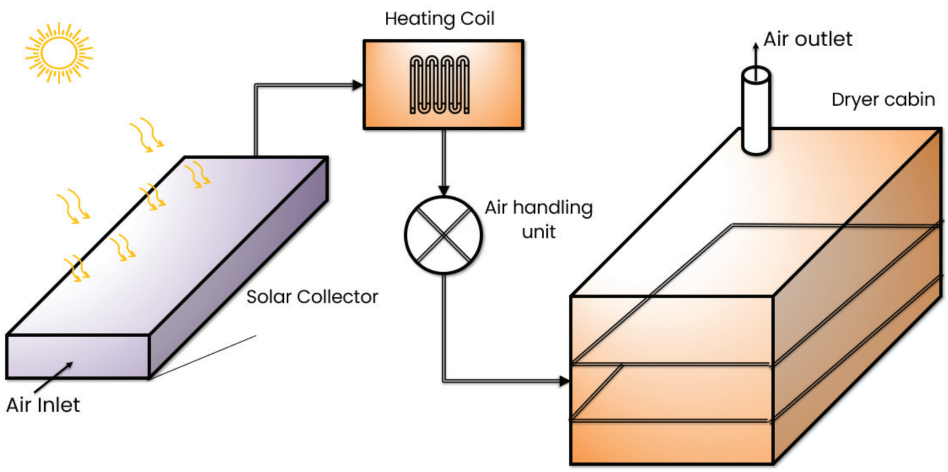

Figure 24. Schematic view of an indirect active solar dryer assisted by heater.

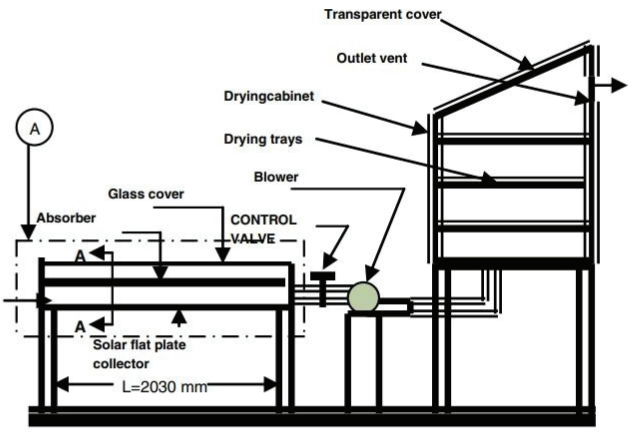

Figure 26. Schematic view of horizontally placed collector, active solar dryer operates on mixed mode [From Pardhi et al. [81], Open access].

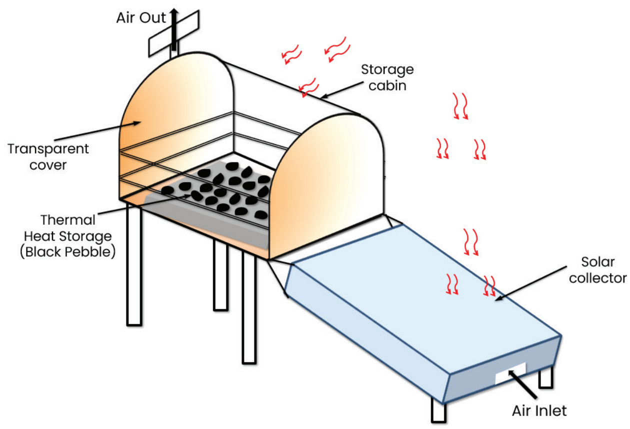

Figure 28. Solar thermal dryer operates on mixed mode energetic with black pebble-based storage material.

An active horizontally placed smooth and rough plate collector for solar dryer operates on mixed mode developed and fabricated by Pardhi et al. [81] as depicted in Figure 26. The grapes capacity of 3 kg took 4 days to reduce moisture to 18.6 % from 81.4% for collector aperture area of 1.03 m^2, while open sun drying took 8 days. The collector efficiency, drying rate and percentage of moisture removed (dry basis) for drying grapes were recorded as 67.5%, 0.38 kg/h and 85.4%, respectively. The grapes drying rate recorded for the solar dryer and open sun drying was 0.24 kg/day and 0.1 g/day, respectively.

In the trials on the conventional solar dryers (indirect type) were conducted and compare the obtained results to an indirect heat storage solar dryer (ITSD-TSS) for tomato drying as illustrated in Figure 27. The Cetina-Quinones et al. [82] developed a twin digital model that able to predicts temperatures of a solar dryer with a storage system, enabling the indicators quantification for exergetic sustainability and conduct a global sensitivity analysis (GSA). The results showed that the solar dryer operates on indirect mode and heat energy storing material as sand on the sea beach yields good outcomes. Moreover, the GSA analysis reveals that ambient temperature and relative humidity of air are the most influential variables on outlet temperatures with 0.6096 and 0.8911 first-order and total-order Sobol's indices achieving maximum values, respectively.

The present study by Andharia et al. [83] utilized solar thermal dryer energetic with black pebble-based heat storage material operated on mixed mode as depicted in the Figure 28 to investigate the performance for desiccating marine products, specifically shrimps. The thermal storage material showed economic feasibility, availability, and easy handling, also it demonstrates that the heat storing material continues to release heat up to 7 h after sunset. During trial overall system thermal efficiency was recorded 25.47%. The study showed that the solar dryer with black pebble-based heat storage technology reduced the moisture from the shrimps to 5.8% (w.b.) from 80.64% (w.b.) in 24 h with an average air temperature of 60.57°C. In contrast, the drying

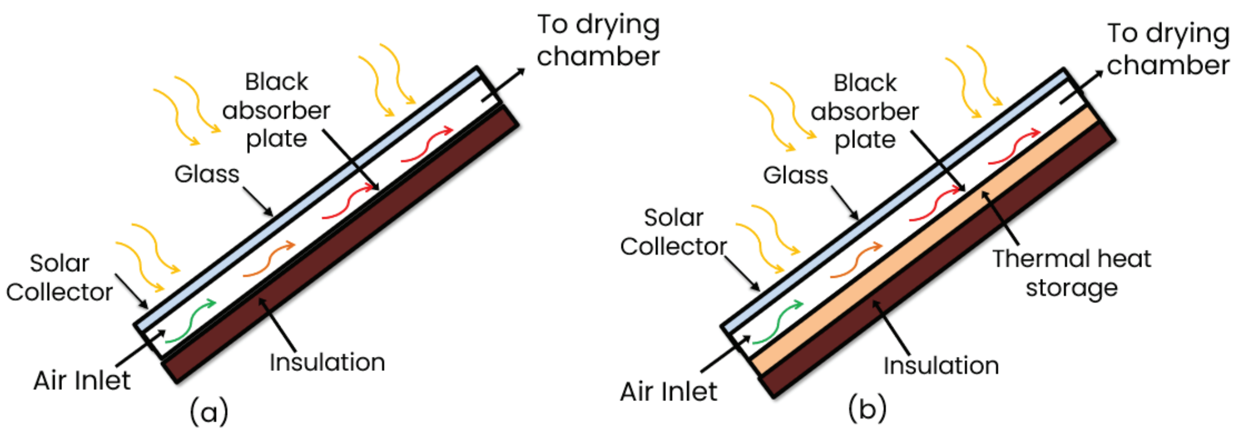

Figure 27. (a) Conventional indirect cabinet solar dryer and (b) an indirect heat storage solar dryer (ITSD-TSS).

