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REVIEW ARTICLE

Eco-friendly drying techniques: a comparison of solar, biomass, and hybrid dryers

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Abstract

Solar energy provides desired thermal energy for diverse applications, including industrial heating, domestic cooking, power generation, desalination, and agri-food preservation. Despite extensive research on solar drying from the scientific community, there are limited practical applications for small-scale use. This review attempts to analyze the design features of three specific types of dryers for food drying applications: solar evacuated tube dryers, biomass dryers, and hybrid solar dryers. The thermal performance of the three dryers is evaluated in terms of drying time, moisture removal, and temperature attained during drying. The review also assesses the prospects of solar dryers, highlighting the need for further research into innovative designs and advanced drying capabilities. The study provides valuable information for enhancing dryer performance with various integrated solutions.

Keywords Solar dryer · Biomass dryer · Hybrid dryer · Evacuated heat pipe · Agro-products · PCM

Introduction

Industrialization and rising population in developing nations cause economic instability due to the depletion of fossil fuels, increased energy consumption, and deterioration of the environment. The pressing issue is that production reserves (fuel and food) are insufficient to fulfill demand at the current utilization rates. According to IEA 2019 report, the world's energy consumption is anticipated to rise by 1.3% annually through 2040. Pursuing clean, renewable, affordable, and secure energy sources is a fundamental goal of humanity. Solar energy is a prominent primary energy source in residential and industrial systems, offering numerous advantages. Similarly, fruits and vegetables are essential to a healthy diet, providing various nutrients such as vitamins, minerals, and fiber. Hence, drying of fruits and vegetables as a preservation method has been practiced since ancient civilizations. It is a typical way of removing moisture and improving product quality. Drying consumes 10–15% of total industrial energy globally, with the food industry accounting for 12% (Bennamoun 2013). Solar thermal systems, like crop drying, are frequently used in agricultural applications (Belessiotis and Delyannis 2011). The main drawback is the intermittency of the sun's energy which cannot be utilized at night or in areas with insufficient solar radiation. Hybrid drying technologies can be used to solve this problem. Dryers in mixed mode are powered by a combination of solar, biomass, wind, and fossil fuels (Banout 2017).

The woody biomass moisture varies between 53 and 63% depending on the conditions, environment, and source. The biomass must be dried to bring the moisture content down to a usable range of 12–15% (Katia et al. 2022). Additionally, thermal drying is carried out for several purposes, such as faster and cheaper biomass transportation, enhancing material strength,

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and enabling processing. It is crucial to select the appropriate drying design for practical use. The predominant source of green energy in rural areas is biomass, notably fuelwood, forestry waste, agricultural field residue, organic waste, poultry, and cattle manure. Compared to other types of dryers, using biomass waste generated from farming activities is considered a low-cost alternative source of heat that offers both ecological and commercial benefits, especially in rural settings.

The study by Dhanuskodi et al. (2014) researched the thermal efficiency of a hybrid solar-biomass dryer. The findings show that the dryer may be utilized in various weather conditions, including as a biomass dryer at night, a solar dryer during the day, and a hybrid dryer during cloudy days. The drier is appropriate for small-scale cashew nut farms in rural areas worldwide. An innovative hybrid active greenhouse sun drier with an internal heat exchanger and a drying bed was investigated by Singh and Gaur (2021). A solar cabinet dryer integrated with an evacuated tube solar collector and a thermal storage system was studied by Iranmanesh et al. (2020) using CFD modelling and performance testing. The PCM storage system's internal thermal behavior and temperature dispersion were also studied. To examine the drying process and the thermodynamic performance of the drying system, apple slices with a thickness of 5 mm were chosen. Yahya (2016) investigated the efficiency of a solar-assisted heat pump dryer coupled with a biomass furnace and the kinetics of drying red chilies. Amer et al. (2010) developed a night-operational banana dehydration dryer using energy stored in a 500-L water tank. Solar heaters were used to heat the air, enabling the drying of 0.30 kg of bananas in 8 h reaching a moisture content of 180 g/kg. A similar method was used to dry medicinal plants in a hybrid sun drier, according to Čipliené et al. in 2015. Hussain Al-Kayiem (2022) introduced an innovative approach to enhance product quality and reduce the drying time. Their solution involved the development of a cutting-edge hybrid solar thermal dryer, specifically designed for drying tilapia fish. Rajkumar et al. (2007) reported drying tomato slices (4, 6, and 8 mm slices and moisture of 940 g/kg) in a lab-scale vacuum drier powered by solar energy. They noted 360, 480, and 600 min of drying times using the vacuum-assisted solar dryer to get a final moisture of 115 g/kg. Lewis et al. (2017) described seawater desalination using a vacuum spray dryer. Researchers proposed using solar energy and heat recovery from a vacuum pump to produce 15 L of clean water daily. The thermal efficiency of an open-sun solar dryer assisted by an evacuated tube solar collector was assessed by Kushwah et al. (2021). The findings demonstrated that using a hybrid greenhouse solar drier might speed up drying while maintaining an open sun drying standard.

Research gap

The number of publications and research reports in this area has dramatically expanded during the last 10 years. However, much of the effort evaluates each solar dryer's performance separately. There is still a lack of a specific literature review on evacuated tube collector (ETC)-based solar dryers, biomass dryers, and hybrid dryers. Less is told about how different dryers compare design and performance. However, the real question is, which drying technique offers the best performance? Which system has advantages and disadvantages over the other? Which drying method will take less time? How effective are the drying systems? Are they affordable? Which drying method is suitable for a place with less sunlight? This article tries to address all these queries. This evaluation report is performed to introduce and analyze the most recent advancement in solar dryers. Figure 1 depicts the various types of solar dryers discussed in this work (Murugan et al. 2021).

Objective of the review

This review paper's primary focus is to:

- Analyze the different designs of evacuated tube heat pipe solar dryers, biomass dryers, and hybrid solar dryers.

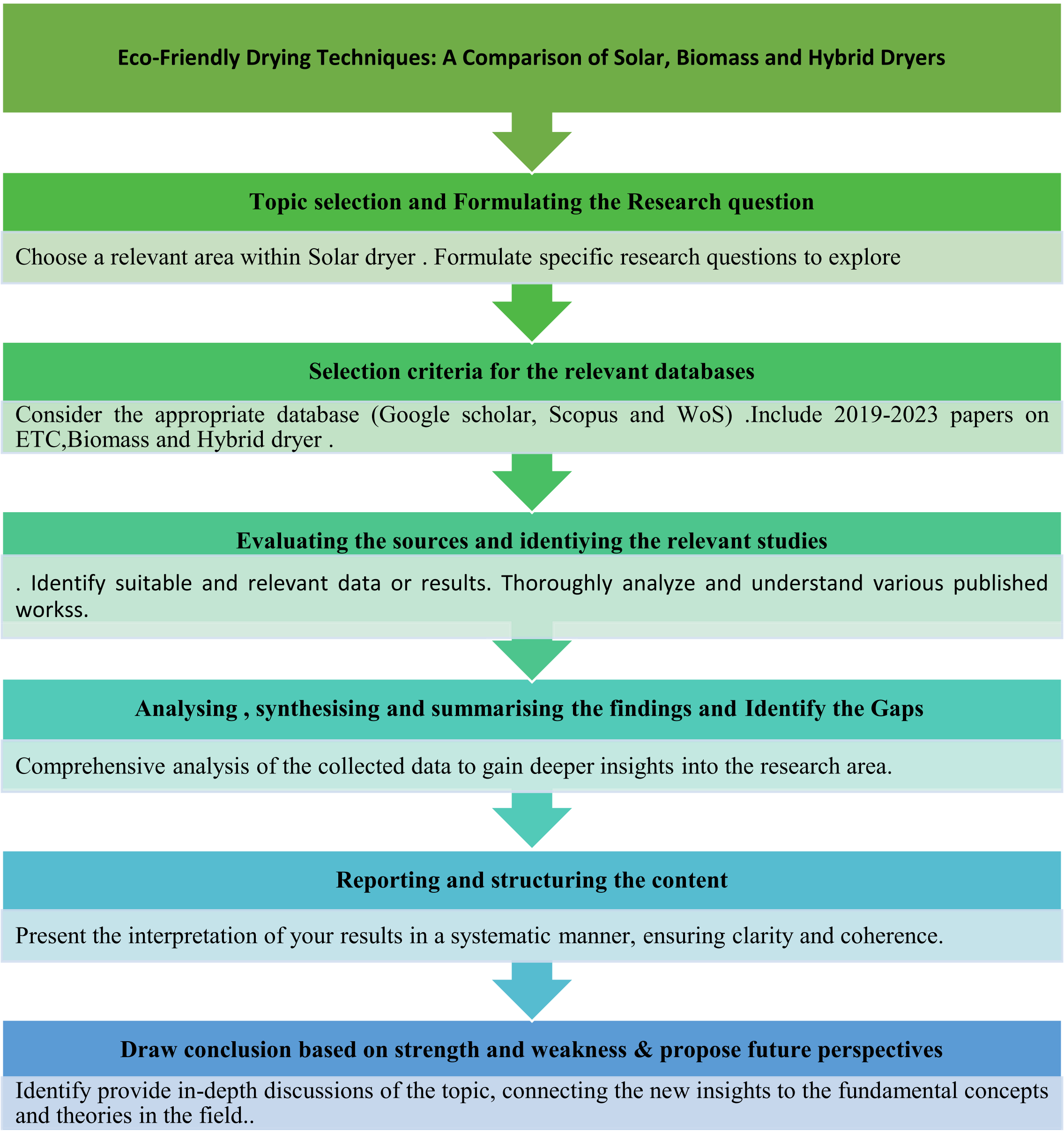
Fig. 1 Various types of dryers reviewed in this study (Source: PRIST University & MANIT-Bhopal)

