Discover Energy

Review

Assessing the carrying capacity of solar dryers applied for agricultural products: a systematic review

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Abstract
Most of the review research papers previously published were mostly focused on solar dryer design, development, performance evaluation, modification, technologies of solar dryers, etc. There were no works of literature reviews that specifically concerned how much solar dryers can carry. So, the review gives some clues about the carrying capacity of solar dryers. Measuring or knowing solar capacity has critical importance in the drying industry. It helps to produce quality dried products, design efficient solar dryers, and provide valuable insights for researchers, engineers and policymakers involved in solar drying technologies. The current review systematically examines the relevant scientific literature published between 2000 and 2023. The exclusion and inclusion criteria were used to identify the documents. A total of 1230 studies were selected for analysis, encompassing a wide range of geographical regions, crop types, and solar drying technologies. Based on the review conducted; solar dryers (direct, indirect, mixed, and hybrid) can vary between 1 and 250 kg in capacity applied for agricultural products drying purposes. According to the reviewed articles, the minimum loading capacities designed and recorded in the first, second, third, and fourth quinquennial periods were 1 kg, 1 kg, 4.75 kg.m^{-2}, and 5.4 kg.m^{-2}, respectively. In the same order as the minimum, the maximum loading capacities observed in the stated quinquennial periods were 250 kg/per day, 250 kg, 70 kg, and 45 kg, respectively.

Keywords Agricultural products · Drying · Loading capacity · Quinquennial periods · Solar dryer technology

1 Introduction

As explored by [1, 2] drying is a common method of protecting agricultural products from microorganisms and a way of extending their shelf life for long periods safely. Drying can also be applied to facilitate post-harvest activities, plan the harvest season, provide long-term storage, increase the standard and decrease the output, which leads to a reduction of the requirement for storage space, transport, and distribution, to fetch better returns for farmers to maintain the viability of seeds, to harness direct or indirect ecological benefits and so on. However, as reported by [3] drying is very energy-intensive process that uses between 10 and 20% of total energy.

Agricultural items were typically dried in the open sun for a very long time and are still exercised especially in third-world countries. However, this type of drying system has many limitations. The main drawbacks as mentioned by [4] it does not have a control system, non-uniformity in the drying process, exposed to various impurities and dust,

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unprotected from rain, susceptible to windborne diseases, high labor cost, needs large areas and infected by various microbiological organisms, fungus, insects, and is eaten by rodents and other animal etc.

Another drawback of open-air solar drying dryers was highlighted by [5, 6]. Among the drawback listed by the authors were: open drying systems are not always suitable for a largescale production, long drying period, and so on. Thus, the limitation of open drying can be solved using solar dryer technology. As described by [3] solar drying is the most eco-friendly method for minimization of post-harvest loss and it can be used for different kinds of food products for long-term preservation with a minimum compromise to the product quality, texture, and color.

Solar drying systems of different kinds have been formulated, explored, evolved, and tested across numerous regions globally, resulting in different performances [7]. Solar driers can also be classified as open-air, indirect and direct solar dryings based on the drying mechanism [8]. According to [9] different types of solar dryers exist. based on different parameters based on airflow as active and passive, based on structure as even span roof type, un even span roof type, tunnel-shaped, parabolic type, and chapel shaped, based on energy back up system as chemical and thermal, etc. Many authors, researchers, and reviewers, etc. such as [10–16] were categorized solar dryers in different ways of classification based on different criteria's (Figs. 1, 2).

There are three discernible subcategories within both active and passive solar drying systems. These subcategories primarily differ in the configuration of system components and how they make use of solar heat. These categories are; integral type of solar dryers (can be exit as active or passive), distributed solar dryers (active and passive mode) and lastly, the combination of these two is called combined -mode types of solar dryers as shown in Fig. 3 [10]: encompass indirect, direct, and mixed configurations of solar dryers.

The difference between active and passive types solar dryers were described by [18] in the following paragraph. Forced convection dryers, also known as active solar dryers, use fans or pumps to move the heated air comes from collectors to drying chamber. On the other side, passive solar dryers rely on organic processes for air circulation and heating, such as buoyancy and wind pressure.

Integral-type natural-circulation solar-energy dryers, often known as direct solar dryers, feature transparent-walled drying chambers where crops receive direct solar radiation. This radiation both extracts moisture from the crop and reduces the air's relative humidity, enhancing its moisture-carrying capacity. In contrast, indirect passive solar dryers, such as trays inside opaque chambers heated by air from a thermo-symphonic solar collector, prevent direct exposure of

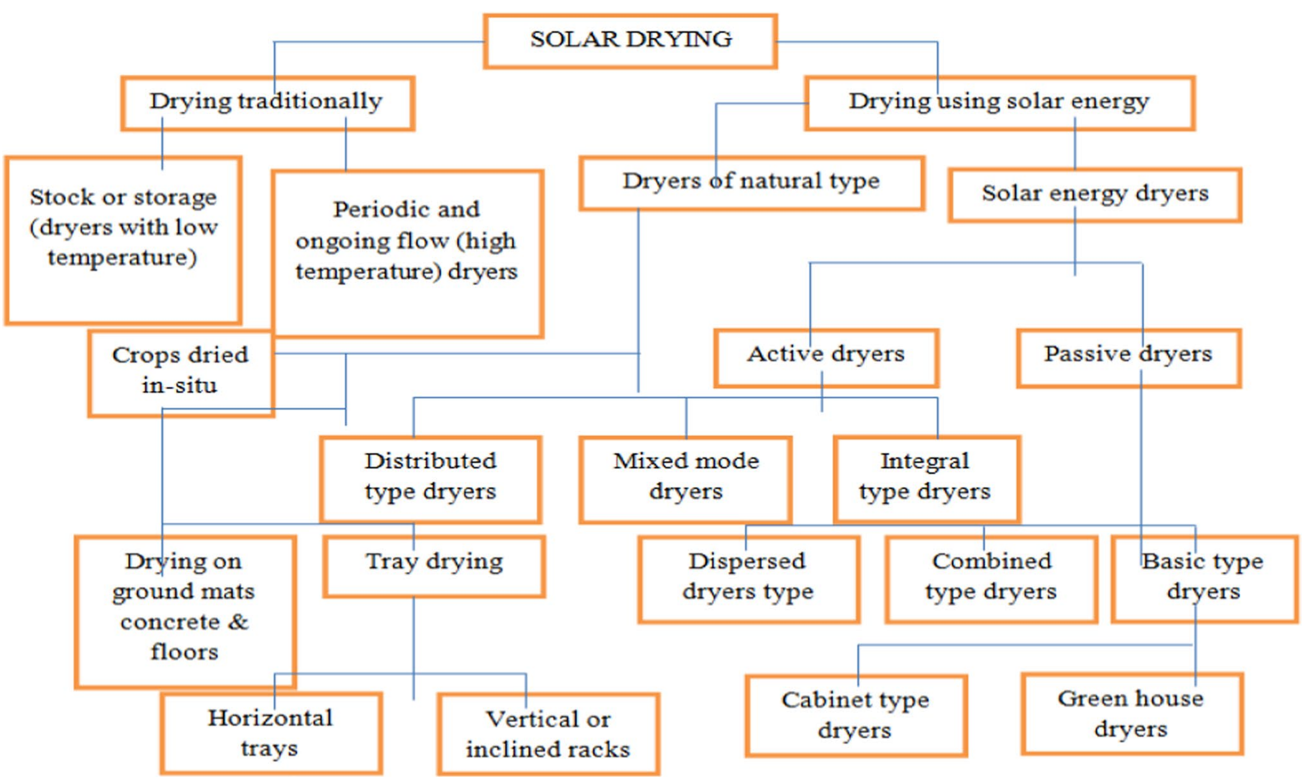


Fig. 1 Solar dryer classification [15]