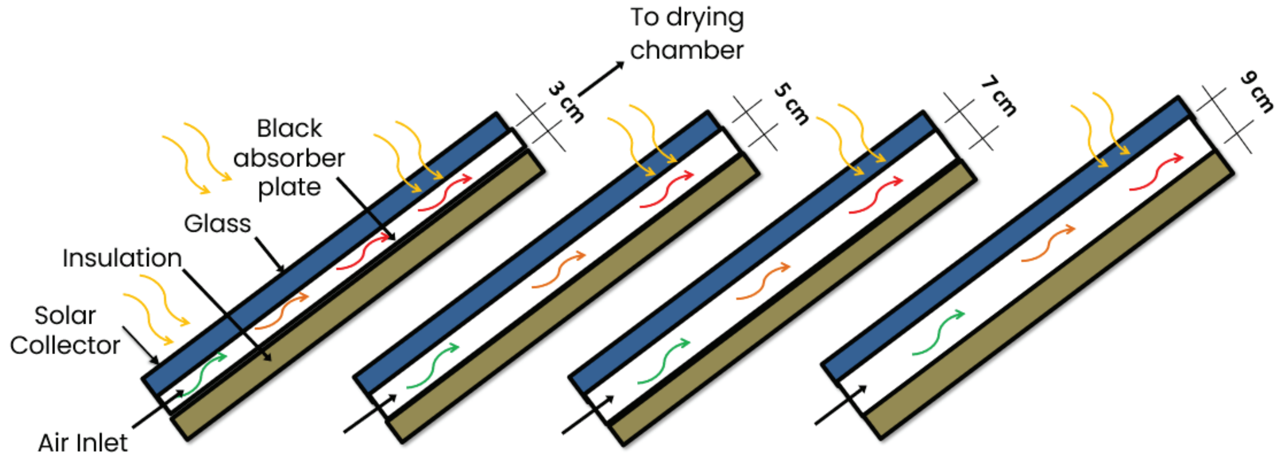

Figure 29. Schematic diagram for cabinet type collector with different air gap.

process without SHS took 28 h with an average drying air temperature of 62.02°C. Moreover, open sun drying took 32 h to achieve the same moisture condition. By summarizing, the solar thermal dryer energetic with black pebble-based heat storage demonstrated significant improvement in drying efficiency and reduced drying time for shrimps, as compared to conventional drying methods.

Dheyab et al. [84] conducted trial on solar air cabinet type collector to determine the optimal air gap height. The study involved four identical solar collector heaters, each with different air gap between glass and absorber plate was 3, 5, 7, and 9 cm as depicted in Figure 29. It was observed that air gap height of 3cm recorded the highest air temperature of 56 °C, attributed to the low volume of air flow in the collector and the temperature of the glass was high, when compared to the other air gap heights. The air gap height of 9 cm exhibited the highest mass flow rate, i.e., 9.0 g/s at 13:00, creating an increase in the heat gained by the air flow and eventually a high efficiency attained by solar air heater 57.3%, compared to other air gap heights studied. Beyond 5cm air gap it was noted the air mass flowrate increased significantly however increase in mass flowrate not able to contribute to increase the efficiency significantly. Moreover, the results highlighted the heat transfer through convection was higher for wider air gap heights.

Various modes have been utilized by authors for the desiccating of agricultural produce. The air reaches towards saturation level while absorbing moisture from the food products in passive solar dryers, and as a result, it takes more time for desiccation compared to active solar dryers. Moreover, the drying rate reduces after the initial period since the moisture content present in the core is not easily removed from the food products, making forced air circulation redundant. Therefore, future research should be emphasis towards exploring the potential of various shape which has ability to receive maximum radiation, concentrate the radiation by using lenses incorporating in glass of solar collector and intermittent air circulation during this stage to improve the performance of solar dryer.

Agricultural Products

Solar drying processes not only preserve the agricultural produce but also inhibit the growth of bacteria. Various agricultural produce such as vegetables, fruits, spices, grains, and meat have been dried using solar drying methods [85]. The types of food product, including their drying time, the setup employed for drying, and the resulting performance, have been studied in detail and presented in Table 1.

Grapes

The Maharashtra state, India, is recognized as a prominent producer of grapes nationwide. The production of raisins by utilizing solar dryer is a widespread agricultural practice, which enables the retention of the fruit's high nutritional content. The initial moisture content of most grape varieties typically ranges from 74% to 85% w.b. while final moisture content should be reduced to 13% to 18% w.b. in order to dry them into raisins. The comparative analysis of the experimental setup, grape varieties and drying durations in open sun drying and solar drying, with and without pre-treatment, has been presented in Table 2-5. The findings of the study indicate that open sun drying of grapes requires a longer duration (treated grapes took 7-17 days and untreated grapes took 20-31 days) to achieve desiccation compared to solar drying (treated grapes took 3-12 days and untreated grapes 7-12 days) in 30-70 °C temperature span. In the majority of experimental setups, the air flow velocity was maintained from 0.4 m/s to 1.5 m/s with a flow rate of air was maintained 1.5 m^3/min to 30 m^3/min. However relative humidity is also deciding factor for drying rate. Furthermore, pre-treatment of the grapes was attributed to a major reduction in the drying time. However, the utilization of chemical pre- treatment techniques negatively impacts the grapes' nutritional value.

Table 1. Food products and their drying duration

Sr. No.	Author Name	Food Product	Set Up Used	Drying duration	Remark
Vegetable					
1	S. Nabnean [86]	Dehydrated cherry tomatoes	water type collector indirect solar dryer	4 days	Dehydration of cherry tomatoes using osmotic treatment. The samples were reduced to a final value of 15% (w.b.) from an initial value of 62% (w.b.) within a span of four days, while sun-dried samples reduced to 40% (w.b.) during the same duration. The solar collector efficiency ranged from 21% to 69%.
2	Djebli et al. [87]	Potatoes	Forced convection indirect (ISD) and mixed (MSD) solar dryer	4h 45min (ISD) 3h 40min (MSD)	The first dryer has 4 kg loading capacity of and can achieve a maximum temperature of 69°C (ISD), while the second dryer has a 130 kg loading capacity and can achieve a higher maximum temperature of 77°C (MSD).
3	Reyes et al. [88]	Mushrooms	Hybrid-solar dryer.	9 hr	The samples with 8 mm slices were able to reduce their moisture content to 0.05 (w.b.) within 9 h of drying, whereas the samples with 12 mm slices required more than 20 hours to achieve the same moisture content level.
4	Folayan et al. [89]	onion	cabinet dryer	-	The drying processes evaluated at temperatures 65°C, 75°C, 85°C, and 95°C for onion thicknesses 0.50cm, 1.00cm, and 1.50cm at various time periods.
5	Deshmukh et al. [90]	Ginger	Cabinet collector mixed mode solar dryer	8 hr	Ginger slices dried to 12.19% (d.b.) from 621.50 (d.b.).
Fruits					
6	Lingayat et al. [91]	Apple	Indirect type solar dryer (ITSD- Passive)	10h	The collector and dryer average thermal efficiency was recorded 54.5% and 25.39%, respectively. The moisture content in the apples was reduced to 0.799 kg/kg (d.b.) from 6.16 kg/kg (d.b.) after drying.
7	Lingayat et al. [91]	Watermelon	Indirect type solar dryer (ITSD- Passive)	10h	The collector and dryer average thermal efficiency was recorded 56.3 % and 28.76 %, respectively. The moisture content in the watermelon was reduced to 0.496 kg/kg dry mass of (d.b.) from 10.76 kg/kg dry mass (d.b.).
8	Akoy et al. [92]	Mango	natural convection cabinet solar dryer	20 h	Using collector area 1.03 m^2 the initial moisture content reduced to 10% from 81.4% wet basis.
9	Amer et al. [93]	Banana	A solar dryer (hybrid mode)	8 h	The dryer had a capacity to dry banana slices approximately 30 kg on a sunny day reducing the final moisture content to 18% from initial 82%(w.b.). In contrast, open sun drying reduced the moisture content to 62% (w.b.) in same duration.