- Evaluate the thermal performance of evacuated tube heat pipe solar dryers, biomass dryers, and hybrid solar dryer designs.
- Explore recent advancements and innovations in solar dryer design.

Novelty and contribution

The prior research on solar and biomass dryers is presented concisely. Three distinct types of thermal dryers (ETC solar, biomass, and hybrid dryer) are studied in terms of design structure and performance efficacy. The paper presents the most recent ETC, biomass, and hybrid dryer developments, analyses, and applications. The methodology employed to review the prior studies in a systematic procedural step is outlined in Fig. 2.

The structure of the paper is explained here: in "Introduction," background research is provided, and the topic is stated. Then, using the literature's data, comparative analyses of ETC solar drying systems are discussed in "Evacuated tube heat pipe–based solar dryer." A case study of current biomass drying systems is presented in "Developments in biomass dryer." The majority of hybrid drying techniques are covered in "Developments in hybrid solar dryers." The discussion, suggestions, and novel approaches are provided in "Discussion, recommendation, and future perspectives" to expand the potential of renewable drying. The results and corresponding conclusions are then summarized in "Conclusion."



Eco-Friendly Drying Techniques: A Comparison of Solar, Biomass and Hybrid Dryers

Topic selection and Formulating the Research question

Choose a relevant area within Solar dryer . Formulate specific research questions to explore

Selection criteria for the relevant databases

Consider the appropriate database (Google scholar, Scopus and WoS) .Include 2019-2023 papers on ETC,Biomass and Hybrid dryer .

Evaluating the sources and identiying the relevant studies

. Identify suitable and relevant data or results. Thoroughly analyze and understand various published workss.

Analysing , synthesising and summarising the findings and Identify the Gaps

Comprehensive analysis of the collected data to gain deeper insights into the research area.

Reporting and structuring the content

Present the interpretation of your results in a systematic manner, ensuring clarity and coherence.

Draw conclusion based on strength and weakness & propose future perspectives

Identify provide in-depth discussions of the topic, connecting the new insights to the fundamental concepts and theories in the field..

Fig. 2 Methodology of the study

Evacuated tube heat pipe–based solar dryer

The evacuated solar collector is the most efficient and widely used solar collection technology, known for its portability and ability to function on overcast, windy, and chilly days. The evacuated tube, a cylindrical structure with a selective coating that absorbs sunlight, is a vital component of this technology (Kumar et al. 2021). The layers are chosen for their low emissivity and ability to absorb all heat radiation, while the vacuum surrounding the coating minimizes thermal losses from conduction and convection. The absorbed heat is then transferred to either a heat pipe or the flowing water within the tube (Knowles et al. 1978). The collector absorber plate, made of a sealed copper pipe filled with refrigerant and attached to a black copper fin, transfers the gathered solar energy to a heat sink or working medium. The evacuated tube's thermal efficiency is enhanced due to the reduced thermal losses from the vacuum surrounding the absorber tube (Fig. 3).

Classification based on configuration

The working principle of evacuated tube solar collectors is based on heat transfer and thermodynamics principles to convert solar energy into thermal energy for use in heating water or other fluids. Evacuated tube solar collectors are a type of solar thermal technology used to heat water or other liquids for residential and industrial applications (Diamante et al. 2010). They are classified into the following types based on their working principles:

Single-tube evacuated tube collectors (STC): These are the most basic type of evacuated tube collectors, consisting of a single glass tube with a copper heat pipe inside. The working principle is simple: when the sun's rays hit the tube, the copper heat pipe absorbs the heat and transfers it to the water in the storage tank (Aggarwal et al. 2023).

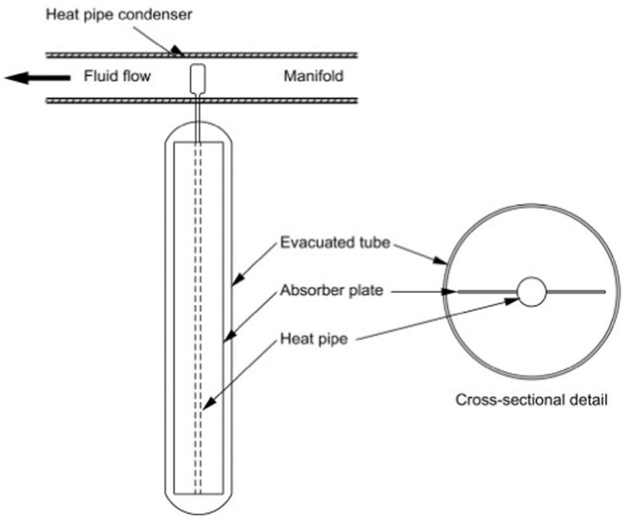


Fig. 3 Schematic of ETSC with a heat pipe (Kumar et al. 2021)

Parallel flow evacuated tube collectors (PFETC): These collectors are arranged in parallel tubes with a heat pipe inside each tube. The working principle is similar to STCs, but the heat is transferred to a standard header pipe that carries the heat to the storage tank (Sabiha et al. 2015).

Counter flow evacuated tube collectors (CFETC): These collectors also consist of a series of tubes arranged in parallel. Still, the flow of the heat transfer fluid is opposite to the flow of the sun's rays. This design helps reduce heat loss and increase the collector's efficiency (Jangde et al. 2022).

Integral collector storage (ICS) evacuated tube collectors: These collectors combine a series of tubes with a storage tank in a single unit. The working principle is similar to that of PFETCs, but the heat is stored in the unit's integral storage tank, making it possible to use the heat even when the sun is not shining (Wang et al. 2022; Ekka and Kumar 2023).

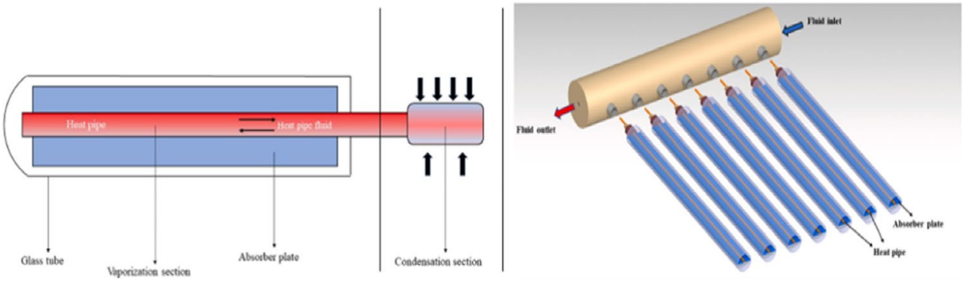
In all cases, the evacuated tubes provide insulation, reducing heat loss and increasing the collector's efficiency. The tubes also protect the heat pipes from freezing, making the collectors suitable for cold climates. The various heat-pipe vacuum tube collector's design is illustrated in Figs. 4, 5, and 6.