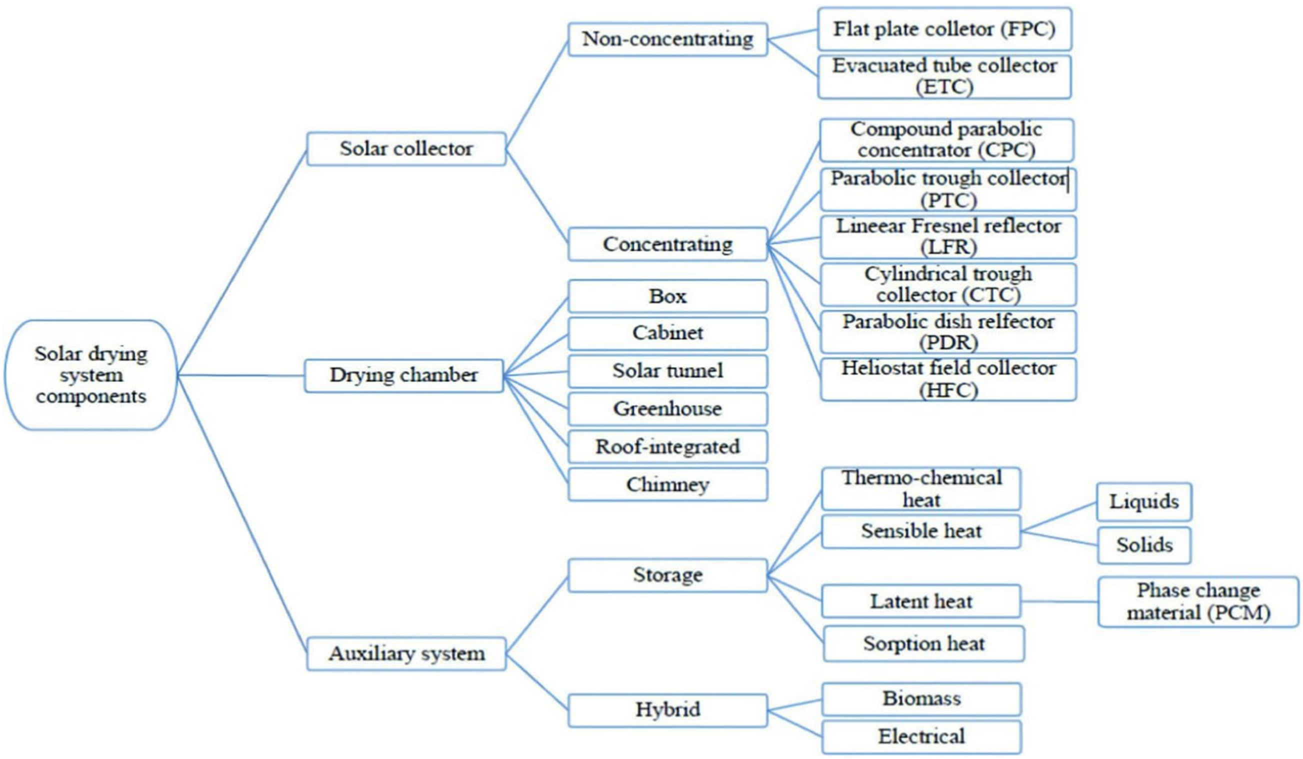


Fig. 2 Solar drying system components [17]

crops to solar radiation. This prevents caramelization and localized heat damage, making them suitable for perishables and fruits sensitive to vitamin loss and color retention issues caused by direct sunlight exposure. Distributed solar dryers achieve higher operating temperatures compared to direct dryers or sun drying [19]. See Fig. 3 for their arrangement.

1.1 Solar dryers' mechanism of operation and description

Solar dryers in general have different components to perform their intended task. A direct solar dryer for example as illustrated by [4] generally have a drying chamber consisting of an insulated box with air apertures that allow air to enter and exit the chamber and is covered in a transparent cover (glass or plastic). When sunlight reaches the glass cover, it warms the air that naturally circulates through wind pressure (passive solar dryer) or artificially circulates through wind pressure (active solar dryer). Similar to the idea of [20] wrote about solar dryers. They stated that solar dryers have translucent covers, which scatter some solar radiation back into the atmosphere while transmitting the remainder into the dryer chamber. The majority of the transmitted radiation is absorbed by the product, while part of it is reflected by its surface. As a result, the product's temperature increases, enabling evaporation to reduce its moisture content. See Fig. 4.

Solar air heater (solar collector), drying system (drying chamber), chimney, ducts for air supply, fans, etc. are the main components of passive indirect solar. However auxiliary parts like fans and blowers are add it is called forced type indirect solar dryer [22].

The general operating idea behind indirect solar dryers is outlined quite well by [23]. The explanation was as follows: air enters the collection through an air intake and heats up by convection after being collected by a solar collector that uses the sun's energy to do so. The glass that often encases the solar collector or absorber allows sunlight to enter while keeping the sun's rays reflected rays from escaping the collection. The bottom surface of the solar collector turns black as a result, which makes it excellent for absorbing solar radiation and raising the air temperature inside the solar collector. In the drying chamber, which contains the agricultural products or other materials to be dried, hot air from the solar collector is driven through the materials. The drying of objects in a drying chamber uses convective heat transfer and evaporative mass transfer. Following the application of heat to the products being dried, the air is discharged into the atmosphere via an exhaust system.

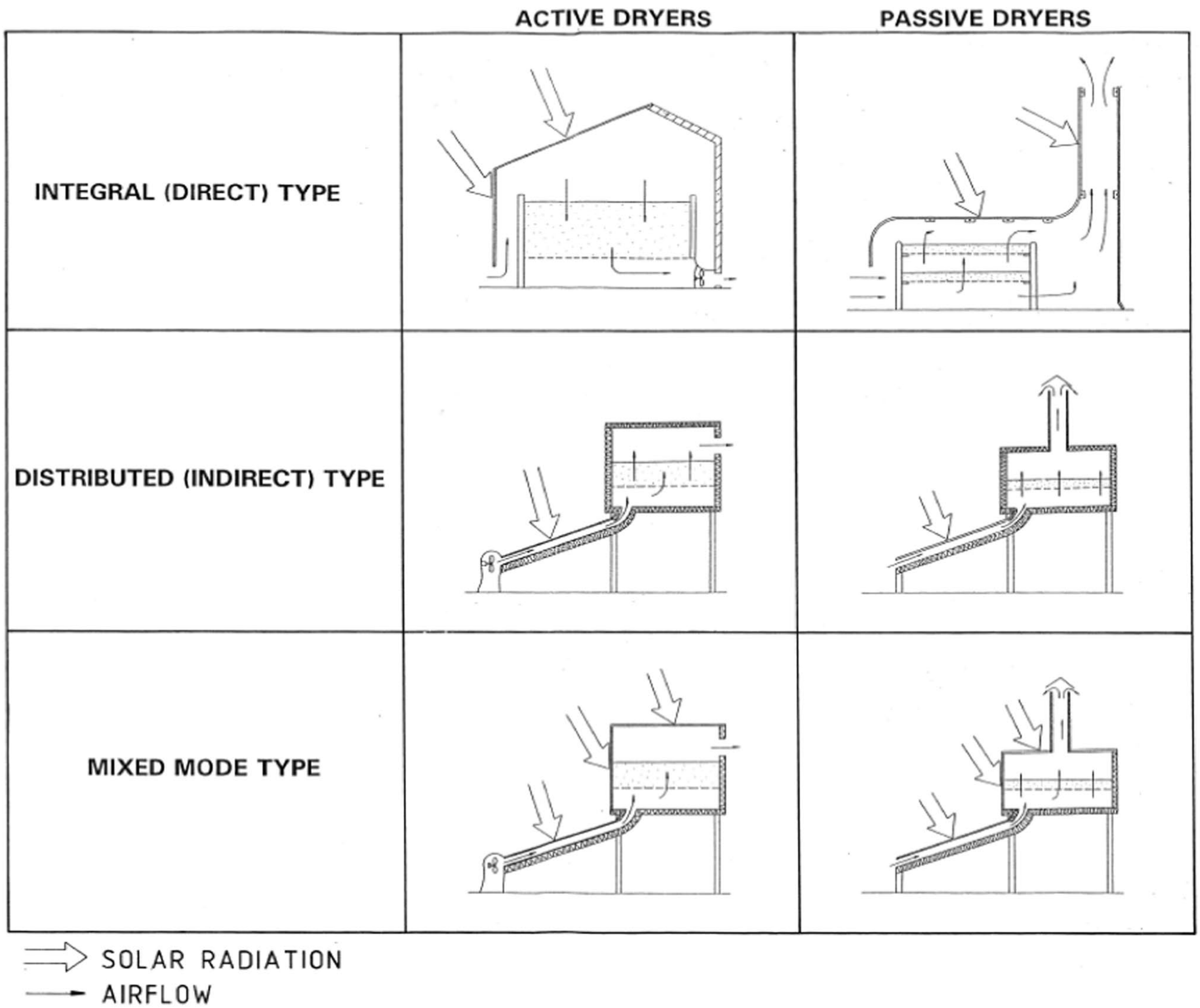
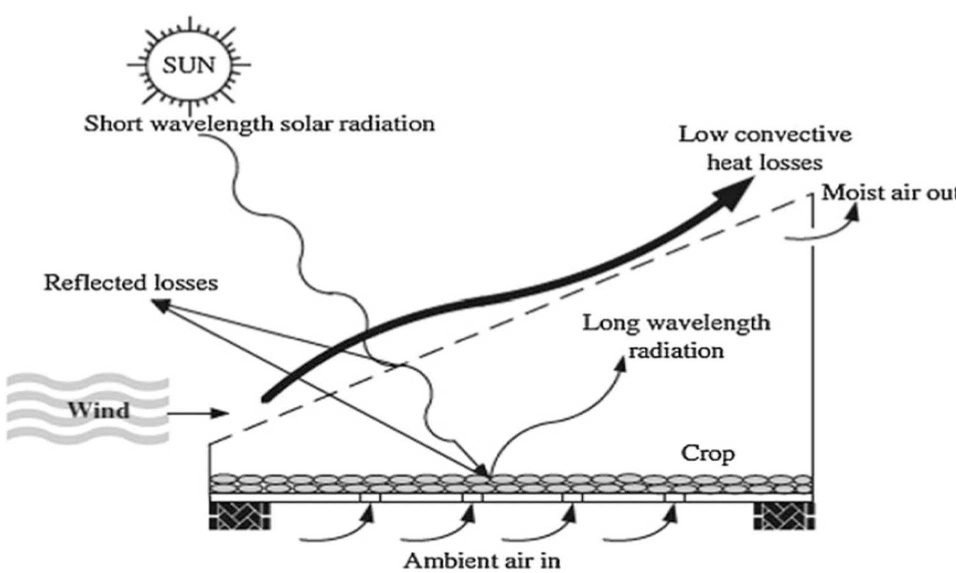