Table 1. Food products and their drying duration (continued)

Sr. No.	Author Name	Food Product	Set Up Used	Drying duration	Remark
Spices					
10	Rabha et al. [94]	Ghost chilli pepper	A forced convection solar tunnel dryer with latent heat storage module	36 h	The drying air temperature range was 42-61 °C, the moisture content of the chilli sample was reduced to 3% (w.b.) from an initial moisture content of 85.5% (w.b.) within 36 h. The average overall thermal efficiency of the air heaters varied between 22.95% and 23.30%.
11	ELkhadraoui et al. [95]	red pepper	mixed mode solar greenhouse dryer with forced convection	17 h	The red pepper dried with an initial moisture content of 12.15 g water/g dry matter, achieved a final moisture content of 0.17 g water/g dry matter within 17 h in greenhouse solar dryer. In comparison, open- sun drying took 24 h to achieve a final moisture content of 0.19 g water/g dry matter.
12	Azaizia et al. [96]	red pepper	solar greenhouse mixed mode dryer with and without thermal storage material	30h	By incorporation of phase change material (PCM) significant reduction in moisture content 95% time period of 30 h. In comparison, the same level of reduction took 55 h and 75 h in the dryer without PCM and in open sun drying, respectively.
Grains					
13	da Silva et al. [97]	Corn grains	Solar cabinet hybrid dryer with forced circulation	8.5 h	Drying process of corn grains resulted in a reduction of moisture from 23% to 13% in a time period of 8.5 h. The average drying efficiency and thermal efficiency and were found to be 6% and 27%, respectively.
Meat					
14	Chaouch et al. [98]	Meat	An indirect and direct passive solar dryer with pebble sensible heat storage material	31 h	The camel meat dried from initial moisture content (on dry basis) 4 kg/ kg dry matter, was reduced to 0.3 kg/ kg dry matter in 31 h in July and 54 h in November.

Table 2. Open sun drying method used to dry untreated grapes

Sr. No.	Experim Experimental Setup and place	Grapes variety and control Parameter	Pre- treatment	Drying duration	References
1	Open solar dryer (OSD), Gebze Kocaeli, Turkey	Grapes dried on plastic sheet on concrete, Initial and final moisture:76% and 13 %w.b., Air temperature: 22.6– 24.2°C, solar intensity: 22.2–23.7 MJ/m^2	Not applicable	480 h (20 days)	Mahmutoglu et al. [99]
2	Open solar dryer (OSD), Aghia Paraskevi, Greece	Sultana grapes dried on plastic Sheets on ground, Initial and final moisture:78% and 15 % w.b., Temperature range: 23–35°C, Air relative humidity: 72%	Not applicable	740 h (31 days)	Karathanos and Belessiotis [100]

Table 3. Open sun drying method used to dry treated grapes (chemically treated)

Sr. No.	Experimental setup and place	Grapes variety and control parameter	Pre- treatment	Drying duration	References
1	Open solar dryer (OSD), Garbenstrasse, Germany	Sultana grapes spread on plastic, Initial moisture 74-78 %w.b., Day temperature: 25–35 °C, Relative humidity: 15–80%, Final moisture: 16% w.b.	Immersed for 3 min. in 2.5% sultafino oil 2% K2CO3 and emulgator	Around 7 days	Lutz et al. [101]
2	Open solar dryer (OSD), Kocaeli-Turkey	Sultana grapes spread on paved grounds, Ambient temperature: 5–32°C, Wind velocity: less than 5.4 m/s, Total solar radiation: >630 W/m^2 , Final moisture content: 17% w.b.	Dipped in a solution of 5% K2CO3 and 0.5% Olive oil	12 days	Tiris et al. ([102]
3	Open solar dryer (OSD), Aghia Paraskevi, Greece	Sultana grapes spread on plastic sheet, Initial moisture: 78% w.b., Temperature range: 23–35 °C Air humidity: 72%, Final moisture: 15% w.b.	Immersed for 2 min. in solution of 2% KHCO3 and 0.2% Olive oil	179 h (7 and 1/2 days)	Karathanos and Belessiotis [100]
4	Open solar dryer (OSD), Indore, India	Thompson seedless spread on plastic net, Initial moisture: 349.59%, d.b. Temperature range: 25.9–40 °C, Solar irradiance: 605–673 w/m^2	Dipped for 3 min into a solution of 2.5% K2CO3 and 2% dipping oil	7 days	Pangavhane et al. [58]
5	Open solar dryer (OSD), Elazıg, Turkey	Grapes spread over wire mesh, Average diameter of grape: 0.024 m, Initial moisture: 4.05 d.b., Ambient temperature: 31-43°C, Solar irradiance: 1.10–2.93, MJ/m2 h Final moisture content: 15 - 17% w.b.	Immersed for 2 min in emulsion of 5% K2CO3 and 0.5% Olive oil	7000 min (117 h)	Turk Togrul and Pehlivan [103]
6	Open solar dryer (OSD), Hammam-lifs, Tunisia	Sultana grapes spread over a grid support, Temperature range: 20-45°C, Final moisture content: 16% w.b.	Immersed 2–3 Times for 2–3 sec in 1% NaOH solution at 90 °C	250 h (10 days)	Fadhel et al. [104]

Table 4. Various solar dryer methods used to dry untreated grapes

Sr. No.	Experimental setup and place	Grapes variety and control parameter	Pre- treatment	Drying duration	References
1	Tunnel dryer (Intermittent fan operation), Northern Victoria, Australia	Grapes loaded: 40 kg/m^2, Initial moisture content: 76% w.b., Dry bulb temperature in dryer: 10– 60°C, Final moisture content: 13% w.b.	Not applicable	12 days	Fuller and Charters [105]
2	Indirect natural convection solar dryer, Tanta, Egypt	Grapes loaded: 1kg, Ambient temperature: 27–31 °C, Inlet drying air temperature: 45.5–55.5 °C, Max. solar irradiance: 988 W/m^2, Final moisture content: 18% w.b.	Not applicable	72 h	El-Sebaii et al. [106]
3	Indirect natural convection solar dryer with storage, Tanta, Egypt	Grapes loaded: 1 kg, Storage material: sand, Ambient temperature:27–31°C, Inlet drying air temperature: 45.5– 55.5°C, Max. solar radiation: 988 W/m^2, Final moisture content: 18% w.b.	Not applicable	60 h	El-Sebaii et al.[106]
4	Natural convection walk- in type solar tunnel dryer, Udaipur, India	seedless grapes (mutant: Sonaka, Cv. Thompson seedless, Udaipur, India), Capacity: 320 kg grape. Drying area: 37.5 m^2, Initial moisture content: 85% w.b. Solar dryer temperature: between 55 °C and 70 °C, Final moisture content: 16% w.b.	Not applicable	7 days	Rathore and Panwar[107]