Developments in evacuated tube heat pipe solar dryer

Iranmanesh et al. (2020) assessed the effectiveness of a solar cabinet dryer that incorporated a phase change material (PCM) thermal storage system and a heat pipe evacuated solar tube collector (ETSC) (as depicted in Fig. 7). The examination included thermal analysis of the collector, system modeling, drying efficiency evaluation, and dried apple slice quality assessment. The dryer was tested through experiments, and data was collected to build a model of the system. Three different air flow rates (0.025, 0.05, and 0.09 kg/s) were used while drying 16 slices of apples, each with a thickness of 5 mm. The thermal analysis results indicated that using PCM improved the input thermal energy by 1.72% and 5.12% for airflow rates of 0.025 and 0.05 kg/s, respectively. However, an increase in air flow rate to 0.09 kg/s resulted in a decrease in input thermal energy. The highest overall drying efficiency of 39.9% was obtained at an airflow rate of 0.025 kg/s with PCM. The dryer and storage system simulation results matched well with the experimental results. Additionally, the application of PCM did not adversely impact the quality of the dried product.

Lamnatou et al. (2012) created a new solar dryer, and its efficiency was analyzed using an evacuated-tube collector (Fig. 8). The dryer was suitable for sun-drying without preheating the output air, and energy/exergy analysis was demonstrated to be an effective tool for evaluating the performance of this type of solar drier. During the study,

Fig. 4 Schematic of **a** a heat pipe and **b** an evacuated tube collector (Kumar et al 2021)



(a) Heat pipe (b) Evacuated tube

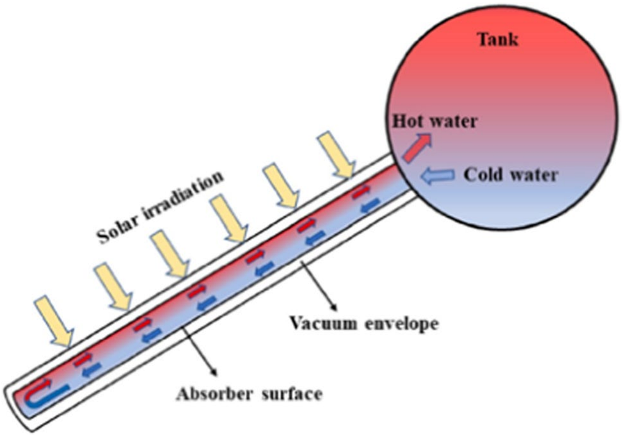
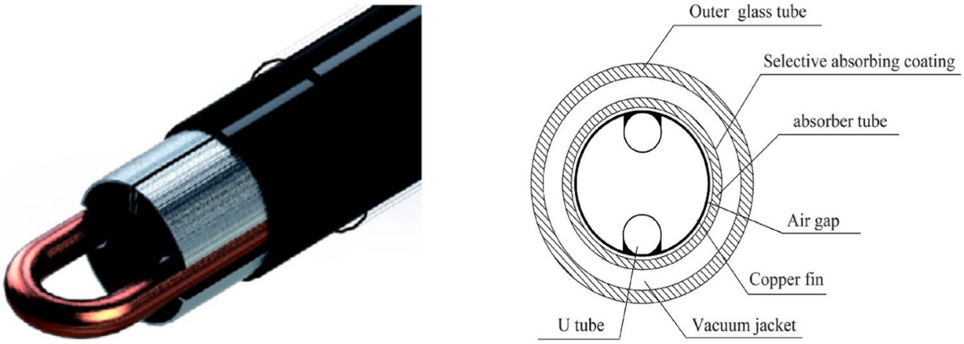


Fig. 5 Schematic of water-in-glass ETSC (Aggarwal et al. 2023)

various fruits and vegetables, such as apples, carrots, and apricots, were dried thin-layer, and the experimental drying results were analyzed using thin-layer drying models. The correlation coefficients were acceptable, and the novel thin-layer drying model of Diamante et al. (2010) was also used to evaluate the drying process. Several performance metrics were calculated to assess the dryer's performance, including the energy utilization ratio, pick-up efficiency, and energetic and exergetic efficiencies. The entropy generation was also analyzed to determine the optimum collector surface area. The results indicated that the proposed drier could dry a wider variety of products than those tested in this study, thanks to its excellent efficiency.

Malakar et al. (2021) designed a garlic clove solar dryer with an evacuated tube collector and a heat pipe (illustrated

Fig. 6 U-tube evacuated tube collector: **a** photographic view; **b** a cross-sectional structure (Malakar et al. 2023)



(a) Photographic view (b) Cross-sectional structure

Fig. 7 Schematic of the evacuated tube-based solar cabinet dryer (Iranmanesh et al. 2020)

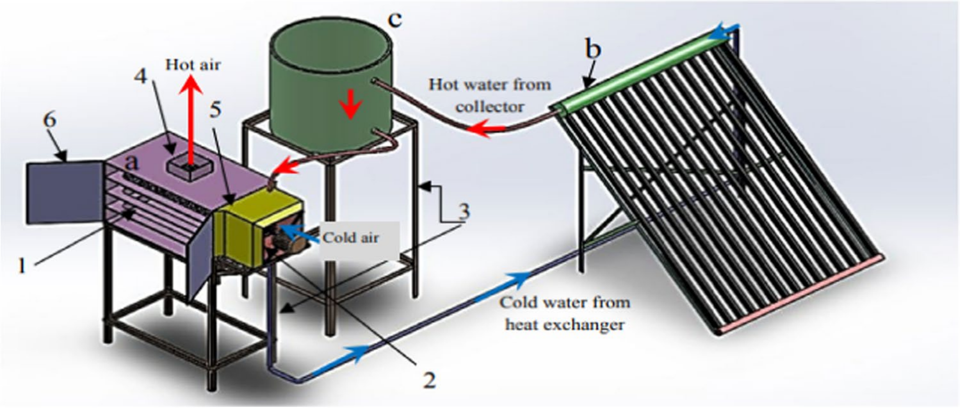


Fig. 8 **a** Evacuated-tube air collector: set-up; **b** the drying chamber (Lamnatou et al. 2012)

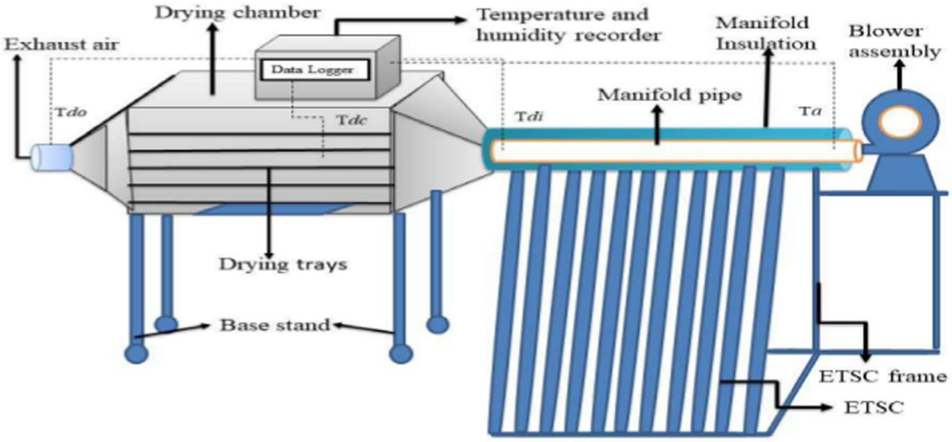


Fig. 9 Solar drier with evacuated tube collector and heat pipe for drying garlic cloves (Malakar et al. 2021)

in Fig. 9). The device's performance was assessed through experiments, where 10 kg of garlic cloves were dried from 69% moisture content to 8% (wb). The evacuated tube sun dryer's (ETSD) thermal performance was evaluated with various airflow velocities (1, 2, and 3 m/s) under both no load and full load conditions. On a day with maximum solar radiation of 1360 W/m^2 and a maximum peak sun hour of 6.27, the highest temperature of 86.7 °C was recorded in the drying chamber. Results indicated that the best drying rate, solar collector effectiveness, and dryer effectiveness were obtained at an airflow velocity of 2 m/s, with values of 1.56 kg H_2O/kg dry solid/h, 42.56%, and 56%, respectively. The average exergy efficiency peaked at 56.59%, with the lowest average exergy loss of 4.74 W at the same air velocity. The garlic cloves were dried within 8 h at 2 m/s airflow velocity, and the developed ETSD had a payback period of 1.3 years.

Amin and Salihoğlu (2021) examined the potential of using PCM-equipped evacuated solar dryer technology in drying different varieties of sludge to alleviate issues in sludge management (as illustrated in Fig. 10). A phase change material, paraffin wax, was integrated into the drying system to assess its drying efficiency. The findings revealed that the moisture content in the wastewater treatment plant and paint sludge was reduced from 80 to 17.2% and from 56 to 4.8%, respectively, while the marble sludge was thoroughly dried with a moisture level of 26%. It was determined that sufficient solar radiation for sludge drying was available for 7 h. The system's efficiency improved as the number of fans and tubes with PCM increased. This solar dryer effectively removed substantial water from the sludge, making

Fig. 10 Experimental setup of solar sludge dryer (Amin and Salihoğlu 2021)

it easier to transport and dispose of. Additionally, it helped reduce the volume and cost of transportation for effective sludge management.