Fig. 3 Common solar dryer designs [10]

Fig. 4 Direct solar drying [21]



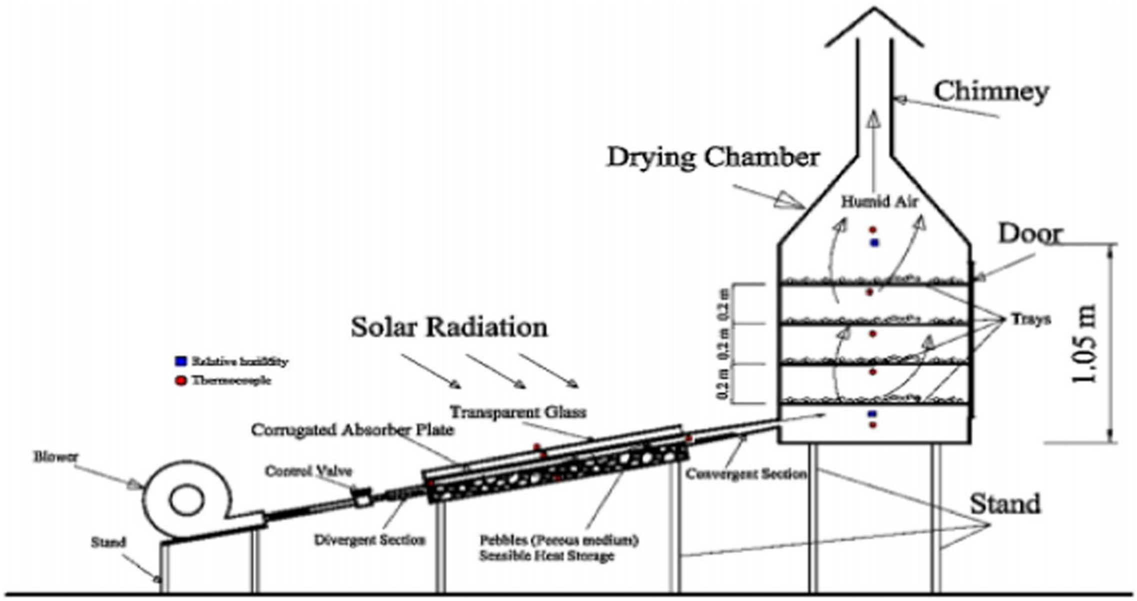


Fig. 5 Common layout of indirect solar dryers [12]

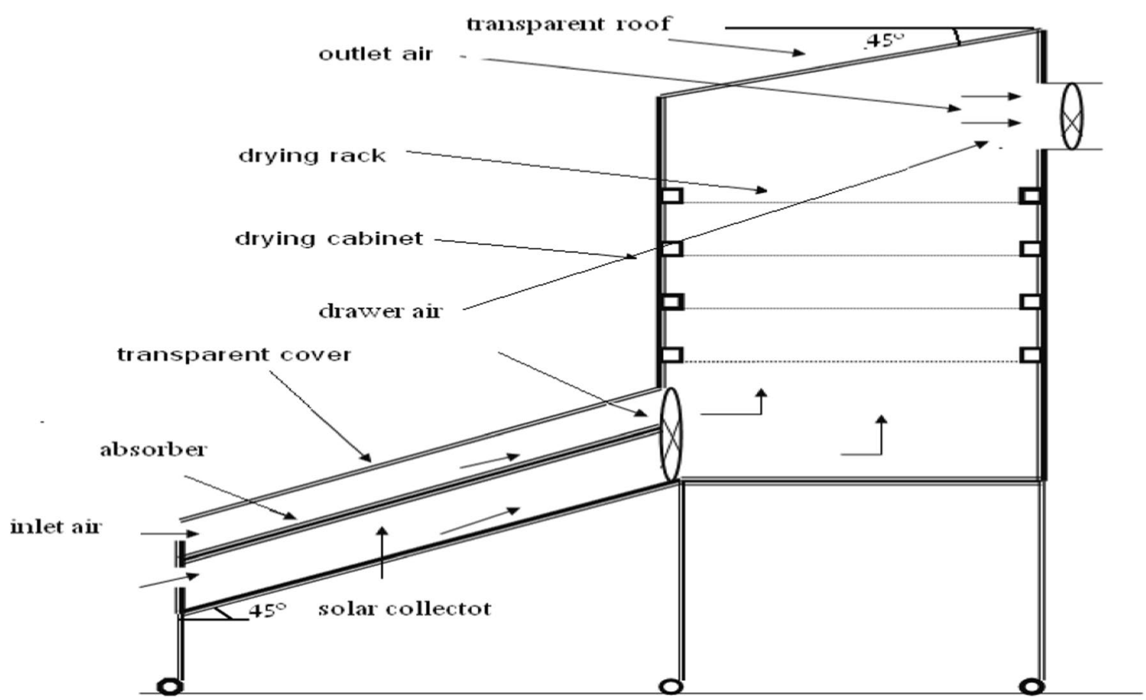


Fig. 6 Solar dryer with mixed modes [24]

Mixed solar dryers combine the benefits of direct and indirect sun energy dryers. The air is preheated in a solar collector heater in these dryers, and incident direct sun radiation on the product to be dried work together to produce the heat needed for the drying process [10]. Mixed type of approach is the most effective for products with higher moisture contents since the dried product's exposure to solar radiation and provided warm air expedite the drying process (Figs. 5, 6).

Authors like [25] clearly defines and states the difference between hybrid and mixed types of solar dryers as follow: hybrid solar dryers are unique due to their capacity to harness heat from multiple sources, including solar energy from the sun, as well as alternative sources like biomass and fossil fuels (see Fig. 7). Mixed-mode solar dryers are distinct from hybrid solar dryers in that they only use solar energy. The hybrid solar dryer, in comparison, uses a variety of energy sources, including biomass and solar energy. Even when there is no sunlight, the hybrid solar dryer can still function. Hybrid dryers shortens the drying process and lowers the chance of product waste.

1.2 Loading capacity of solar dryers

Solar dryers have variable loading capacities based on their design and size. Generally, they can accommodate a range of a few kilograms to several hundred kilograms of agricultural or other materials for drying. It is worth considering that the loading capacity is influenced by factors like the material being dried and the desired drying conditions. Moreover, diverse types various solar dryers, including batch dryers or continuous flow dryers, possess distinct loading capacities and operational characteristics. Knowing the loading capacity also helps full investigate quality of the products, economic viability of the dryers. Assessing the capacity helps estimate potential income generated from dried products, calculate return on investment, and make informed decisions about the profitability of the drying operation. It aids in determining the economic viability of investing in solar drying technology and guides users in optimizing their production and marketing strategies.

The physical size of the dryer, also known as batch drying capacity or loading density, is a direct indicator of the drying capacity and can be used to designate different drying chamber sizes and structures. This is the number of products (in kg of fresh products) that were dried in a single batch using the product's loading density. Drying capacity is primarily determined by the collector's aperture area, the dryer's size, the nature of the product prepared to dry or loaded, and its content of moisture. Loading capacity is among the parameters considered in the analysis of solar dryers [8, 27] convenience element is a crucial concern in the construction of a solar dryer.

The performance of cabinet-type solar dryers with the loading of 20 kg of wheat and under the unloading stage. Was compared by [28]. According to the results, the maximum plate temperature with a load of 20 kg of wheat was 45–50 °C, whereas the maximum temperature with no load was projected to be 80–85 °C during the noon hour. This implies that loading has an advantage over small loading capacity in terms of commercial purposes [29]. Investigated the effectiveness of a solar-powered device for drying produce. They used Grapes and apricots weighing 10 kg during their experiment. The result shows that the drying chamber has a 20% when drying 10 kg of grapes and a 33% efficiency when drying 10 kg of apricots. Thus, they conclude that even different products that have the same load, the dryer efficiency can vary. [30] tested a solar dryer at various loading capacities of 1500 g, 2000 g, and 2500 g, the drying process for shiitake mushrooms to reach a safe moisture content took approximately 15 h, 17 h,