Table 5. Various solar dryer methods used to dry treated grapes (chemically treated)

Sr. No.	Experimental setup and Place	Grapes variety and control parameter	Pre- treatment	Drying duration	References
1	Tunnel dryer, Garbenstrasse, Germany	Sultana grapes, Initial moisture: 74–78% w.b., Temperature: 25–35 °C, Relative humidity: 15–80%, Average solar irradiance: 6 kW h/ m^2 day, Air flow rate: 1200 m^3/h, 600 m^3/h, Final moisture content: 18% w.b.	Immersed for 3 min in 2.5% sultafino oil, 2% K2CO3 and emulgator	Around 5 days	Lutz et al. [101]
2	Forced convection solar dryer, Kocaeli-Turkey	Sultana grapes, Ambient temperature: 10–32 °C, Air inlet temperature:30–60 °C, Relative humidity: 40–87%, solar irradiance >630 W/m^2,	Dipped in a solution of 5% K2CO3 and 0.5% Olive oil	5 days	Tiris et al. [102]
3	Direct type passive solar dryer, Bethlem, West bank, Via Israel	Grapes Ambient temperature: 22–31 °C, Relative humidity: 25–48%, solar irradiance: 180–920 W/m^2, Air flow rate: 1.5 m^3/min., Final moisture content: 14% w.b.	Immersed for 1 h in a solution made from 7 g of Na2CO3/ l of water + 1 tsp. of Olive oil	3 days	Hallak et al. [108]
4	Active solar dryer, Antalya, Turkey	Sultana grapes Packing density: 16 kg/m^2 Initial moisture: 2.6–3.3 kg water/ kg dry matter, Drying air temperature: 32.4– 40.3 °C, Drying air humidity: 57.73– 75.11%, solar irradiance: 790.3–802 W/m^2, Air velocities: 1.5, 1, 0.5 m/s, Final moisture content: 0.16 kg water/kg dry matter	Dipped in solution containing 6% K2CO3 and 0.5% Olive oil	82 h (1.5 m/s) 66 h (1 m/s) 58 h (0.5 m/s)	Yaldiz et al. [109]
5	Indirect natural convection solar dryer, Indore, India	Thompson seedless, Initial moisture: 349.59% d.b., Inlet temperature in dryer: 51.9–64.6°C, solar irradiance: 605–673 W/m^2, Final moisture content: 17% w.b.	Dipped for 3 min into a solution of 2.5% K2CO3 and 2% commercial dipping oil	4 days	Pangavhane et al. [58]
6	Indirect Passive solar dryer with storage, Tanta, Egypt	Grape quantity: 1 kg, Storage material: sand, Ambient temperature: 27–31 °C, Drying air temperature:45.5–55.5 °C, Max. solar irradiance: 988 W/m^2, Final moisture content: 18% w.b.	Dipped for 60 s in boiling water with 0.3% NaOH and 0.4% Olive oil	8 h	El-Sebaii et al. [106]
7	Forced convection solar dryer without obstacles, Valenciennes, France	Grapes, Solar radiation:520–960 W/m^2, Ambient temperature: 7–27 °C, Relative humidity: 40–90%, Air flow rate: 31.3 m3/hm^2	Not mentioned	13 h 20 min	Abene et al. [53]
8	Forced convection solar dryer with obstacle type – TL, Valenciennes, France	Grapes Solar radiation: 520–960 W/ m^2, Ambient temperature: 7–27 °C, Relative humidity: 40–90%, Air flow rate: 31.3 m^3/h-m^2	Not mentioned	5 h 50 min	Abene et al. [53]
9	Tunnel dryer, Tunisia	Sultana grapes Initial moisture: 5–6.2 w.b., Max. product temperature: 60 °C, Final moisture content: 16% w.b.	Immersed 2–3 times for 2–3 sec. in solution 1% NaOH heated to 90 °C.	119 h	Fadhel et al.[104]

Table 5. Various solar dryer methods used to dry treated grapes (chemically treated) (continued)

Sr. No.	Experimental setup and Place	Grapes variety and control parameter	Pre- treatment	Drying duration	References
10	Indirect natural convection solar dryer, Tunisia	Sultana grapes Initial moisture: 5–6.2 w.b., Temperature range: 20–45 °C, Final moisture content: 16% w.b.	Immersed 2–3 times for 2–3 sec. in alkali solution 1% NaOH heated to 90 °C	77 h	Fadhel et al. [104]
11	Forced convection solar dryer, Baghdad, Iraq	Grapes Initial moisture: 80%, Chamber temperature: 65 °C, Relative humidity in the chamber: 30%, Air flow rate: 0.4 m/s, Final moisture content: 8% w.b.	Not mentioned	2.5 days	Al-Juamily et al. [110]
12	Mixed mode solar dryer, North of Portugal	Red seedless grapes from the cultivar Monukka, (Tras-os-Montes, Portugal), capacity: 250 kg of grapes, Initial water content 83.0±1.6%	Grapes were blanched in hot water (~99 °C) and for approximately 15sec.	_	Ramos et al. [111]
13	Mixed mode solar greenhouse dryer with forced convection, Tunis, Tunisia	Sultana grape (Tunis, Tunisia), capacity: 130 kg of grape, Solar collector is 2 m^2, air temperature of solar dryer: between 28.08 °C and 55.94 °C, Final moisture content: 18% w.b.	The sample was soaked in alkali solution (1% of sodium hydroxide) heated to 90°C for 3 sec.	128 h	Hamdi et al. [39]

Heat Storing Material

The drying rate in solar dryers depend upon the solar energy irradiance, temperature of the air, and humidity levels. During cloudy periods and at night (means in the), the drying rate decreases significantly attributed to the absence or less amount of sunlight leads to lower atmospheric temperatures. To extract moisture from food products during nighttime hours, heat energy must be stored in a thermal storage material during the daytime for utilization at night [112]. Many authors have employed various heat storing materials, such as NaCl [26], sand beds [113], gravels [114], rock beds [115,116], liquid likes water [117]. However, the use of phase change material [118–121] as the thermal energy storage element is widely used by researchers and explored in detail in the following section. The incorporation of nanofluids to enhance the heat transfer and desiccants to reduce humidity from the air requires further research to improvement in the performance of the solar dryer.

Madhankumar et al. [122] compare the experimental results of three different dryer modifications in an indirect solar dryer setup, namely: without (setup1) and with (setup 2) phase change material and fins inserted to phase change material (setup 3), as illustrated in the accompanying Figure 30. The drying behavior capacity of 2 kg of bitter gourd, was analyzed for flow rate of air 0.06 kg/s under three distinct environmental conditions that varied with solar irradiation. The drying time for bitter gourd in all modification in set up from 92% to 12% (wet basis) was determined 15 h, 11 h, and 11 h in setup1, setup2, and setup3, respectively, while open sun drying required 18h. The efficiencies of the ISD setups were found to be 17.3%, 18.9%, and 19.6% for setup1, setup2, and setup3, respectively.