Umayal Sundari et al. (2014): A solar dryer that utilizes an ETC has been established in Thanjavur, Tamilnadu, India, and its efficacy in drying muscat grapes was investigated (Fig. 11). The dryer is capable of drying a variety of agricultural produce. Throughout the drying process, parameters like temperature, relative humidity, wind speed, and sample mass are monitored hourly. Solar radiation levels vary from 155.6 to 1115 W/m^2, and the ambient temperature ranges from 29.5 to 33.2 °C. The temperature of the collector's output and the inside of the chamber varies from 74 to 130 °C and 50 to 87 °C, respectively. The proposed dryer takes 14 h to reduce the moisture content of muscat grapes from 78 to 9.5% (wb), making them safe for storage. Its highest efficiency for muscat grapes was found to be 29.92%. The quality of the solar-dried muscat grapes was deemed high, as evidenced by their appearance, texture, and color. Mathematical thin-layer drying models were applied to align with the experimental moisture ratio as the drying process occurs during a falling-rate period. The page model was the most appropriate to describe the drying behavior of muscat grapes, as it had the highest R^2 value, and the lowest reduced chi-square and root-mean-square error (RMSE) values among the six models considered.

Mathew and Thangavel (2021) designed, constructed, and its performance evaluated a unique evacuated tube heat pipe sun dryer (Fig. 12). The solar collector was enhanced with a novel standard condenser heat pipe system and Therminol 55 as thermal energy storage. The performance study was carried out using air mass flow rates varying from 0.003 to 0.02 kg/s and a combination of two rates between 0.015 and 0.0065 kg/s. The maximum temperature reached by the air from the solar collector was 118 °C. The solar collector's energy and exergy efficiency ranged from 10 to 30% and 1.9 to 5.6%, respectively. The dryer was used for drying agricultural produce like tomatoes and carrots, and the impact of moisture diffusivity on the drying process was analyzed. The Newton model effectively predicted the drying of tomatoes. The combination of mass flow rates elevated the average outlet temperature of the collector to 67 °C and decreased the drying time by 2 h. The payback period for the dryer is 2.6 years. Table 1 presents several studies on Evacuated solar collector-based solar dryers conducted over the last decade. Each system's product, drying time, and drying temperature are provided for easy reference.

Fig. 11 Photograph of evacuated tube collector-based solar dryer (Umayal Sundari et al. 2014)

Developments in biomass dryer

Crops are dried using biomass dryers powered by agricultural feedstock. It is a device used to dry wet biomass materials to reduce their moisture content to an acceptable level for storage and utilization.

Working principles

Drying with the biomass system begins by feeding the material into the dryer. The moist air is then expelled from the system, and hot air is circulated through the biomass to transfer heat and evaporate the moisture (Sachin et al. 2012). The drying procedure is repeated until the targeted moisture level is reached. The waste biomass is burned to generate hot gases, which are then channeled through a heat exchanger. This process creates hot, pure air that flows through the drying chamber, where crops are loaded onto trays. The system's design, which uses biomass to dry crops, is depicted in (Fig. 13). Key components of the system include the following:

Fig. 12 Photographic view of evacuated heat pipe solar dryer (Mathew and Thangavel 2021)

Table 1 Comparative studies of selected evacuated heat pipe solar dryer

S. no	Type of dryers	Drying type/place	Agro-product	Thickness (mm)	Drying time (h)	Temp (°C)	Research findings	Reference
1	Evacuated-tube air collector–based solar dryer	Iran	16 nos of apple	5 mm	–	69 °C	0.025, 0.05, and 0.09 kg/s air flow rates Reduction in drying time of 9.37%, 9.67%, and 10.02% for air flow rates of 0.025, 0.05, and 0.09 kg/s, respectively The highest efficiency was achieved with PCM at 39.9% at 0.025 kg/s For air flow rates of 0.025 and 0.05 kg/s, PCM increased the input thermal energy by 1.72 and 5.12%, respectively	Iranmanesh et al. (2020)
2	Evacuated-tube air collector	Athens, Greece	Carrot	5 mm	6.5 h	60 °C	Carrot drying took 6.5 h at 60 °C intake temperature and 5 h at 54 °C inlet temperature Apricot drying took 9 h at 59 °C inlet temperature Apple drying took 8 h at 59 °C inlet temperature	Lamnatou et al. (2012)
				3 mm	5 h	54 °C		
			Apricot	10 mm	9 h	59 °C		
			Apple	5 mm	8 h	59 °C		
3	Evacuated-tube air collector	Haryana, India	Garlic	10 kg	8 h	86.7 °C (max)	Tested at different air flow velocities when under no load and full load scenarios (1, 2, and 3 m/s) Drying time: 8 h Moisture content: 69–8% (wb) Average exergy efficiency: 56.59% Average exergy loss: 4.74 W at 2 m/s air velocity Payback period: 1.3 years	Malakar et al. (2021)
4	PCM integrated evacuated solar dryer	Bursa, Turkey	Sludge	–	7 h	50 °C	The moisture level of the wastewater and sludge decreased from 80 to 17.2% and from 56.5 to 4.8%, respectively, and the marble sludge was totally dried with a moisture content of 26%. The effectiveness of the system grew with the quantity of fans and tubes holding PCM	Amin and Salihoğlu (2021)

Table 1 (continued)

S. no	Type of dryers	Drying type/place	Agro-product	Thickness (mm)	Drying time (h)	Temp (°C)	Research findings	Reference
5	ETC solar dryer	Thanjavur, India	Muscat grapes	–	14 h	50–130 °C	Moisture content: 78 to 9.5% (wb) Highest efficiency: 29.92% Page model is confirmed as the best thin layer drying behavior	Umayal Sundari et al. (2014)
6	Evacuated tube heat pipe solar dryer	Chennai, India	Carrot	10 mm	10 h	71 °C	Carrot drying took 10 h, 11 h, and 13 h at temperatures (71 °C, 73 °C, and 71 °C) Tomato moisture removal: 1 kg (95% wb) to 33 g (2.036% wb)	Mathew and Thangavel (2021)
				30 mm	11 h	73 °C		
				50 mm	13 h	71 °C		
			Tomato	–	14 h	–		

1. The heating chamber: The door of this chamber must stay shut during use to enhance efficient fuel combustion through thermochemical reactions.
2. The duct/channel: This component, usually made of mild steel, acts as the core of the dryer and draws in air from the heating chamber.
3. The drying chamber: This area is where the crop's moisture content is decreased through a hot air flow. The size of the chamber can be adjusted based on the crop capacity.
4. The tray: Trays, made of stainless steel to prevent rusting, hold the crops during the drying process. The number of trays required will vary based on the size of the dryer.
5. The chimney: This component helps regulate the gas flow appropriately within the drying chamber.

Classification of biomass dryers

Classification of biomass dryers is based on the type of heat source used, such as direct or indirect heating. The biomass material does not directly contact the heating source in indirect heating. Instead, heat is transferred to the drying air, which dries the biomass. Direct heating involves heating the biomass material directly with a heat source, such as a hot air generator or a furnace. Temperature and airflow control is critical to the drying process in direct and indirect heating systems. Properly dried biomass is essential for its efficient utilization and storage.

Basic overview of various studies

There is a considerable body of literature on biomass dryers, covering multiple aspects of the technology, including design, performance, efficiency, cost, and applications. Some of the critical areas of research in the literature on biomass dryers include the following:

1. Design and optimization: Numerous studies have focused on the design and optimization of biomass dryers. These studies have aimed to improve energy efficiency and drying performance.
2. Performance evaluation: The effectiveness of biomass dryers in terms of drying efficiency, energy consumption, and product quality have been assessed in several studies.
3. Cost analysis: The cost of biomass dryers is critical for widespread adoption. Studies have been carried out to establish the cost-effectiveness of different types of dryers and to identify ways to reduce the cost of biomass drying.
4. Application: Biomass dryers have vast applications in various industries, such as agriculture, food processing, and bioenergy production. Literature has been published on using biomass dryers in these industries, including case studies and practical applications.