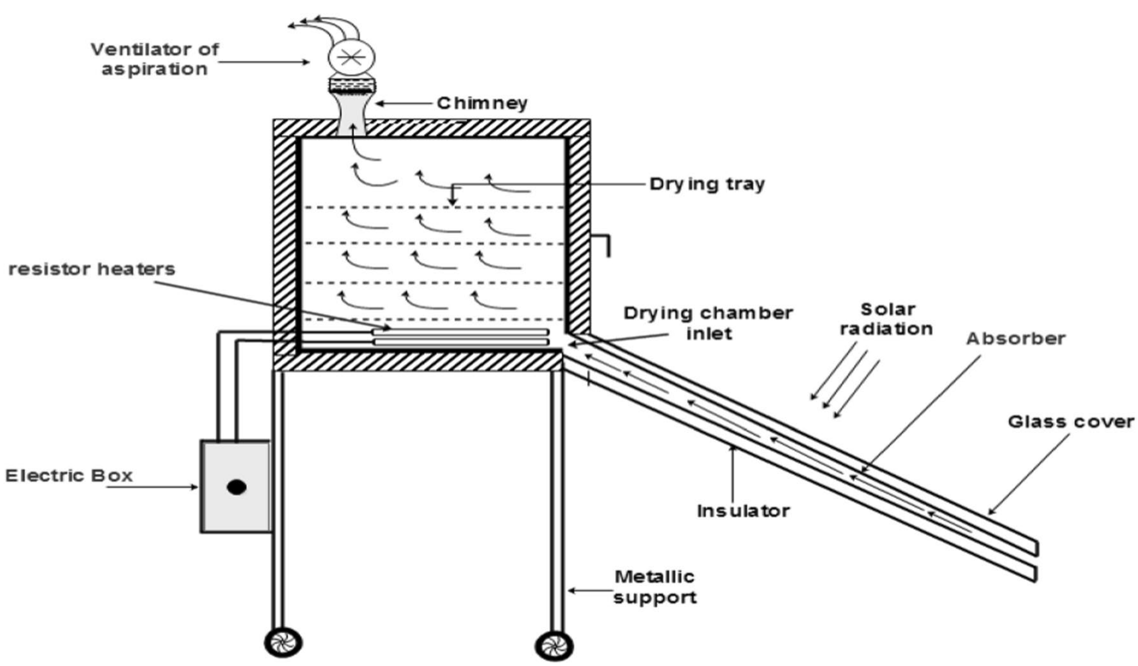


Fig. 7 Schematic representation of the hybrid solar dryer [26]

and 19 h, respectively. The time needed to warm the shiitake mushroom increased due to the increase in loading capacity. Additionally, it reduced the drying rate by lowering the average temperature in the drying chamber. On the other side higher loading capacity will result in an air exit from the drying chamber with a higher moisture content.

The effect of the load was also studied by [31] during their experiment, three trays containing 10 kg and 5 kg of evenly distributed tomato slices each were used for two sets of experiments. The drying rate increased for a load of 10 kg, by 8%, and for a load of 5 kg, by 14% [32]. Marked out that the simplest solar dryer setups are cabinet and greenhouse dryers, which employ passive drying. Due to their simplicity and low cost, cabinet dryers are typically built in 1–2 m^2 sizes with capacities ranging from 10 to 20 kg, they are suitable for drying produce, spices, herbs, etc.

The drying capacity is calculated using Eq. (1) [33]

$$\text{Drying capacity} = \frac{\textit{Initial Weight}(kg)}{\textit{Drying Time}(hr)} \tag{1}$$

The loading density of a solar dryer with more than a tray is computed as follows [34]

$$\rho_l = \frac{m_p}{A_c} \tag{2}$$

where:

m_p = mass of given product ready to dry (kg).

ρ_l = loading density ($kg.m^{-3}$).

A_c = Area of the solar collector (m^2).

2 Methodology

The main purpose of the review was to conduct an assessment of solar dryers' loading capacity for agricultural products. So, to achieve the main target of the research a systematic review approach was applied. This approach was used by a lot of authors and it was mostly exercised by social science and medical researchers.

As explored by [35] systematic review's use of explicit and rigorous procedures to locate, critically evaluate, and synthesize pertinent studies in order to address a specific question is one of its key characteristics. As stated by [36] systematic review is useful tool for those seeking to promote research knowledge and put it into action. As described by authors and co-authors of [37] despite being crucial components of evidence-based healthcare, systematic reviews and meta-analyses are still rather opaque.

The paper provides a review of many studies related to the capacity and size of solar dryers which were published in the last twenty-one years with the exception of solar tunnel dryers and other solar dryers applied to purposes other than agricultural products. The main databases or search engines used to collect the journal articles were Web of Science and Scopus i.e. (. conference papers, book chapters, technical notes, communications, reports, periodicals, case studies, and review papers are not included in the main topic of this review. However, in the introduction part, some review papers and books were included without any limitation on the year of publication. A total of 1230 documents were obtained from both data bases (i.e., Web of Science (685 documents) and Scopus (545 documents)).

In a systematic review, inclusion and exclusion criteria were employed to identify what data should be included in the review and to ensure that only papers relevant to the question(s) addressed by the literature review were included [36].

The focus of the exclusion and inclusion criteria, as outlined in Table 1, was primarily on the main part of the review, encompassing subsections like 1.2 (sub title) and the discussion section. The remaining sub-sections consisted of sources such as books, book chapters, and peer-reviewed materials that were published prior to 2000. Twenty-nine papers were used in the introduction part and around four documents were also used in the methodology part. In other words, thirty-three references in-validated the inclusion and exclusion criterions.

Table 1 Selection criteria of the systematic review of capacity solar dryers

Criterion	Inclusion	Exclusion
Publication type	Originals articles	Any other publication types
Availability of sources	Available online as full texts and freely accessed and sources subscribed by our university	Not available online as full form and paid
Language	English	Any other languages
Used solar dryer types	All types of solar dryers	Greenhouse solar dryers and open sun dryers
Type of products being dried	Horticultural products	Any other products
Documents published period	2000-August 2023	Any research published before 2000 and after 2021
Databases	Web of Science and Scopus	Any other databases

3 Discussion

To make it clear and easily understood the review was done by dividing it into four quinquennial periods (quinquennial periods is period of time occurring every 5 years).

3.1 First quinquennial period (2000–2005)

In this quinquennial period in all year, a lot of papers were published however only papers with specified written their drying capacity were included. In this quinquennial period, the minimum capacity was found 1 kg per batch that been created by [38] which was applied to dry lemon slice. The main finding of the research was lemon slices dried in a closed-type solar dryer had a higher overall in terms of sensory quality criteria. And in this quinquennial period the maximum capacity was 250 kg per day to dry onion and hay made by [39]. In the study the air temperature, the collector's surface, and the product quality were the main parameters that influence drying. In the year 2001 related to the solar loading dryer capacity specified literature was not found.

Authors in reference list [40] were designed a hybrid drier powered by solar and biomass with a 16 kg loading capacity for fruits and vegetables specifically bananas and chili. [4manufactured a 2–3 kg-capable air solar collector (ASC) attached to a rotating column cylindrical dryer (RCCD) that can dry apricots [42]. Used a solar dryer that has 9 kg loading capacity to investigate drying kinetics of pumpkinseed. The result reveals that the temperature of the air was the most important parameter that affected drying kinetics and increased the drying rate [43]. Used a solar dryer with a capacity of 5 kg to model a mathematically thin layer of apricots. And it has been demonstrated that the logarithmic drying model accurately depicts the apricots' sun-drying curve [44]. Demonstrated on an indirect type natural convection solar drier capable of drying 10 kg of chemically treated grapes or green peas in 20 h of sunlight. The authors' findings show that storage and chemical pre-treatment significantly shortened the drying times for all the crops they were used.

For drying agricultural products, a direct-type solar dryer with a burner was created by [45]. The researchers made a number of system evaluation tests, it was discovered that the dryer had a 20–22 kilo gram carrying capacity of fresh pineapple slices that were 0.01 m thick. In addition, they illustrated that integrating biomass burner with solar dryers increase the system efficiency [46]. Worked on the optimization of mixed-mode and indirect-mode natural convection solar dryers with a 90 kg grain capacity. The author comes to the conclusion that the indirect way of solar drying results in grain of a greater quality than the mixed approach.

A 5 kg carrying capacity included a solar air collector, a heat storage cabinet, and a solar chimney was designed, tested, and simulated of a unique low-cost tray drier with by [47, 48]. Conducted an empirical investigation on a solar-biomass combination dryer by subjecting it to a load trial using 18 kg of fresh ginger produce [49]. Studied the technical and economical viability and designed a solar dryer with a maximum batch size of 150 kg utilizing the products being dried and tested, chili and beef. As a result, drying beef with a solar dryer system was determined to be less expensive than drying chili with an electric heating system [50]. Tested how well a solar dryer performed utilizing hot air from solar collectors placed into the roof. In 4 and 3 days, respectively, the dryer can dry 200 kg of rosella flowers and lemongrass. Both as a solar collector and a farmhouse roof, the created solar dryer works well.

3.2 Second quinquennial period (2006–2010)

In this quinquennial period, the solar capacity dryer's capacity ranges between 1 and 250 kg. Among the developed solar dryers for instance researchers [51] built and tested built and tested three perforated trays stacked vertically accommodating 1.2 kg of fenugreek leaves to be used in household multi-shelf solar dryers [52]. Formulated innovative solar-enhanced drying setups capable of handling 10.3 kg of fresh tea leaves for the drying process [53]. Conducted an empirical study exploring forced convection and solar drying with integrated desiccant. The drying process focused on green peas as the drying product, while the drying tray was loaded at a density of 4 kg/m^2.

Researchers listed in reference [54] carried out an experiment to study the solar dehydration of preserved greengages. The drying chamber has the capacity to process 60 kg of salted greengages in one cycle. The results showed that the drying air inside the chamber was substantially warmer than the ambient air even on cloudy days [55]. Designed and examined a forced convection solar heat collector in a flat-plate configuration, intended for the drying of pre-treated cauliflower in batches of 100 kg each. The authors were used different pre-treatment chemicals. They found that Sodium chloride and sodium benzoate were not as effective as potassium metabisulphite in pretreatment process [56]. Assessed the effectiveness of a hybrid drier.150 kg of fresh turmeric rhizomes was used for the five distinct trials, and they were examined visually for any flows. The solar dryers with biomass have shorter drying times and higher-quality products than the open drying system.