Gilago and Chandramohan [123], proposed indirect solar dryers developed to investigate passive and active (PISD and AISD) mode drying kinetics of pineapple with a heat energy storage material using paraffin wax, as depicted in Figure 31. The paraffin wax incorporated in the experiment has a melting point temperature range of 56-60°C and possesses desirable attributes such as non-hazardous nature, physical solid state, colorless appearance, chemical stability, and recyclability. During the evening period of the experiment, the PISD and AISD were monitored, and their respective average temperatures (T_{av}), maximum temperatures (T_{max}), and minimum temperatures (T_{min}) were recorded. The PISD yielded measurements of 38.6°C, 42°C, and 35°C for T_{av}, T_{max}, and T_{min}, respectively, while the AISD yielded T_{av}, T_{max}, and T_{min} values of 34.6°C, 41°C, and 30°C, respectively. Furthermore, the dryer and collector efficiencies of the active dryer were observed to be 25.77% and 16.52% higher, respectively, compared to the passive dryer. The respective drying efficiencies of the PISD and AISD were found to be 9.7% and 11.9%. Additionally, pineapple took 16 h to dry in the passive dryer and 14 h in the active dryer, to decrease the moisture to 0.417 from 7.91 (d.b.), with average drying rates of 0.408 kg/h and 0.45 kg/h, respectively.

The present study by Kondareddy et al. [124] proposed a modified solar dryer that operates on active mode (MFCSD) with a capacity of 20 kg to dry elephant apple slices,

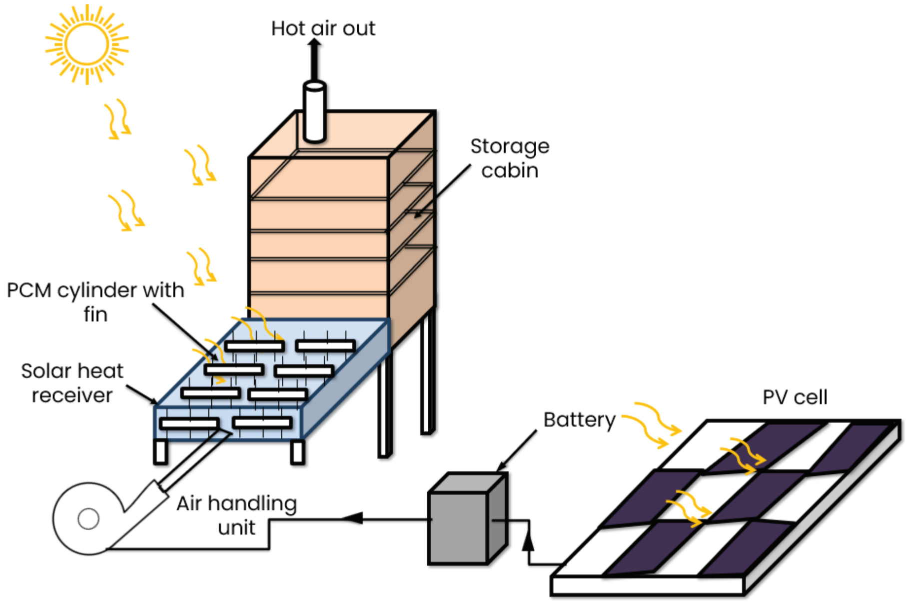

Figure 30. Schematic view of an active indirect solar dryer (ISD) with thermal energy storage material.

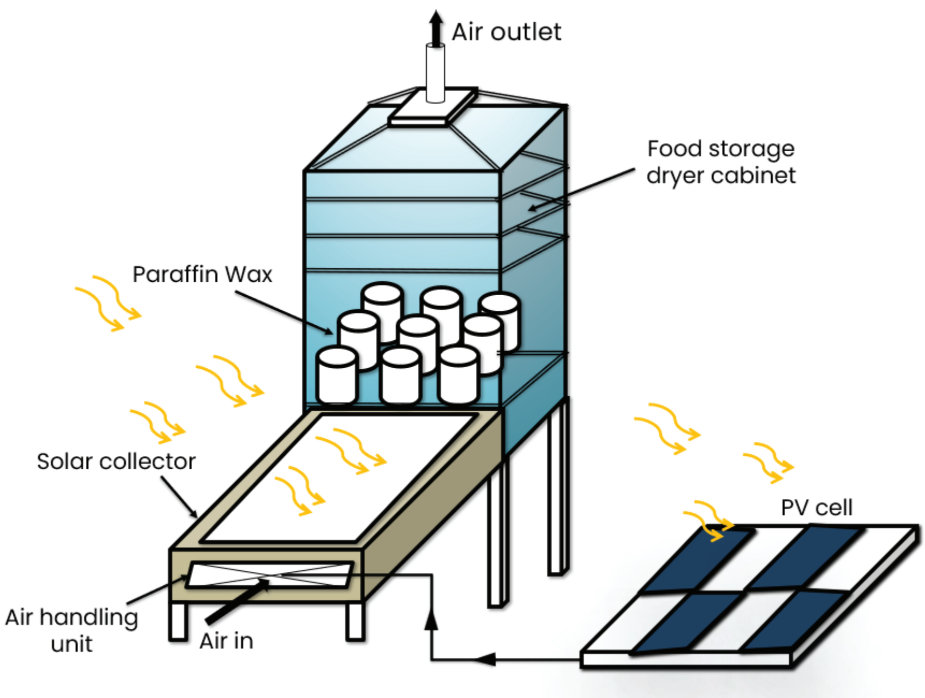

Figure 31. Indirect solar dryer experimental setup with energy storage using paraffin wax.

consisting of a drying chamber and two solar collectors. The dryer was equipped with paraffin wax PCM-OM-50 as a heat energy storing element, as depicted in Figure 32. Food product was tested on the quality analysis of various parameters such as protein content, fiber content, ash content, total soluble solids content, carbohydrate content estimation, fat content estimation, and color indices. The study demonstrated an increase in the air gap (10 to 20 mm) heat loss coefficients increases attributed to higher convection and lower reflection losses. The proposed design recorded a 12% increment in the thermal collector efficiency in comparison to a conventional glass collector under specific conditions of solar irradiance (965 W/m^2), the velocity of air (0.70 m/s), and atmospheric temperature (33°C). From the

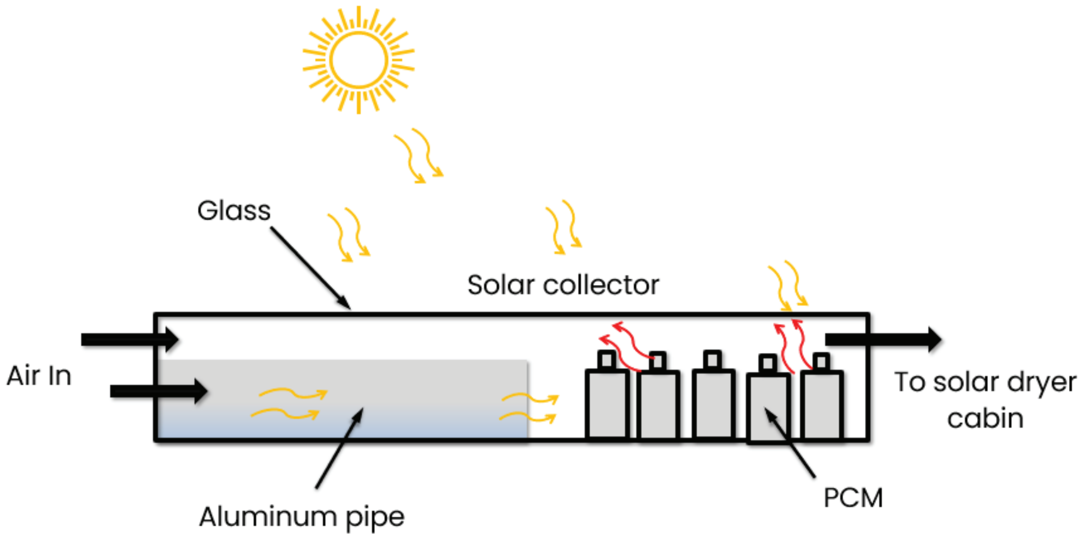

Figure 32. Modified solar dryer operates on active mode with PCM-OM-50.

experimental data, the inference that modified solar dryer operates on active mode with PCM-OM-50 as a heat storing element and two solar collectors proved to be an effective solution for drying elephant apple slices with improved thermal efficiency and maintained quality parameters. The findings of this study can be employed in other similar agricultural products.