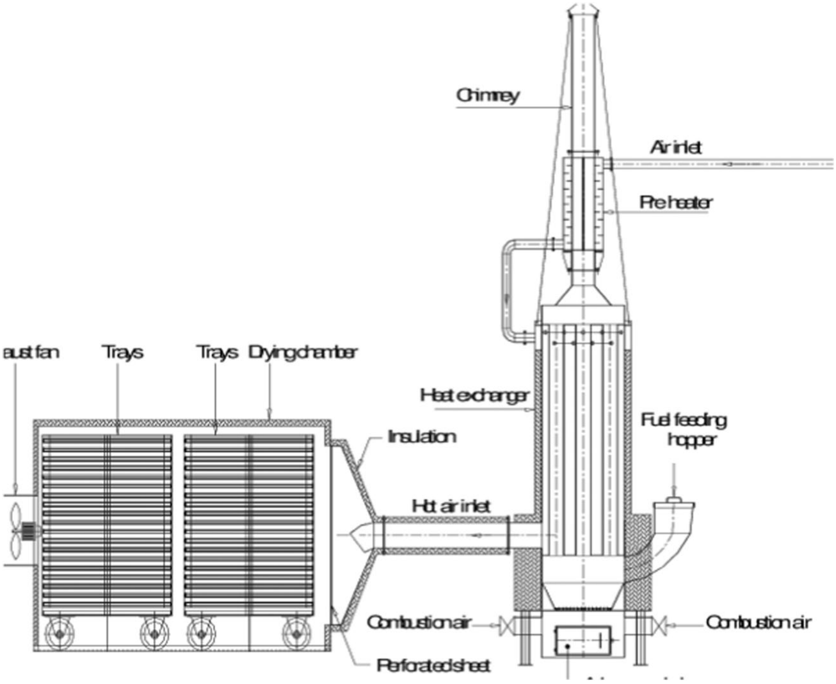


Fig. 13 Schematic and block diagram of biomass dryer (Sachin et al. 2012)

5. Environmental impact: The drying of biomass has the potential to generate air pollutants and contribute to greenhouse gas emissions. There have been studies on the environmental impact of biomass dryers and the potential for mitigation strategies.

Previous design and performance studies on biomass dryer

Engola et al. (2022): The development and evaluation of a biomass dryer designed to assist small-scale farmers in Cameroon are described in the article (referenced as Fig. 14). This project aims to tackle the issues farmers face who rely on traditional methods to dry their crops. The performance of the dryer was assessed by measuring the temperature during the drying process while burning charcoal fuel. The findings suggest that the prototype biomass dryer can potentially be a sustainable solution for drying certain agricultural products, such as cocoa, ginger, and fruits, on a small scale.

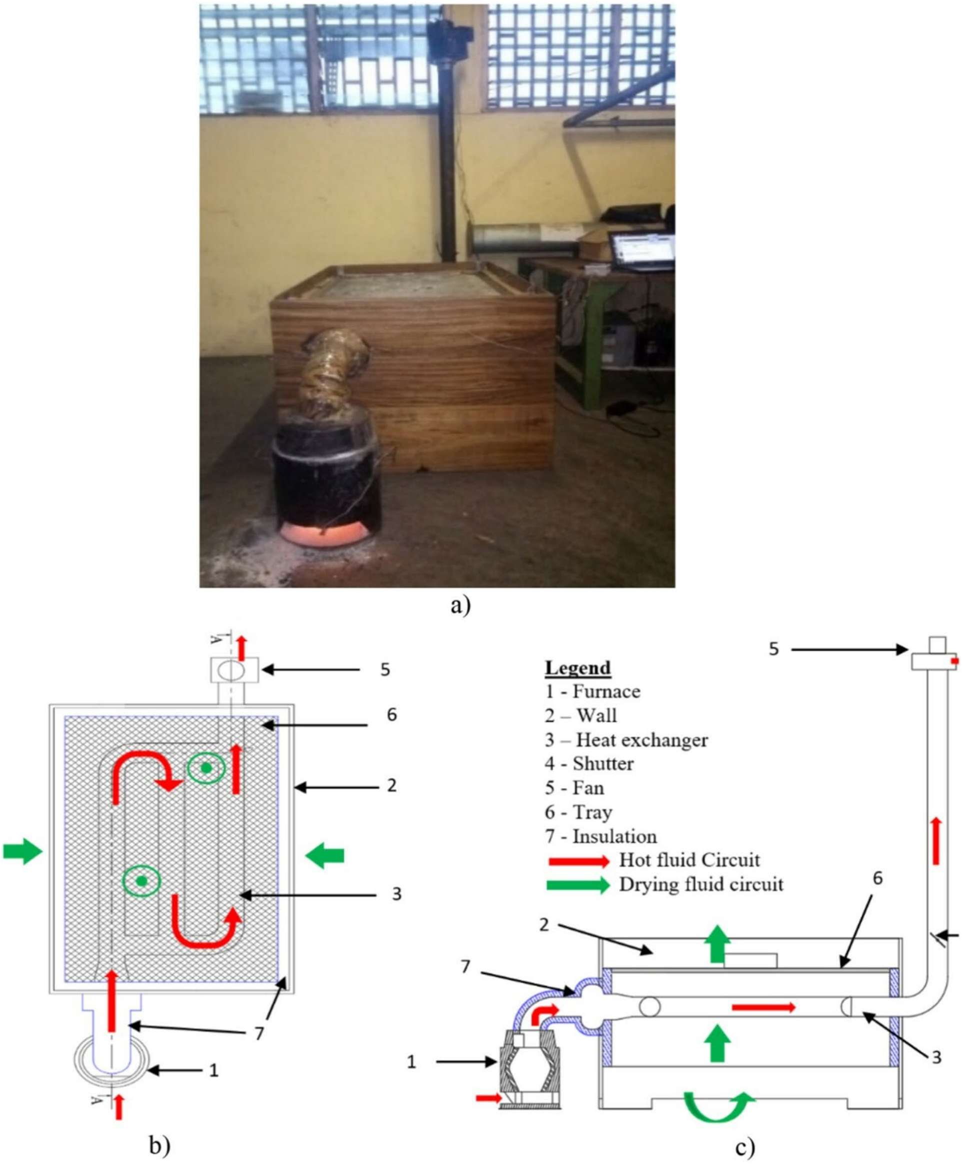
Uthman et al. (2017) designed a drying system for agricultural goods, particularly groundnuts, produced and evaluated (Fig. 15). The findings indicated that elevated temperatures of 60 °C and 65 °C were more efficient for drying groundnuts. As the temperature increased, the drying time decreased, but the drying rate decreased as the weight of the goods increased. This drying system is suggested for farmers and merchants who work with peanuts**.**

Muritala et al. (2022) focuses on designing and evaluating a forced convective dryer for processing plantains (Fig. 16). The dryer's performance was analyzed through numerical simulation and experimental testing. The air velocity in the drying chamber varied between 1.5, 2.5, and 3.5 m/s, and the heat flow was calculated and confirmed through experimentation. With an air temperature of 55 to 60 °C and a maximum air velocity of 3.5 m/s, the dryer could dry 5 kg of plantain chips from 60% moisture content to 13% in 12 h. This drying efficiency was significantly higher than open-air solar drying, which only had a drying rate of 0.0035 kg/h. The forced convective dryer speeds up the drying process. It enhances product quality by directing flue gas outside through a heat exchanger and chimney, thus reducing waste and increasing cleanliness compared to open sun drying.

Murugan and Raveendran (2021) focused on creating a rural-based biomass dryer that can dry agricultural products (as depicted in Fig. 17). The dryer uses readily available and low-cost biomass as fuel through its gasifier system. Tapioca was used as the test material, and its drying efficiency was monitored throughout the process at temperatures between 60 to 70 °C with a consistent producer gas flow. The results showed that the dried tapioca had minimal color, flavor, or quality changes and had a final moisture content ranging from 5 to 12%. The closed environment of the dryer ensures no pollutants like dust during the drying process. This method can also benefit cash crops like black pepper, cardamom, and chilies.

Rabha (2021): The dryer described in this article consists of three parts: a heat exchanger, a combustion, and a drying chamber (as depicted in Fig. 18). It can operate in passive and active modes, as demonstrated in drying chopped turmeric fingers. By utilizing 24–25.5 kg of mango wood with a moisture content of 12.5%, the turmeric slices were dried from 87.62 to 12.78% over 32 h. The thermal efficiency of the dryer was found to vary between 4.35 and 4.62%. In

Fig. 14 Biomass dryer. **a** Photograph. **b** Top view. **c** Section A–A (Engola et al. 2022)



terms of fuel, the dryer can utilize various biomass sources. Its ability to function in both passive and active modes makes it a suitable choice for rural areas where access to electricity may be limited or unreliable. Table 2 summarizes the findings of selected studies on biomass dryers, including details on the product, drying time, and drying temperature.