A solar-assisted dryer was created, and the amount of energy needed to dry 2 kg of onions was assessed [57]. The result indicates total energy consumption reduced as the fraction of recycled air increased, and [58] utilized a drying chamber tray that has a loading density of 5 kg/m^2 to study the solar drying characteristics of strawberries. Increased surface area caused more moisture to evaporate while drying [59]. Developed, constructed, and tested an indirect type natural convection sun dryer with integrated collector-storage solar and biomass-backup heaters for drying twelve batches of fresh pineapple, each batch weighing around 20 kg. The researchers deduced that even in unfavourable weather conditions, the drying process was successfully accomplished when utilizing the solar-biomass operational mode [60]. Constructed and examined an indirect forced convection solar dryer that integrated a desiccant system. This setup was utilized to dry 20 kg of green peas and slices of pineapple and rice. Thus, they discovered that adding a reflective mirror to the desiccant bed enables solar drying with faster desiccant material renewal.

A semi-continuous solar drier for cereals was conceived, made, tested, and optimized by [61]. The dryer could hold up to 132 kg of rough rice at a time. They conclude that there was a substantial relationship between air mass flow rate and discharge interval time and rough rice moisture content along the dryer bed [62]. Introduced a mixed-mode natural convection solar crop dryer (MNCSCD) for drying crops like cassava. A batch of cassava weighing 160 kg was dried and examined [63]. Compared solar hybrid dryers and improved copra kilns to investigate the drying behavior and quality of copra. In each trial, 700 nuts were converted into around 147 kg of copra, and each batch's moisture content was reduced by about 116 kg [64]. Demonstrated experimental performance and modelled roof-integrated solar dryer's that can dryer up to 200 kg of fresh rosella and chilli. Good agreement was also found between experimental and simulated moisture contents.

A biomass burner, heat storage, and a backup heater for natural convection that was designed and tested by [65]. It was discovered through a series of system evaluation studies that the dryer could store 60–65 kg of newly harvested, unshelled groundnuts. They noticed adding heat storage with biomass burner to solar dryer increases the thermal efficiency [66]. Convection solar dryer used to dry cop. They observed the trays had different capacities for removing moisture content. Thus, the bottom tray was removing a little greater moisture than the top tray [67]. Built and tested a cabinet dryer for drying fruit and vegetables using indirect solar energy. During the test, a drier was used to dry 4 kg of fresh bitter gourd [68]. Made and evaluated a cabinet-style dryer designed for the dehydration of fruits and vegetables utilizing indirect solar energy. In the testing phase, the dryer was employed to desiccate 4 kg of freshly harvested bitter gourd.

The best design for a solar-assisted drying system for bananas was determined using a mathematical model. It has been used for drying since 2000 and has a capacity of drying 250 kg of bananas [69, 70]. Figured out how to dry apples using a heat pump and a sun dryer. For testing, a digital balance with a 6 kg apple capacity was employed. In the end, they find that raising the internal air consumption ratio raises the temperature of the drying air, but lowers the moisture absorption capacity of both heat pump and solar dryer dryers when the relative humidity of the drying air increases [71]. Examined the kinetics of drying tomato slices that had been dehydrated in a solar-electric drier using a drying chamber that held 6 trays and 12 kg. With $R^2 = 0.9999$, the Middli model emerged as the most reliable predictor of tomato slice drying behavior among the models tested [72]. Created solar dryer for cocoa beans that runs intermittently. A batch of 50 kg wet cocoa beans was intended to fit inside the prototype.

It has been developed and tested to work as a forced indirect convection solar drier in conjunction with numerous useful heat storage mechanisms. Performance for drying chill under the measured conditions at Pollachi, India by [73]. The dryer had the capacity to accommodate approximately 50 kg of chili per cycle. The conclusive assessment demonstrated that a solar dryer utilizing forced convection is more effective in generating superior quality dried chili, particularly suitable for small-scale farmers [74] built and assessed a double-pass solar dryer's effectiveness for drying red chili. A total of 45 kg of fresh chili was used for each experimental set. Red chilies were dried in central Vietnam using a double-pass solar dryer, which was found to be both technically and economically practical.

3.3 Third quinquennial period (2011–2015)

In a similar manner to the previous quinquennial period in this time frame also a lot of authors designed, and develop different solar dryers with different loading capacities. For example, For the purpose of drying red chili, a double-pass solar dryer with a 45 kg capacity was created, and its performance was assessed by [75] and contrasted with that of a standard cabinet dryer and the conventional open-air sun. The results demonstrate that, in order to achieve the desired moisture content of 10% (on a wet basis), the drying times (including nights) were 32 and 73 h, respectively. But even after 93 h (including nights), open-air solar drying is unable to achieve the desired moisture content of 10%. (On a wet basis) [76]. Designed and built a cylindrical solar drier with a 70-kg drying capacity that was used to dry bean crops [77]. Carried performed experiments and created a numerical model of a solar dryer with a packing density of the drying tray of 16 kg.m^{-2} to characterize apple slices. The authors learn more about the actual effects of interruptions on the product from the numerical simulations used in the intermittent tests.

A distinctive solar dryer for crops was designed by [78] providing uninterrupted drying capabilities and a capacity of up to 12 kg of freshly harvested green herbs, ensuring the retention of their flavor and vibrant color. Six crop trays with an effective size of 0.50–0.75 m^2 and a maximum collector area of 1.5 m^2 were included. As a result, it was discovered at Jodhpur in the middle of the night in June that the drying chamber's temperature was 6 °C higher than the ambient air temperature. This was because there was more storage material there [79]. Introduced laboratory models of direct (cabinet), indirect and mixed mode solar dryer were designed and constructed to perform no-load steady state experiments for natural and forced air circulation to determine convective heat transfer coefficient from plate to air of collector(h_{cpf}) (W/m^2 °C). The authors reported that natural convection cabinet dryers of the direct type with carrying capacity of 10–15 kg are popular among farmers, especially in India to dry 10–15 kg of fruits and vegetables at the household level A forced convection system powered by solar energy was designed by [80]. The solar dryer has a 6 kg loading capacity for drying fresh chili [81]. Examined the effectiveness of a solar-gas dryer combination. In the chamber, the load density was 4.75 kg per square meter of the tray. They conclude that the factors that had the greatest effects on the collector's thermal efficiency were air mass flow, collector angle of inclination, and the difference between the temperature inside and outside the collector. Additionally, they noted that while the hybrid drying system's effectiveness was comparable to that of a liquid propane gas (LPG) drying system, it had the benefit of utilizing 20% less fuel without compromising the dried product's quality (Fig. 8).

The life cycle cost of solar biomass hybrid dryer systems for drying cashew nuts, in India was investigated by [82]. A 40 kg loading capacity for renewable energy-based drying devices was suggested for use in small-scale cashew nut processing enterprises. To evaluate the viability of three renewable-based drying systems, four economic variables were evaluated. It was concluded that the development of a solar-biomass hybrid dryer was crucial for small-scale processing industries.

3.4 Fourth quinquennial period (2016–2023)

The drying process inside a chimney-dependent solar crop dryer (CDSCD) with a loading density of 5.4 kg/m^2 has been simulated and validated by [83]. The validation results indicate that the simulation code can serve as a valuable instrument for comparing and enhancing the design of CDSCD to achieve optimal drying performance [84]. Employing a double-pass solar air collector, heat pump, and photovoltaic unit, a novel form of solar dryer with a 6.1 kg capacity was conceived, built, and experimentally proven. The trial results showed that the double-pass collector had a thermal efficiency that ranged from 60 to 78 percent [85]. Conducted an experimental research and evaluation of a hybrid solar/thermal dryer with a capacity of 60–65 kg paired with an additional recovery dryer for drying fresh, unshelled groundnuts.