In this research paper, M.I. Hussain designed and developed a multi-conical concentrating collector solar dryer system as shown in Figure 33, to investigate drying rate for carrot slices and green pumpkin of varying thickness (3, 6, and 9 mm). The dryer performance was analysed and compared for two different heat transfer fluids, namely water and copper oxide/water nanofluid. It was noted that the solar dryer with nanofluid maintained 12°C average temperature difference, in contrast water-maintained 8°C average temperature difference. The use of nanofluid as the heat transfer fluid in the multi-conical solar concentrating system resulted in enhanced performance. The exergy efficiencies (average) for drying pumpkin slices of 3, 6, and 9 mm were determined to be 34.9%, 33.8%, and 32.4%, respectively [125]. It is recommended that exploring nanofluid as heat transfer fluid needs more research in the future to improve the performance of the solar dryer.

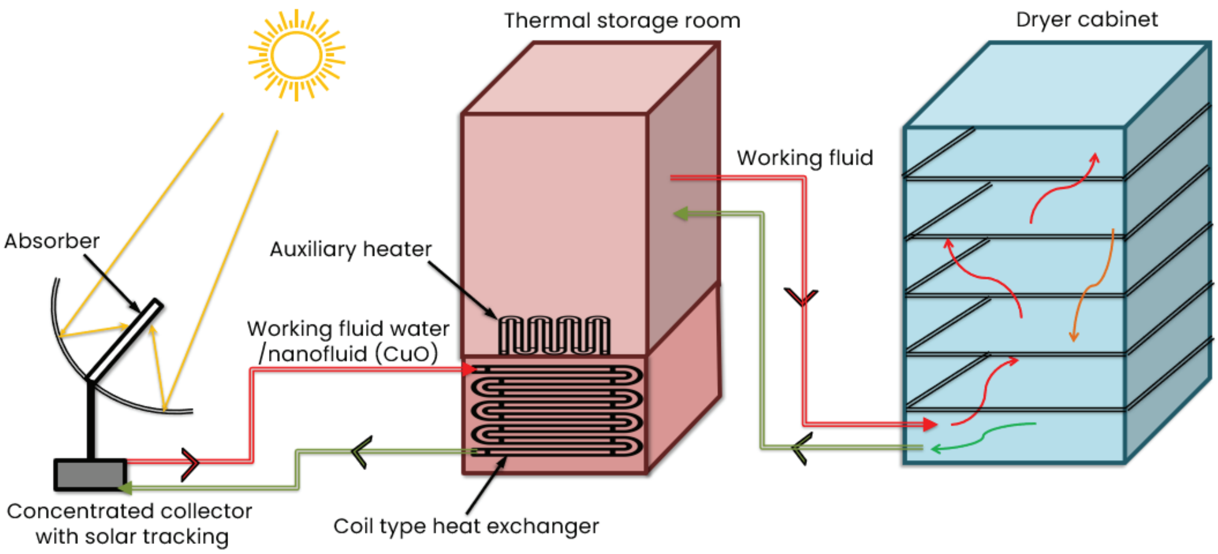

Figure 33. Multi-conical concentrating collector solar dryer system with thermal storage.

Mathematical Model

The drying kinetics behavior of food products is often studied using distributed models which are based on simultaneous heat and mass transfer. These mathematical models are effective in predicting temperature and moisture gradients, accounting for both external and internal heat and mass transfer. However, the analytical solving difficulties associated with these models have limited their use in literature. Lumped parameter models, which assume one single air temperature uniformly distributed in the dryer, however prone to errors when the atmospheric air temperature is considered the same as the product temperature. To address this issue, thin layer drying has evolved as a method to ensure uniform temperature distribution. Thin layer drying involves drying the product one layer or slices, leading to more accurate predictions of drying rate. The thin layer model equations, can be classified as 1. theoretical: based on the theory of heat and mass transfer, 2. semi-theoretical: based on the theory and the experimental results, and 3. empirical: purely based on the experimental results, as discussed in Table 6 are derived to forecast drying rate [126]. Researchers have used different thin layer drying mathematical models discussed in Table 7, to validate experimental results and predict the drying kinetics of food products.

FEA Analysis

The validation of experimental results for the solar dryer can be checked by incorporating the input design parameter and boundary conditions in finite element analysis software. This software can demonstrate the internal temperature counter and velocity flow pattern at various positions, which can aid in the development of the setup [66]. The researcher used ANSYS Fluent, COMSOL Multiphysics and GAMBIT software for simulation of the solar dryer condition. From Table 8 it is observed that tetrahedral, hexahedral and triangular elements were generally used for meshing due to more accuracy in results by the various researchers. The subsequent section gives a comprehensive discussion of the simulation of the solar dryer.

In this study, Mohd Nasir [147] incorporated Finite Element Analysis (FEA) to assess the simulation data analysis of a mobile solar dryer, specifically its temperature counter. The investigation was carried out under two distinct ambient parameters, inside and outside the laboratory environment at inlet, bottom drawer, middle drawer,

Table 6. Mathematical model

Sr. No.	Thin layer model	Model equation	References
	Semi-theoretical models (Newton's law of cooling)		
1	Lewis (Newton) model	$MR = \exp(-kt)$	Lewis [127]
2	Modified page-I models	$MR = \exp(-kt)^n$	Overhults et al. [128]
3	Modified page-II model	$MR = \exp - (kt)^n$	White et al. [129]
4	Page model	$MR = \exp(-kt^n)$	Diamante and Munro [130]
	Semi-theoretical models (Fick's second law of diffusion)		
5	Henderson and Pabis (single-term) model	$MR = a \exp(-kt)$	Henderson and Pabis [131]
6	Two-term model	$MR = a \exp(-k1\ t) + b \exp(-k2\ t)$	Henderson [132]
7	Two-term exponential model	$MR = a \exp(-k\ t) + (1- a) \exp(-kb\ t)$	Sharaf-Eldeen et al. [133]
8	Modified two-term exponential models (Verma model)	$MR = a \exp(-k\ t) + (1- a) \exp(-g\ t)$	Verma et al. [134]
9	Logarithmic (asymptotic) model	$MR = a \exp(-kt) + c$	Chandra and Singh [135]
10	Modified Henderson and Pabis (three term exponential) model	$MR = a \exp(-k\ t) + b \exp(-g\ t) + c \exp(-ht)$	Karathanos [136]
11	Midilli model	$MR = a \exp(-kt) + b^* t$	Midilli et al. [137]
12	Modified Midilli model	$MR = \exp(-kt) + b^* t$	Ghazanfari et al. [138]
13	Demir et al. model	$MR = a \exp[(-kt)]^n + b$	Demir et al. [139]
	Empirical models		
14	Thompson model	$t = a \ln(MR) + b[\ln(MR)]^2$	Thompson et al. [140]
15	Wang and Singh model	$MR = 1 + b^*t + a^*t^2$	Wang and Singh [141]
16	Kaleemullah model	$MR = \exp(-c^*T) + b^*t^{(pT+n)}$	Kaleemullah and Kailappan [142]
17	Hii model	$MR = a \exp(-kt^n) + b \exp(-gt^n)$	Hii et al. [143]