Developments in hybrid solar dryers

Hybrid drying aims to take advantage of the abundant solar radiation in developing countries for drying various agricultural and food products and reduce the reliance on costly fossil fuels with other energy sources.

Working principles

In the context of drying agricultural and food products in developing countries, hybrid solar dryers have gained popularity due to their efficient use of solar radiation and the increasing cost of fossil fuels. These dryers combine solar energy with other energy sources to enhance the drying process of biomass materials. The dryer utilizes solar energy to heat air, circulating through the drying chamber to evaporate moisture from the dried material. When solar energy is insufficient, the dryer can switch to an additional energy source, such as biomass, conventional electricity, or thermal energy storage, to supplement the drying process.

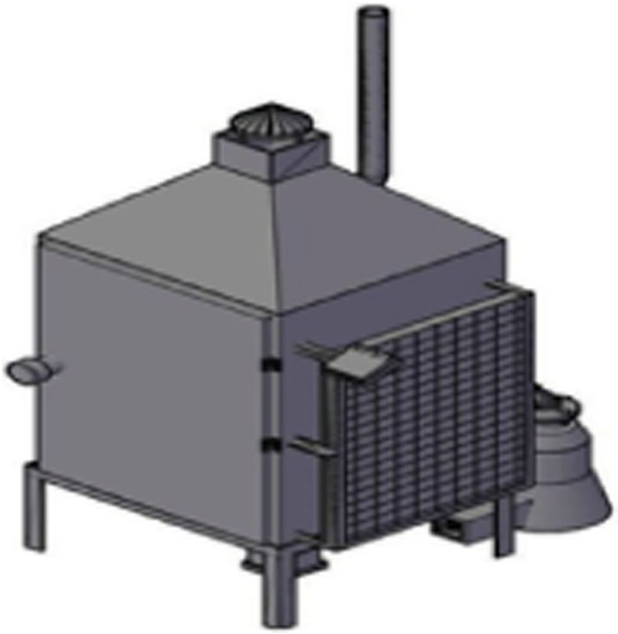


Fig. 15 Biomass dryer design (Uthman et al. 2017)

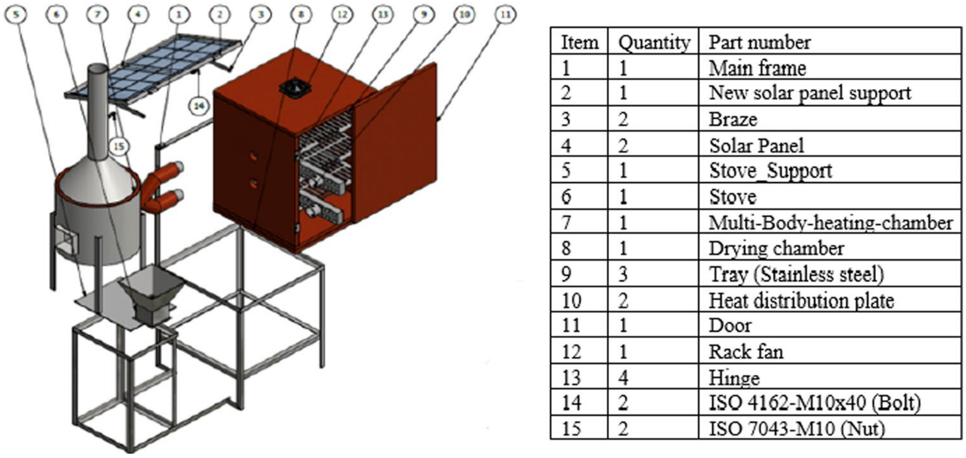
Application of hybrid solar dryers

Combining solar and additional energy sources in a hybrid solar dryer provides several advantages, including improved drying efficiency, reduced energy consumption, and lower greenhouse gas emissions. Hybrid solar dryers are handy for drying applications in remote or off-grid areas, where access to electricity is limited, and for applications where cost-effectiveness is a priority. These dryers are designed to harness the advantages of both solar energy and other energy sources to provide efficient and cost-effective drying solutions. As a result, the dehydration process is constant, continuous throughout daylight hours, and faster and the food is protected against microbial destruction resulting in higher-quality dried foodstuff.

Previous design and performance studies on hybrid dryers

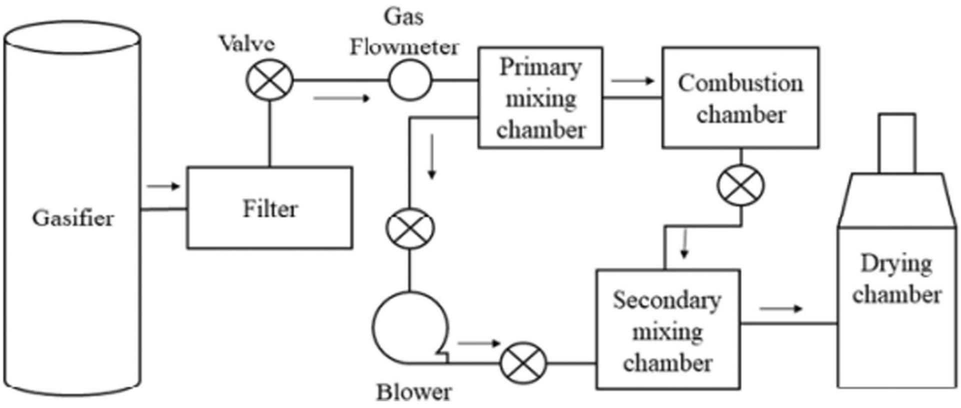
Singh and Gaur (2021) created a cutting-edge hybrid active greenhouse solar dryer with an internal heat exchanger and a drying bed (Fig. 19). The authors assessed the new hybrid active greenhouse solar dryer's cost-effectiveness, drying time, environmental implications, and energy efficiency.

Fig. 16 Experimental biomass dryer unit (Muritala et al. 2022)



Item	Quantity	Part number
1	1	Main frame
2	1	New solar panel support
3	2	Braze
4	2	Solar Panel
5	1	Stove_Support
6	1	Stove
7	1	Multi-Body-heating-chamber
8	1	Drying chamber
9	3	Tray (Stainless steel)
10	2	Heat distribution plate
11	1	Door
12	1	Rack fan
13	4	Hinge
14	2	ISO 4162-M10x40 (Bolt)
15	2	ISO 7043-M10 (Nut)

Fig. 17 Schematic of the biomass gasifier unit (Murugan and Raveendran 2021)



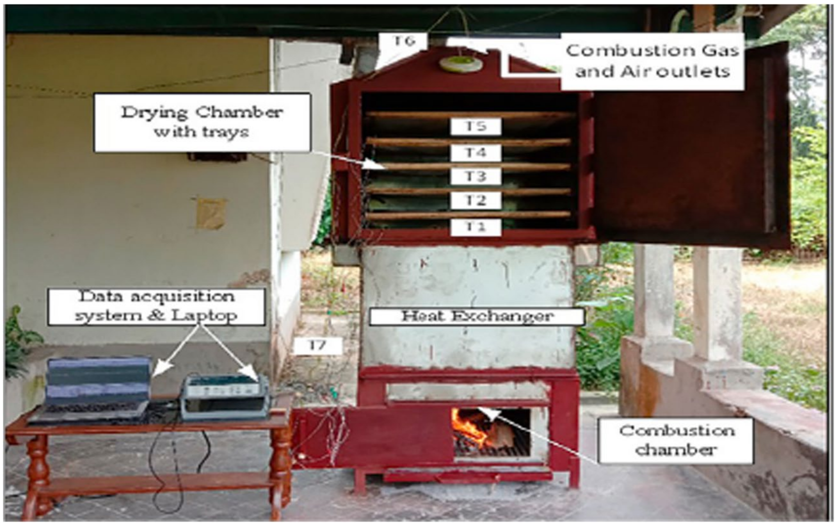


Fig. 18 Biomass-fired heater (Rabha 2021)

Using three crops, they compare the hybrid solar dryer's performance to conventional and classic greenhouse solar dryers: ginger, tomatoes, and bottle gourd. According to the study's findings, the hybrid active greenhouse solar dryer with an evacuated tube solar collector performs better in terms of energy efficiency and drying time than conventional greenhouse solar dryers. The study also demonstrates that the hybrid solar dryer may be economically viable due to its decreased maintenance and operation expenses. Overall, the study emphasizes the potential advantages of using a hybrid evacuated tube solar collector and active greenhouse solar dryer as a sustainable method for food drying, with favorable effects on drying time, cost, and energy efficiency.