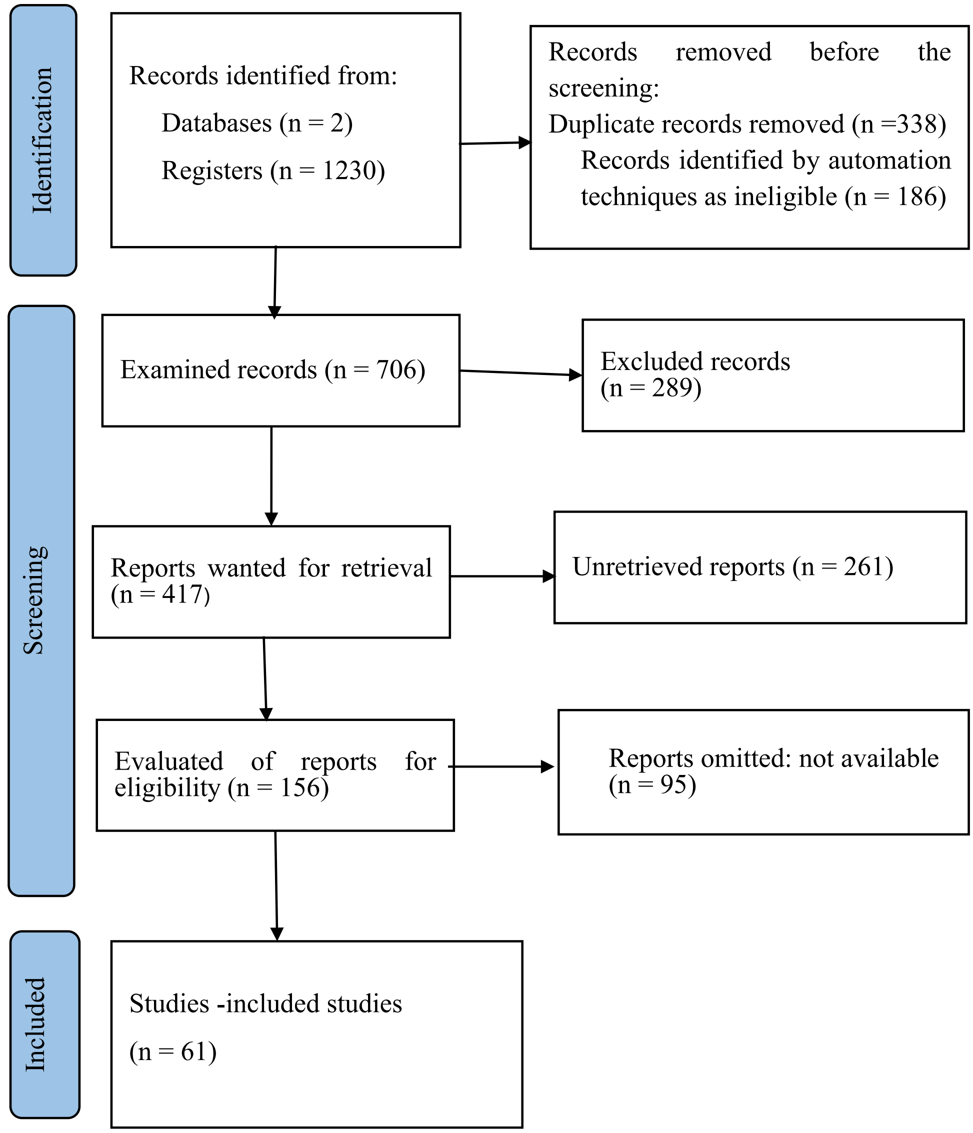


Fig. 8 Flow chart of the selection process

The overall drying efficiency increased from 10.3 to 13% when a hybrid dryer and recovery dryer were used, as opposed to hybrid drying alone. The use of sub dryers for thermal recovery was encouraged and confirmed enhancement way to maximize fuel efficiency and increase system capacity.

A solar air heater was created to assess the drying rate of apples. To enable a continuous drying process, an energy storage system was devised and produced for packed beds. Throughout the research, batches of apples weighing between 5 and 7.5 kg were dried using this equipment [86]. The importance of the developed system's was that, compared to other drying technologies, it uses 76.8% less energy [87]. Examined the energy and exergy used in the solar drying of ginger and ghost pepper. During the experiment, nine kilograms of newly harvested, ripe ghost peppers and thirteen kilograms of sliced ginger were dried. On the same year [88]. Examined the results of performance tests on a forced convection sun dryer and a shell and tube latent heat storage unit made of paraffin wax. Red chilies weighing 20 kg were dried in the dryer at a temperature range of 36–60 °C [89]. Introduced and studied the performance of an innovative solar drying system designed for the dehydration of osmotically treated cherry tomatoes. 100 kg of cherry tomatoes were osmotically dried in each of three batches between May and June 2014. In comparison to natural sun drying, the new solar drier significantly reduced drying time.

A multi-pass solar air heating collector system's thermal performance was studied for drying roselle by [34]. The purpose of the study was to evaluate the efficiency of a granite-enhanced forced convection multi-pass solar air heating collector (MPSAHC) system. A total weight of between 75.2 and 81.3 kg can be dried by the MPSAHC system. The MPSAHC dryer revealed a significantly faster drying time of 21 h when compared to the open sun drying method (OSDA), which was carried out concurrently under comparable weather circumstances [90]. Fabricated a solar energy dryer with a 10 kg capacity and examined for its performance in drying tomatoes.

An indirect forced convection sun dryer (IFCSD) with an extra heating source has been described by [91]. During the experiment, 24 kg of mango slices were dried at four different temperatures [92]. Locally created and tested active (forced) and passive (natural) modes for a 4 kg sun drying system [93]. Developed and evaluated both active (forced) and passive (natural) modes for a 4 kg solar drying setup on a local scale [94]. Examined how well a step-type natural convection sun drier worked for drying beans. For tests on dehydration, 5 kg of processed beans were spread out on 10 trays [95]. Carried out an experimental analysis of an indirect forced convection solar dryer with sensible heat storage material (SHSM) and phase change material (PCM) integration with a loading density of 9 kg/m^2 in the Himalayan climate (latitude 30.91°N). Performance evaluation of a packed bed thermal energy storage (TES) system-integrated solar dryer.

A Takagi Sugeno fuzzy (TSF) model was created for an indirect hybrid solar-electrical dryer operating under forced convection at a rate of 0.027 kg/s. by [96]. The drying chamber has a total capacity for four mesh trays, covering a drying area of 0.94 m^2. The TSF model was applied to forecast the drying temperature under no-load conditions [97]. Explored the drying behavior of orange slices that had an average thickness of 5 mm. Each experimental trial consisted of drying an average batch of 10 kg of orange [98]. Investigated how the solar drying technique affected the bioactive profile of Moroccan sweet cherry as well as drying kinetics. With a volume flow rate of 0.1845 m^3/s and constant temperatures of 60, 70, and 80 °C, 3 kg of cherries were placed on drying trays and dried for 8, 6, and 4 h, respectively [99]. Demonstrated how effectively bananas may be dried at home using direct forced convection. On a flat plate collector, a parabolic-shaped solar dryer was built, complete with a polycarbonate plate cover. 10 kg of bananas were dried for each batch [100]. Examine the drying model and assess the quality of the turmeric utilizing a solar thermal system. In addition, they did performance and quality testing of the 10 kg capacity INCSD is carried out at various drying temperatures. Experimental data show that the page model is more appropriate for INCSD and open sun drying (OSD).

The performance of a hybrid solar biomass dryer for drying shelled corn was enhanced by using an ANSYS workbench [101]. The drier can dry 90 kg (on a wet basis) of maize per batch. The study suggests that the hybrid solar biomass drier (HSBD) was appropriate for drying maize and other agricultural goods because continuous interrupted drying is possible. The dryer's ability to maintain a steady temperature and air flow in the drying chamber allows for the speedy production of high-quality dried goods [102]. Developed and evaluate the performance passive flat plate collector solar dryer for agricultural product with carrying capacity of 7. 5 kg used to dry mushrooms. They also compared with open drying system. And the results showed that after 21 h of developed dryer, the samples' moisture ratio was zero, whereas it took 33 h of open sun drying for the same sample to reach zero.

An assessment of the solar grain dryer designed by science for society (S4S) for the drying of paddy seeds was carried out by [103]. The capacity of the dryer was varying between 42.4 and 55.0 kg batch-1. Depend on the paddy the assessment of the dryer's efficiency and seed quality was conducted using established formulas and techniques [104]. Presented an innovative through-flow evacuated tube collector for air heating in an active-mode indirect solar dryer. Depending on the drying product, the tray-style dehydration chamber's loading capacity ranges from 6 to 45 kg. The study's concluding finding said that dried fenugreek leaves and turmeric were found to be of greater quality than open sun drying (OSD). When compared to the entire present value of life cycle savings, the capital cost of the solar dryer is negligible, according to its economics [105]. Devised, constructed, and assessed the effectiveness of a vacuum tube solar dryer engineered for the drying of garlic cloves. A batch of 10 kg of dried garlic cloves was employed to appraise the operational efficiency of the developed experimental setup.

Authors mentioned under number [106]. Evaluated in terms of performance and cost and modified solar drier with thermal energy storage that was used to dry blood fruit. The drying unit consists of two shelves with four aluminium plate trays of 20 kg drying capacity and an iron frame holder. Exergy analysis, energy payback period, carbon dioxide emissions, and cost payback period were conducted for the MSD (Modified Solar Dryer) and demonstrated superior results compared to the tray dryer (TD) The newly constructed solar dryer may be expanded to any capacity and will be perfect for small businesses and marginal farmers [107]. Investigated the practical testing of a residential solar dryer for drying bananas and introduced a modeling approach for optimizing banana drying using this solar dryer. The dryer was used to conduct 10 full-scale experimental runs, with 10 kg of ripe bananas being dried for each trial, to examine the experiment's performance. A set of partial differential equations that characterize the heat and moisture transfer in the process of banana drying was formulated and solved using numerical methods, specifically the finite difference method [108]. Designed innovative hybrid-solar-vacuum dryer with a maximum load of 4 kg to dry banana slices. The dryer was tested with persimmons and carrots, successfully producing dried and crispy products within 3–4 h. The hybrid solar dryer, operating in a vacuum environment, represents an innovative and environmentally friendly technology that consistently delivers high-quality products. It exhibits significant potential for adoption in small-scale farming operations.

A new method of drying cashew kernels has been introduced by [109] for the drying of cashew kernels. With the aid of this innovative technique, cashew kernels with a capacity of up to 30 kg solar dryer have been successfully dried in batches over the course of 360 min of solar radiation at an average energy consumption of 255 kJ. The results of the trials were supported using an artificial neural network (ANN) and response surface methodology (RSM), leading to improved performance parameter prediction and optimization [110]. Discussed the development and assessment of a cabinet-style shrimp drying system that combines both solar and an additional infrared heat source. The drying chamber can hold a maximum of 2500 g and operates at a 16.37 percent efficiency. The hybrid dryer has four drying modes and three different pre-treatment kinds.