Table 7. Review of thin layer model used to various agricultural produce

Sr. No.	Author Name	Food Product	Number of models used	Best Fitted Model	Set Up Used	Remark
1	Alara et al. [144]	Vernonia amygdalina leaves	11	Midilli- Kucuk drying model	universal oven	Vernonia amygdalina leaves were dried at 40, 50 and 60°C air temperatures. During the drying processes, the flow rate air was held at 1 m/s.
2	Nukulwar et al. [23]	Turmeric	7	Page model	Scheffler dish collector steam-based dryer	Drying air temperatures and velocity were observed in the range of 55 °C– 68 °C and 0.7 m/s–1.4 m/s, respectively, in the drying experiments.
3	Dejchanchaiwong et al. [145]	Natural rubber	10	Hii model	Indirect and mixed-mode solar drying systems	In indirect solar and mixed-mode solar dryer reduces the moisture contents of rubber sheets from 32.3 to 2.0% and 29.4 to 8.0% on a wet basis, respectively, in 4 days.
4	Yaldiz et al. [109]	Sultana grapes (Thompson seedless)	8	A two-term drying model	An indirect active solar dryer	This final model describes the drying behaviour of Sultana grapes with the drying air temperature range from 32.4 to 40.3°C and velocities of 0.5, 1 and 1.5m/s. Drying rate was higher at drying air velocity of 1.0 m/s for the first 34 h, then the drying rate at drying air velocity of 1.5 m/s was superior to the others.
5	Lingayat et al. [91]	Apple	6	Page model	Indirect type solar dryer (ITSD-Passive)	The thermal efficiency of the collector and dryer was 54.5 % and 25.39 % during apple drying & Moisture content of apple decreased from 6.16 to 0.799 kg/kg of dry basis (db)
6	Lingayat et al. [91]	Watermelon	6	Midilli et al. model	Indirect type solar dryer (ITSD-Passive)	The thermal efficiency of the collector and dryer was 56.3 % and 28.76 % for watermelon drying, & Moisture content of watermelon reduced from 10.76 to 0.496 kg/kg of db
7	Deshmukh et al. [90]	Ginger	5	Page model	Mixed mode solar cabinet dryer	Ginger slices were successfully dried from initial moisture content of 621.50 to 12.19% (d.b.) within 8 h.
8	Wang et al. [68]	Mango	7	Page's model	Indirect active solar dryer (evacuated tube solar air collector)	Average thermal efficiency of IFCSD was ranged from 30.9% to 33.8%. Initially Moisture content in mango of 3.42 (kg water/kg dry matter) (d. b), reduce to 0.25 (kg water/kg dry matter) (d. b).

Table 7. Review of thin layer model used to various agricultural produce (continued)

Sr. No.	Author Name	Food Product	Number of models used	Best Fitted Model	Set Up Used	Remark
9	Kokate et al. [146]	Garlic	6	Logarithmic mathematical model	Indirect Solar Dryer	Moisture content of garlic was reduced from 70 to 56% in 24 h in solar dryer in case of nitrate salt with silica gel.
10	Kokate et al. [146]	Onion	6	Two-term mathematical model	Indirect Solar Dryer	Moisture content of the onion was reduced from 86% to 15% in 24 h in solar dryer in case of nitrate salt with silica gel method.

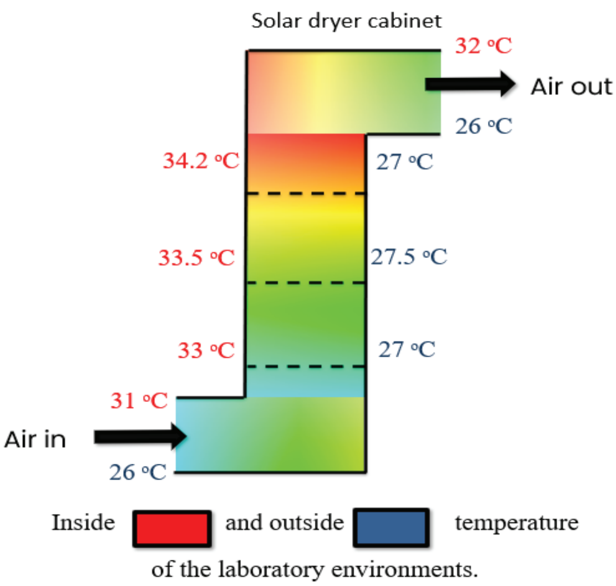

Figure 34. Temperature contour at various position in the dryer.

top drawer, and outlet of the solar dryer (five position), as depicted in Figure 34. The inlet ambient pressure was set at 101.325 kPa and outlet velocity 4.62 m/s in the FEA for drying of shrimp paste. A tetrahedral mesh element was chosen as an element, resulting in the creation of a total of 3,72,147 elements. No-slip boundary conditions were imposed on the surface walls of the solar dryer, and an assumption was made that zero-quantity radiation was received for the inside of the laboratory case. The top position of the drawer showed the highest temperature 34.2 °C in the mobile solar dryer, which was validated by FEA.

The performance evaluation of a cabinet dryer incorporating phase change materials (PCMs) was investigated by Mirzaee et al. [148] in their research paper. The dryer was utilized for drying 5 mm-thick slices of tomatoes, with three different fan air velocities (1, 1.5, and 2 m/s) applied, along with PCM placed at different position e.g. bottom, middle, and upper trays, as illustrated in Figure 35. The findings revealed that placing the PCMs on the lower tray of the cabinet dryer resulted in shorter drying

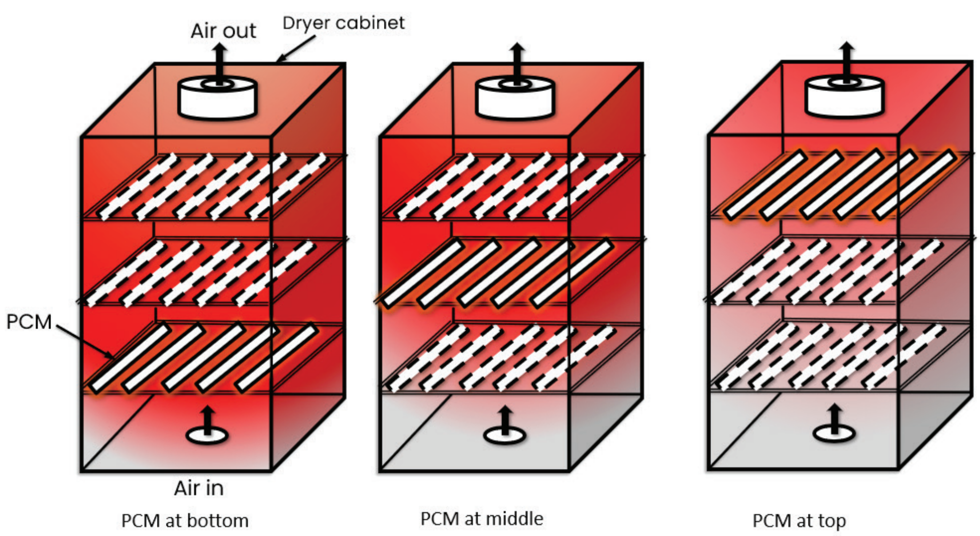

Figure 35. Solar dryer with PCM place at different position.