Chekol et al. (2021) evaluated the efficiency of a solar maize dryer equipped with a biomass backup heater (Fig. 20). The dryer, which measures 2 m in length and 1 m in width, has a transparent glass cover that allows solar radiation to penetrate the collector. The drying performance was analyzed based on temperature, moisture content, sun exposure, and air velocity. The researchers calculated the drying rate, final moisture content, and dryer's energy efficiency. The findings showed that implementing the thin layer drying curve in the solar maize dryer and the biomass backup heater can increase energy efficiency.

Yahya (2016) conducted a study to assess the design and performance of a drying system that combined a solar-assisted heat pump with a biomass furnace for drying red chili (Fig. 21). The aim was to determine the system's drying rate, final moisture content, and energy efficiency. The results indicated that this hybrid drying system effectively dried red chili and provided better energy efficiency than traditional drying methods. However, more details on the exact specifications of the solar-assisted heat pump and biomass furnace would have provided a better understanding of the system's potential. A comparison with other drying techniques, like conventional heat pump drying or solely relying on solar drying, would have given a clearer perspective on the strengths and limitations of the combined system.

Dhanuskodi et al. (2014) highlighted the development of a hybrid drying system for cashew nuts that leverages solar energy and biomass (e.g., sawdust, shells, or coconut coir) as heat sources. The system's thermal performance was evaluated through experiments to find the optimal drying conditions and assess its effectiveness (Fig. 22). The study found that the hybrid system significantly reduced drying time and improved the quality of dried cashews compared to conventional sun-drying methods. These results suggest the hybrid solar biomass drying system is a practical option for cashew processing in areas with ample solar radiation and biomass resources. This system can potentially improve efficiency and lower the cost of cashew drying, making it a valuable technology for small-scale cashew processors in developing countries. The information provided in the study can help design and deploy hybrid solar biomass drying systems for cashew nuts and other agricultural products.

Wang et al. (2022) presented a multi-objective evaluation of a hybrid drying system utilizing evacuated tubes and solar electricity to dry lotus bee pollen (Fig. 23). The authors assess multiple aspects that impact the efficiency of the drying system, including drying temperature, drying duration, energy usage, and financial cost. The findings indicate that the evacuated tube solar-electric hybrid drying setup presents a practical solution for drying lotus bee pollen. It offers efficient drying with low energy consumption and economic cost. This study provides insightful information for designing and optimizing hybrid drying systems utilizing solar electricity for other agricultural products. The design encompasses the utilization of both evacuated tube collectors and photovoltaic technologies, offering an enhanced form of the evacuated tube solar-electric hybrid drying setup.

Table 2 Comparative study of selected biomass dryers

S.no	Type of dryers	Location	Agro-product	Thickness (mm) /kg	Drying time (h)	Temp (°C)	Research findings	Reference
1	Prototype biomass dryer	Douala, Cameroon	Fuel: charcoal	0.4 kg/18 min		32–69 °C	Firewood (charcoal) as fuel Shutter position in middle to ensure a uniform air distribution and drying temperature	Engola et al. (2022)
2	Biomass dryer	Kwara state polytechnic, Ilorin	Groundnut	–	6 h	65 °C	The time needed to dry groundnuts varies depending on the temperature, averaging 3 h and 30 min at 65 °C, 412 h at 60 °C, and 6 h at 55 °C	Uthman et al. (2017)
3	Forced convective biomass dryer	Kota Langsa, Indonesia	Plantain chips	5 kg	12 h	55–60 °C	Drying efficiency: 77.8% Mean drying rate: 0.0140 kg/h Moisture content: 60–13% Heat is uniformly transferred by a distribution plate from the inlet of the drying chamber to other areas near the trays	Muritala et al. (2022)
4	Biomass gasifier	Erode, India	Tapioca	16 kg	4–5 h	60–70 °C	Reduced drying time by 50% Moisture reduction: 12–5%	Murugan and Raveendran (2021)
5	Biomass-fired heater	Assam, India	Turmeric	2 kg 24 kg mango wood (fuel)	32 h	58.2 °C	Moisture reduction: 87.62 to 12.78%	Rabha (2021)
6	Biomass dryer	IIT Guwahati dryer	Paddy	–	–	60–70 °C	Heat is generated using woodchips (biomass) Produces hot air in the 60–70 °C range Moisture content reduction: 33% to 14% (wb)	Mohapatra et al. (2013)

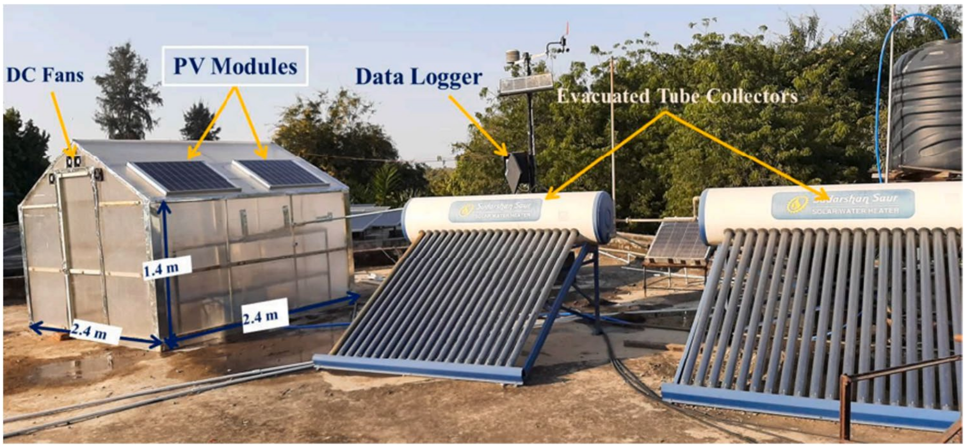


Fig. 19 HAGSD with solar collector (Singh and Gaur 2021)

Fig. 20 Solar air heater assisted by biomass back-up heater (Chekol et al. 2021)

Fig. 21 Photograph of the solar-assisted heat pump drying integrated with biomass furnace (Yahya 2016)

Heydari (2022) focused on analyzing the performance of a hybrid drying system that integrates a spiral solar air heater with a supplementary heating system (Fig. 24). The authors aimed to assess the system’s energy, exergy,

Fig. 22 Pictorial view of biomass dryer and drying chamber (Dhanushkodi et al. 2014)

Fig. 23 Evacuated tube solar-electric hybrid dryer (Wang et al. 2022)

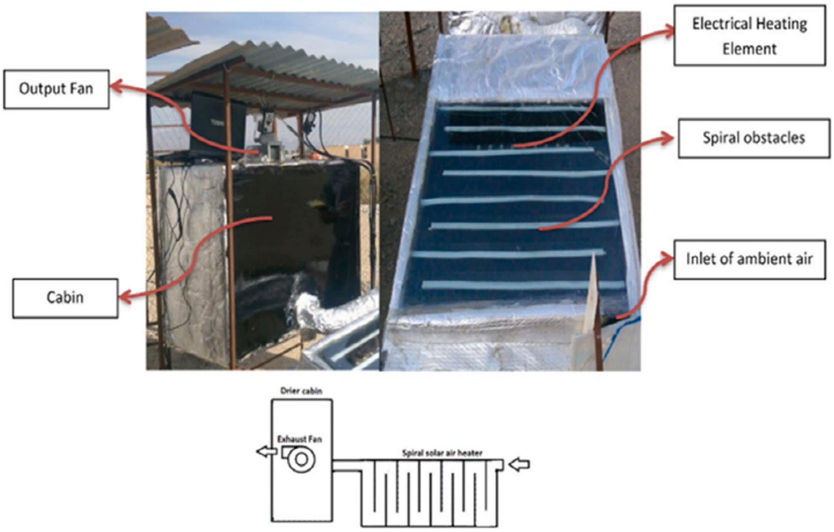


Fig. 24 Hybrid cabin dryer and the collector (Heydari 2022)

and economic efficiency to enhance its performance and reduce energy consumption. The study results showed that the hybrid system outperformed the conventional drying system, offering improved energy and exergy efficiency and being more cost-effective. To evaluate the system's performance, four types of fruits, including apple, kiwi, banana slices, and quince julienne strips, were dried within the system, and their drying processes were meticulously recorded. The economic analysis of the system was conducted after monitoring the temperature and humidity variations, quantifying the energy produced and consumed and evaluating the system's energy and exergy efficiency. Table 3 presents a compilation of selected studies on hybrid dryers. The table provides insights into the drying product, drying time, and drying temperature for each study.