A recirculating solar energy dryer equipped with an energy-saving feature and a recuperative heat exchanger has been designed for the purpose of drying agricultural products, with a capacity of loading 30 kg drying fresh product was developed by [111]. Additionally, a mathematical model has been introduced to describe the drying processes within this particular solar energy dryer. Among the models considered, the Henderson and Pubis model demonstrated the closest alignment between the calculated results and the experimental data [112]. Developed, tested and modified force convection sun dryer (MFCSD) for drying elephant apple slices. The MFCSD comprises of two solar collectors and a drying chamber with a 20 kg drying capacity. It was discovered that the two-term exponential model was very effective at describing the drying kinetics of elephant apple slices dried in MFCSD.

A solar dryer with a drying capacity of 15 kg has been created and manufactured specifically for mango drying purposes They were also evaluated the performance of indirect type forced convection solar dryer used to dry mango. Different performance indicators parameters such as instantaneous collector efficiency, drying efficiency, drying rate, coefficient of performance (COP), heat utilization factor, and moisture content on a dry basis were used to evaluate the performance of the dryer [113, 114]. Designed and presented prototype hybrid photovoltaic thermal (PV—T) solar dryer aided with an evacuated tube collector (ETC) with loading capacity of 1.5–2 kg for drying of cassava slices under the meteorological conditions of Thanjavur, Tamilnadu, India. The suggested hybrid dryer was profitable and able to produce high-quality dried products.

To reduce reliance on the non-renewable commercial tea drying technology, a sustainable solar-powered PVT tea drying system that can with loading of 4 kg of green tea has been developed and tested [115]. An indirect mode solar dryer utilizing forced convection and powered by photovoltaic technology (PVT) has been constructed and examined. 5 kg kilograms of tomatoes in total were dried in the PVT solar drier; one kilogram of tomatoes was dried in each drying tray [116, 117]. Evaluated the environmental and economic implications of a mixed-mode solar dryer that uses photovoltaic assisted with thermal energy storage and exhaust air recirculation. The dryer was designed to hold up to 5 kg of drying items and consist of two trays of 80 × 50 cm each.

For drying ber (Zizyphus mauritiana) fruit, a hybrid solar dryer with the drying load of 18 kg that combines photovoltaic and thermal (PV/T) technology was being designed and its performance assessed[118].assessed the performance and quality parameters of photovoltaic-thermal solar dryer with drying capacity of 2 kg for drying neem leaves. The aim of this study was to assess, through experimentation, how well a photovoltaic-thermal indirect mode solar drier performs when drying neem leaves in different weather situations throughout the year [119]. Developed a sustainable photovoltaic-thermal (PVT) solar drying system to maintain zero carbon emission in the drying process. A total of 2.5 kg of star fruits were used during the experiment, and each drying tray contained 0.5 kg of product. Sustainability indicators were evaluated using energy and exergy performance, and environmental and economic evaluations (4E) will be conducted for both forced convection drying (FCD) and natural convection drying (NCD) scenarios [120]. Assessed the performance and quality parameters of photovoltaic-thermal solar dryer with drying capacity of 2 kg for drying neem leaves. The aim of this study was to assess, through experimentation, how well a photovoltaic-thermal indirect mode solar drier performs when drying neem leaves in different weather situations throughout the year.

4 Conclusion

This comprehensive analysis explores the vital area of solar dryers in the context of preserving agricultural products. With the development of solar dryers, post-harvest losses in agricultural product have decreased and food security has increased. Solar dryers are a sustainable and environmentally friendly option for drying produce. To determine the carrying capacity of these solar drying systems, the study carefully evaluates a broad range of research articles covering various geographical regions and technology advancements. In conducting this review, we first embarked on a comprehensive search of peer-reviewed literature, conference proceedings, and technical reports to identify a diverse array of methods and technologies employed in solar drying chambers used for agricultural products.

The review's conclusions offer useful information for farmers, decision-makers, and researchers alike by illuminating the potential and restrictions of solar dryers in strengthening agricultural value chains. As mentioned in numerous articles, the temperature in the solar drying chamber was significantly elevated compared to the ambient temperature, even under overcast conditions. The quality of the dried products achieved by solar drying was on par with commercial branded products. The integration of heat storage by a biomass burner into the solar drying process increases its thermal efficiency. Among the parameters of the drying system, the air temperature is the most important. Higher temperatures lead to shorter drying time and higher efficiency. It was also found that increasing the surface area increases the moisture loss during the drying process.

"In conclusion, this systematic review offers a comprehensive assessment of the carrying capacity of solar dryers for agricultural products. Through an analysis of numerous research studies, it becomes evident that solar dryers hold considerable promise in mitigating post-harvest losses and promoting sustainable agriculture. The findings underscore the importance of continued advancements in solar dryer technology to enhance drying performance, reduce energy consumption, and improve overall cost-effectiveness. Furthermore, the environmental benefits of utilizing solar energy for drying operations are significant, contributing to a reduction in the carbon footprint associated with conventional drying methods.

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Author contributions Halefom Kidane: planned and collected the papers to be reviewed, analyzed, and interpreted collected and wrote Janos Buzás: Formulated and devised the review framework, conducted data analysis and interpretation, and supplied necessary documents Istvan Farkas: Advised and planned to write the paper; analyzed and interpreted the information; provided supplementary documents and data. Wrote the paper.

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Declarations

Competing interests The authors declare no competing interests.

References

1. Kant K, Shukla A, Sharma A, Kumar A, Jain A. Thermal energy storage based solar drying systems: a review. Innov Food Sci Emerg Technol. 2016;34:86–99. https://doi.org/10.1016/j.ifset.2016.01.007.
2. Tiwari GN, Shyam AT. Energy systems in electrical engineering handbook of solar energy theory, analysis and applications. Singapore: Springer; 2016.
3. Prakash O, Kumar A. Fundamentals of solar drying systems. In: Prakash O, Kumar A, editors. Solar drying systems. Boca Raton: CRC Press; 2021. p. 1–12.
4. Sharma A, Chen CR, Vu Lan N. Solar-energy drying systems: a review. Renew Sustain Energy Rev. 2009;13(6–7):1185–210. https://doi.org/10.1016/j.rser.2008.08.015.
5. Saleh A, Badran I. Modeling and experimental studies on a domestic solar dryer. Renew Energy. 2009;34(10):2239–45. https://doi.org/10.1016/j.renene.2009.03.001.
6. Sontakke MS, Salve SP. Solar drying technologies: a review. Int Refereed J Eng Sci. 2015;4(4):29–35.
7. Fudholi A, Sopian K, Ruslan MH, Alghoul MA, Sulaiman MY. Review of solar dryers for agricultural and marine products. Renew Sustain Energy Rev. 2010;14(1):1–30. https://doi.org/10.1016/j.rser.2009.07.032.
8. Leon MA, Kumar S, Bhattacharya SC. A comprehensive procedure for performance evaluation of solar food dryers. Renew Sustain Energy Rev. 2002;6(4):67–393. https://doi.org/10.1016/S1364-0321(02)00005-9.