Table 8. Summary of FEA analysis

Sr. No.	Experimental Set up and Food product dried	Modeling software used	Element (Number of elements used)	Remark	References
1	Direct passive mode solar dryer (Direct multi-shelf solar dryer), No load	ANSYS Fluent (14.0 software)	Tetrahedral/mixed (288463)	Solar flux contour and heat flux counter in the dryer depicted by the simulation. Simulation showed the temperature distribution profile inside the solar dryer and noticed the maximum temperature attainted up to 60°C.	Jain et al. [149]
2	Direct passive mode solar dryer (Solar conduction dryer), No load	Academic ANSYS Fluent (16.0 software)	Hexahedral mesh.	The laminar velocity profile demonstrated by the software.	Chavan et al. [150]
3	Passive mixed mode solar dryer, Potato (13 mm dia. and 50 mm length)	COMSOL Multiphysics (5.3. software)	Tetrahedral and triangular (230690/17324)	The temperature distribution profile depicted the solar dryer temperature increases from 299K to 315K. Also, software simulates the moisture distribution profile.	Dhalsamant [151]
4	Direct passive thermal storage solar dryer, No load	ANSYS Fluent	_	Software simulation results depicted temperature distribution profile in the dryer where air temperature increased by 4°C.	Sandali et al. [152]
5	Direct active dryer, Fish	ANSYS Fluent	_	Temperature distribution profile studied at 0, 1.5,2.5,3.5 m/s velocity in the simulation.	Alonge and Obayopo [153]
6	Greenhouse solar dryer, Olive mill waste water drying (OMWW	Commercial software COMSOL Multiphysics	Triangular mesh (26527)	The temperature profile, velocity distribution profile and vapor mass fraction distributions studied in the simulation. The average OMWW and at interface of air-OMWW recorded 320.5K and 323.7K, respectively.	Bouraoui and Ben Nejma [154]
7	Indirect solar dryer with evacuated tube solar collector and PCM, Apple slices	ANSYS Fluent (14.0 software)	Hexa (fluid) and tetra (solid) (Tube: 114584, PCM: 492754, Fluid: 1548796)	The temperature distribution profile velocity distribution Profile studied by using simulation. At 0.025 kg/s mass flowrate inlet and cabinet wall temperature during charging (02:00PM) 69.2 °C and 48.2 °C while during discharging (08:00PM) 42.3°C and 22.1 °C determined by software	Iranmanesh et al. [155]
8	Greenhouse solar dryer, No load	GAMBIT software	hexa-pave and hexahedral mesh (477050)	Temperature distribution profile studied by using the simulation for different polycarbonate thickness 100 micro meter and 200 micro meters.	Purusothaman and Valarmathi Valarmathi [156]
9	Indirect active solar dryer, Tomato slice	ANSYS Fluent	Unstructured mesh (1500000)	Temperature distribution profile, 3D and 2D streamline flow and turbulent viscosity profile studied by using the simulation and maximum 2.1% error determined between experimental and the simulated results.	Moghimi et al. [157]
10	Indirect solar dryer (One / two solar air heater), Fig	ANSYS Fluent	79701 (one solar air heater) 48136 (two solar air heater)	Simulation for temperature distribution profile and velocity distribution profile in the software depicted that maximum mass flow rate and efficiency recorded 0.00417kg/s, 96.1% and 0.01008 kg/s, 97.36% in one and two solar air heater respectively. The highest temperature 59 °C recorded between 1:00pm to 3:00pm	Salhi et al. [158]

times compared to other tray positions. The overall thermal efficiency of the cabinet dryer ranged from 35.23% to 38.92%. Computational fluid dynamics (CFD) simulations were conducted to validate the experimental data. The software input parameters included the PCM wall temperature, fluid flow rate, and inlet fluid temperature. Three different types of meshing, namely very fine (2,200,000 elements), fine (1,000,000 elements), and coarse (480,000 elements), were considered, and the problems were solved and analyzed using the software, taking approximately 3 hours and 45 minutes, 70 minutes, and 20 minutes respectively. The experimental results were validated using the fine element meshing simulation. Furthermore, a Life Cycle Impact Assessment (LCIA) was carried out, focusing on four main categories: human health, ecosystem quality, climate change, and resource impact. The results demonstrated significant differences in emissions effects between the electric thermal dryer and the solar dryer for all four indicators.

CONCLUSION

The present work recapitulates the literature that provides a comprehensive review of multiple geometries and different modes of solar dryers and their corresponding performance parameters. Also, different types of solar dryers used for desiccating various agricultural produce such as vegetables, grains, fruits, spices and meat are presented in detail.

The literature highlights are,

- The efficiency of the cabinet, solar collector and overall solar dryer system ranges 10% - 30%, 11% - 74%, and 13% - 40%, respectively, with the most attained efficiencies during experimentation found approximately 25%, 55%, and 25%, respectively.
- The findings of the experiment showed that the temperature inside the solar drying chamber varied between 28°C and 86°C when drying different agricultural products. The most efficient drying occurred when the air temperature was between 50°C and 65°C.
- In solar dryers, the speed of the air varied between 0.5 m/s and 2 m/s, while the rate of air flow varied between 0.003 kg/s and 0.09 kg/s to achieve an optimal drying rate. Enhanced moisture removal rates were observed for 0.06 kg/s and 0.07 kg/s air flow rates.
- As compared to solar drying, an open sun drying of grapes requires a longer duration to achieve grape desiccation. In the solar dryer treated grapes took 3-12 days while untreated grapes took 7-12 days to dry for the temperature range of 30°C to 70 °C. While open sun drying required 7 -17 days for treated grapes and 20-31 days for untreated grapes. Moreover, when drying grapes, the majority of experimental setups maintained an air velocity between 0.4 m/s and 1.5 m/s, along with a flow rate ranging from 1.5 m^3/min to 30 m^3/min.
- Furthermore, the research has investigated the mathematical models employed in forecasting the drying rate of solar dryers, emphasizing the utilization of FEA (Finite Element Analysis) software to simulate the situation present in the solar dryer's collector and storage cabinet to validate the experimental findings.

Based on the insights gathered from this literature review, it is envisaged that there is enough scope to explore new geometries, intermittent and effective air circulation throughout the drying chamber, lenses incorporating in glass of solar collector to concentrate the energy, desiccants to reduce air humidity, and innovative techniques for solar dryers.

NOMENCLATURE

w.b.	Wet bulb
d.b.	Dry bulb
h	Time in hours
min	Time in minutes

AUTHORSHIP CONTRIBUTIONS

Authors equally contributed to this work.

DATA AVAILABILITY STATEMENT

The authors confirm that the data that supports the findings of this study are available within the article. Raw data that support the finding of this study are available from the corresponding author, upon reasonable request.

CONFLICT OF INTEREST

The authors declared that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

ETHICS

There are no ethical issues with the publication of this manuscript.

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