Discussion, recommendation, and future perspectives

Solar evacuated dryers: The future of solar evacuated dryers looks promising as the world becomes more focused on reducing its carbon footprint and transitioning to renewable energy sources. With the increasing availability of advanced technologies, we can expect to see a rise in the use of solar-evacuated dryers in various industries.

Biomass dryers: Biomass dryers use renewable energy sources such as wood chips, sawdust, and agricultural waste to dry products. These energy-efficient and environmentally friendly dryers use waste products that would otherwise go to waste. In the coming years, we can expect to see a growing demand for biomass dryers as the world becomes more conscious of its environmental impact. With the increasing availability of biomass resources and technological advances, we can expect a rise in biomass dryers in various industries.

Hybrid dryers: With the increasing demand for energy-efficient and cost-effective drying solutions, hybrid dryers are gaining popularity. Hybrid dryers combine the advantages of traditional drying methods with renewable energy sources, resulting in more efficient and sustainable drying. Hybrid dryers' future looks bright as more industries seek eco-friendly and cost-effective drying solutions. In the coming years, we can expect an increased demand for hybrid dryers and a rise in research and development in this area.

SWOT analysis is a tool used to identify a product's or system's strengths, weaknesses, opportunities, and threats. Here is a comparison of the SWOT analysis of solar, biomass, and hybrid dryers:

Strengths:

- Solar dryers: high energy efficiency, low operating cost, no fuel consumption, no emissions.
- Biomass dryers: lower operating cost compared to traditional fossil fuel dryers, use of renewable resources, low emissions.
- Hybrid dryers: A combination of two or more drying methods provides more efficiency, flexibility, and cost-effectiveness than single drying methods.

Weaknesses:

- Solar dryers: reliance on weather conditions, limited drying capacity during cloudy or overcast days, higher initial cost.
- Biomass dryers: limited availability of biomass resources in some regions, potential fire hazards if not properly maintained, need for constant fuel supply.
- Hybrid dryers: Complex system, high initial cost, requires technical expertise to operate and maintain.

Table 3 Comparative study of selected hybrid dryers

S. no	Type of dryers	Drying type/place	Agro-product	Thickness (mm)	Drying time (h)	Temp (°C)	Research findings	Reference
1	Hybrid greenhouse + evacuated tube solar collector	Gwalior, India	Tomato Ginger Bottle gourd	6 mm 6 mm 6 mm	10 h 29 h 8 h	46.9 °C	Outside temperature: 31 °C Drying time reduction: Tomato: 47.36% Bottle gourd: 61.90% Ginger: 34.09%,	Singh and Gaur (2021)
2	Solar dryer + biomass back-up heater	Dilla, Ethiopia	Maize	–	10 h	50 °C	Drying chamber temperature > 3.66 °C than solar dryer Drying rates: Solar: 0.0895 kg/h Biomass: 0.1877 kg/h, Collection efficiency: Solar dryer: 64%,	Chekol et al. (2021)
3	Solar heat pump + biomass furnace	West Sumatr, Indonesia	Red chili	–	11 h	70.5 °C	Dried quantity: 22 kg Moisture reduction: 4.26 to 0.08 db Open sun drying took 62 h Mass flow rate: 0.124 kg/s	Yahya (2016)
4	Flat plate collector + biomass dryer	PRIST-Puducherry	Cashew	–	7 h	65–75 °C	The designed system is suitable for drying 40 kg of cashews Fuel use: 0.5–0.75 kg/h Temperature range: 65–75 °C Drying time: 7 h Moisture reduction: 9 to 3% Overall, efficiency: 9.5%	Dhanushkodi et al. (2014)
5	Hybrid evacuated tube solar + electric	Beijing, China	Lotus bee pollen	–	–	40 and 50 °C	Significant economic benefits with payback less than 1 year	Wang et al. (2022)

Table 3 (continued)

S. no	Type of dryers	Drying type/place	Agro-product	Thickness (mm)	Drying time (h)	Temp (°C)	Research findings	Reference
6	Spiral solar air heater + auxiliary heating system	Horasan Razavi, Iran	Apple, banana, kiwi, quince	–	12.5 h, 23.5 h, 23.6 h, 24 h	45 °C	Drying period Apple slices: 12.5 h, Kiwi: 23.5 h and banana slices Quince strips: 24 h EUR: 0.9 and 0.7 for quince strips	Heydari (2022)

Opportunities:

- Solar dryers: growing demand for renewable energy sources, increasing consumer awareness of environmental issues, and potential for large-scale implementation.
- Biomass dryers: growing demand for sustainable energy solutions, increased availability of biomass resources, and the potential for local economic development.
- Hybrid dryers: rising demand for energy-efficient and cost-effective drying methods, the potential for improved drying quality, and the potential for reduction in energy consumption.

Threats:

- Solar dryers: competition from other renewable energy sources, potential government support reduction, and technical difficulties.
- Biomass dryers: competition from other renewable energy sources, potential reduction in government support, possible fluctuations in biomass prices.
- Hybrid dryers: competition from other drying methods, potential government support reduction, and technical difficulties.

SWOT analysis may vary based on the specific conditions and context in which the dryers are being used, as well as other factors such as the type of crop being dried, the local climate, and the availability of resources.

Specific design modifications and augmentation strategies suggested to improve dryer performance are as follows.

1. Increasing the collector area: This can be achieved by using larger or additional collectors to capture more solar energy, resulting in faster and more efficient drying.
2. Improving insulation: improved insulation of the drying chamber helps decrease heat loss, keeping the dryer chamber at a higher temperature for extended periods.
3. Optimal air flow management: Proper air flow is essential for efficient drying in a solar dryer. To promote consistent drying, the design should ensure that air flows smoothly and evenly through the drying chamber.
4. Enhanced heat retention: This can be achieved using heat storage materials with high thermal mass, such as bricks or concrete, to store heat within the dryer and release it over time.
5. Use of reflective materials: Reflective materials, such as aluminum sheets, can increase the collector's solar energy absorption and improve the dryer's efficiency.
6. Temperature control system: A temperature control system, such as a thermostat, can regulate the drying chamber temperature and ensure that the drying process occurs at the optimal temperature for the specific product.
7. Humidistat for moisture monitoring: A humidistat can monitor the moisture levels within the drying chamber and adjust the drying process accordingly.
8. Dehumidification system: A dehumidification system, such as a desiccant wheel or refrigeration system, can be used to remove excess moisture from the air within the drying chamber and improve the efficiency of the drying process.
9. Multiple tray system: A multiple tray system, in which drying trays are stacked on top, can increase the drying capacity and improve efficiency.
10. Supplementation with biomass or fossil fuels: Biomass or fossil fuels can supplement solar energy, providing additional heat when solar radiation is low or when faster drying is required. This can improve the overall performance and efficiency of the solar dryer.

Conclusion

This review study comprehensively examines evacuated solar tube dryers, biomass dryers, and hybrid solar dryers used for food product drying. The dryers' design, performance, and specific modifications are critically discussed. The analysis leads to the following main conclusions:

- Renewable energy–based dryers are the most sustainable choice, characterized by their simplicity in construction, operation, and maintenance. The heated airflow rate, driven by green energy, and product characteristics significantly impact the drying process's quality and quantity. Furthermore, the moisture content is crucial in determining thermal efficiency and product quality, regardless of the dryer design.
- Evacuated solar dryers offer numerous advantages, including energy efficiency, cost-effectiveness, and a clean and renewable energy source. However, they also present challenges like weather dependence and high initial costs.
- Biomass dryers exhibit certain disadvantages, such as limited drying capacity, dependence on biomass availability, and potential emissions. These factors should be carefully considered when evaluating the suitability of biomass dryers for specific drying operations.
- Hybrid solar dryers are more efficient and provide a flexible solution, protecting items from external contamination during severe weather and nighttime. However, their drawbacks include high capital costs and complex construction.
- Future dryer designs must consider technological, economic, social, and environmental factors to develop appropriate systems that meet specific drying energy requirements.
- The comprehensive assessment presented in this study offers valuable insights into the current systems and limitations of various dryers, providing a foundation for technological advancements and practical applications. It is expected that this study will serve as a guide for the design and optimization of solar-based dryers for drying a wide range of agricultural products

Author contribution Naveen Prabhu performed the literature search and data analysis and drafted the article. Dhanushkodi Saravanan supervised and critically revised the work. Sudhakar Kumarasamy co-supervised and contributed to the idea for the article. All authors read and approved the final manuscript."

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Declarations

Ethics approval Not applicable.

Consent to participate Not applicable.

Consent for publication Not applicable.

Competing interests The authors declare no competing interests.

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