9. Mohana Y, Mohanapriya R, Anukiruthika T, Yoha KS, Moses JA, Anandharamakrishnan C. Solar dryers for food applications: concepts, designs, and recent advances. Sol Energy. 2020;208:321–44. https://doi.org/10.1016/j.solener.2020.07.098.
10. Ekechukwu OY, Norton B. Review of solar-energy drying systems II: an overview of solar drying technology. Energy Convers Manage. 1999;40(1999):615–55. https://doi.org/10.1016/S0196-8904(98)00093-4.
11. Hage H, Herez A, Ramadan M, Bazzi H, Khaled M. An investigation on solar drying: a review with economic and environmental assessment. Energy. 2018;157:815–29. https://doi.org/10.1016/j.energy.2018.05.197.
12. Kumar P, Singh D. Advanced technologies and performance investigations of solar dryers: a review. Renew Energy Focus. 2020;35:148–58. https://doi.org/10.1016/j.ref.2020.10.003.
13. Lingayat AB, Chandramohan VP, Raju VRK, Meda V. A review on indirect type solar dryers for agricultural crops—dryer setup, its performance, energy storage and important highlights. Appl Energy. 2020;258:1–22. https://doi.org/10.1016/j.apenergy.2019.114005.
14. Srinivasan G, Rabha DK, Muthukumar P. A review on solar dryers integrated with thermal energy storage units for drying agricultural and food products. Sol Energy. 2021. https://doi.org/10.1016/j.solener.2021.07.075.
15. Joshi M, Kumar N, Baredar P. The optimization techniques used in solar dryers: a review. Int J Mechan Prod Eng Res Dev. 2019;9(4):83–92.
16. Mustayen AGMB, Mekhilef S, Saidur R. Performance study of different solar dryers: a review. Renew Sustain Energy Rev. 2014;34:463–70. https://doi.org/10.1016/j.rser.2014.03.020.
17. Kamarulzaman A, Hasanuzzaman M, Rahim NA. Global advancement of solar drying technologies and its future prospects: a review. Sol Energy. 2021;221(May):559–82. https://doi.org/10.1016/j.solener.2021.04.056.
18. Tolmare A. 2021. Study on Solar Dryers for drying Agricultural Products 1. 6(3), 54–57. https://ijaite.co.in/downloads/volume_6/issue_3/8.pdf.
19. Rawat P, Kumar S. Designing and construction of low-cost hybrid photovoltaic-thermal (pvt) solar dryer. Int J Creat Res Thoughts. 2022;10(May):890–8.
20. Kumar M, Sansaniwal SK, Khatak P. Progress in solar dryers for drying various commodities. Renew Sustain Energy Rev. 2016;55:346–60. https://doi.org/10.1016/j.rser.2015.10.158.
21. Sharma A, Shukla A, Aye L. Fundamentals and performance evaluation parameters of solar dryer. Low Carbon Energy Supply. 2018. https://doi.org/10.1007/978-981-10-7326-7.
22. Devan PK, Bibin C, Asburris Shabrin I, Gokulnath R, Karthick D. Solar drying of fruits—a comprehensive review. Mater Today: Proc. 2020;33:253–60. https://doi.org/10.1016/j.matpr.2020.04.041.
23. Hasan Masud M, Karim A, Ananno AA, Ahmed A. Sustainable food drying techniques in developing countries: prospects and challenges, prospects and challenges. Cham: Springer international publishing; 2020.
24. Gatea AA. Performance evaluation of a mixed-mode solar dryer for evaporating moisture in beans. J Agric Biotechnol Sustain Dev. 2011;3(4):65–71.
25. Abdul Razak A, Tarminzi MASM, Azmi MAA, Ming YH, Akramin M, Mokhtar N. Recent advances in solar drying system: a review. Int J Eng Technol Sci. 2021;8(1):1–13. https://doi.org/10.1528/ijets.8.1.2021.1001.
26. Zoukit A, El Ferouali H, Salhi I, Doubabi S, Abdenouri N. Fuzzy modeling of a hybrid solar dryer: experimental validation. J Energy Syst. 2019;3(1):1–12. https://doi.org/10.3052/jes.457645.
27. Fodor E. Design considerations for solar dryers. In: Fodor E, editor. the solar food dryer how to make and use your own high-performance, sun-powered food dehydrator chapter. Gabriola Island, B.C: New Society Publishers; 2005.
28. Jay Sharma S, Sharma VK, Jha R, Ray RA. evaluation of the performance of a cabinet-type solar dryer. Energy Convers Manag. 1990;30(2):75–80. https://doi.org/10.1016/0196-8904(90)90016-R.
29. Al-Juamily KEJ, Khalifa AJN, Yassen TA. Testing of the performance of a fruit and vegetable solar drying system in Iraq. Desalination. 2007;209(1–3):163–70. https://doi.org/10.1016/j.desal.2007.04.026.
30. Xu B, Wang D, Li Z, Chen Z. Drying and dynamic performance of well-adapted solar assisted heat pump drying system. Renew Energy. 2021;164:1290–305. https://doi.org/10.1016/j.renene.2020.10.104.
31. Teklu H, Bayray M, Abay D, Kalamegam M. Performance enhancement of natural convection indirect solar dryer by integrating reflectors. Momona Ethiop J Sci. 2021;12(2):212–22. https://doi.org/10.4314/mejs.v12i2.4.
32. Mehta P, Samaddar S, Patel P, Markam B, Maiti S. Design and performance analysis of a mixed-mode tent-type solar dryer for fish drying in coastal areas. Sol Energy. 2018;170:671–81. https://doi.org/10.1016/j.solener.2018.05.095.
33. Rome RJ, Samson C, Macabale N Jr. Drying capacity calculator program for paddy using sun drying and flatbed drying methods. CLSU Int J Sci Technol. 2022;6(2):37–47. https://doi.org/10.2213/ijst.2022.v6n2.04.
34. Kareem MW, Habib K, Ruslan MH, Saha BB. Thermal performance study of a multi-pass solar air heating collector system for drying of Roselle (*Hibiscus sabdariffa*). Renew Energy. 2017;113:281–92. https://doi.org/10.1016/j.renene.2016.12.099.
35. Aveyard H. Doing a literature review in health and social care doing a literature review in health and social care a practical guide, second edition. Nurse Res. 2011. https://doi.org/10.7748/nr.18.4.45.s2.
36. Lacey, J.K.J. son with L.M. and F.M., 2011. The systematic review. In doing Your Literature review Jill K. Jes son with Lydia Matheson and Fiona M. Lacey traditional and systematic techniques 103–127. https://doi.org/10.7748/nr.19.4.45.s7.
37. Khan KS, Kunz R, Kleijnen J, Antes G. Five steps to conducting a systematic review. In J R Soc Med. 2003;96:118–21. https://doi.org/10.1258/jrsm.96.3.118.
38. Chen HH, Hernandez CE, Huang TC. A study of the drying effect on lemon slices using a closed-type solar dryer. Sol Energy. 2005;78(1):97–103. https://doi.org/10.1016/j.solener.2004.06.011.
39. Bennamoun L, Belhamri A. Design and simulation of a solar dryer for agriculture products. J Food Eng. 2003;59(2–3):259–66. https://doi.org/10.1016/S0260-8774(02)00466-1.
40. Bhattacharya SC, Ruangrungchaikul T, Pham HL. Design and performance of a hybrid solar/biomass energy powered dryer for fruits and vegetables. World Renew Energy Congr VI. 2000. https://doi.org/10.1016/B978-008043865-8/50240-3.
41. Sarsilmaz C, Yildiz C, Pehlivan D. Drying of apricots in a rotary column cylindrical dryer (RCCD) supported with solar energy. Renew Energy. 2000;21(2000):117–27. https://doi.org/10.1016/S0960-1481(00)00077-X.

42. Can A. Drying kinetics of pumpkinseeds. Int J Energy Res. 2000;24(11):965–75. https://doi.org/10.1002/1099-114X(200009)24:11%3c965::AID-ER635%3e3.0.CO;2-W.
43. Toğrul İT, Pehlivan D. Mathematical modelling of solar drying of apricots in thin layers. J Food Eng. 2002;55(3):209–16. https://doi.org/10.1016/S0260-8774(02)00065-1.
44. El-Sebaii AA, Aboul-Enein S, Ramadan MRI, El-Gohary HG. Experimental investigation of an indirect type natural convection solar dryer. Energy Convers Manag. 2002;43(16):2251–66. https://doi.org/10.1016/S0196-8904(01)00152-2.
45. Bena B, Fuller RJ. Natural convection solar dryer with biomass backup heater. Sol Energy. 2002;72(1):75–83. https://doi.org/10.1016/S0038-092X(01)00095-0.
46. Simate IN. Optimization of mixed-mode and indirect-mode natural convection solar dryers. Renew Energy. 2003;28(3):435–53. https://doi.org/10.1016/S0960-1481(02)00041-1.
47. Vlachos NA, Karapantsios TD, Balouktsis AI, Chassapis D. Design and testing of a new solar tray dryer. Dry Technol. 2002;20(6):1243–71. https://doi.org/10.1081/DRT-120004050.
48. Prasad J, Vijay VK. Experimental studies on drying of *Zingiber officinale*, *Curcuma longa* l. and *Tinospora cordifolia* in solar-biomass hybrid drier. Renew Energy. 2005;30(14):2097–109. https://doi.org/10.1016/j.renene.2005.02.007.
49. Lhendup T. Technical and financial feasibility of a solar dryer in Bhutan. Energy Sustain Dev. 2005;9(4):17–24. https://doi.org/10.1016/S0973-0826(08)60496-2.
50. Janjai S, Tung P. Performance of a solar dryer using hot air from roof-integrated solar collectors for drying herbs and spices. Renew Energy. 2005;30(14):2085–95. https://doi.org/10.1016/j.renene.2005.02.006.
51. Singh PP, Singh S, Dhaliwal SS. Multi-shelf domestic solar dryer. Energy Convers Manage. 2006;47(13–14):1799–815. https://doi.org/10.1016/j.enconman.2005.10.002.
52. Othman MYH, Sopian K, Yatim B, Daud WRW. Development of advanced solar assisted drying systems. Renew Energy. 2006;31(5):703–9. https://doi.org/10.1016/j.renene.2005.09.004.
53. Shanmugam V, Natarajan E. Experimental investigation of forced convection and desiccant integrated solar dryer. Renew Energy. 2006;31(8):1239–51. https://doi.org/10.1016/j.renene.2005.05.019.
54. Li Z, Zhong H, Tang R, Liu T, Gao W, Zhang Y. Experimental investigation on solar drying of salted greengages. Renew Energy. 2006;31(6):837–47. https://doi.org/10.1016/j.renene.2005.05.008.
55. Kadam DM, Samuel DVK. Convective flat-plate solar heat collector for cauliflower drying. Biosys Eng. 2006;93(2):189–98. https://doi.org/10.1016/j.biosystemseng.2005.11.012.
56. Prasad J, Vijay VK, Tiwari GN, Sorayan VPS. Study on performance evaluation of hybrid drier for turmeric (*Curcuma longa* L.) drying at village scale. J Food Eng. 2006;75(4):497–502. https://doi.org/10.1016/j.jfoodeng.2005.04.061.
57. Sarsavadia PN. Development of a solar-assisted dryer and evaluation of energy requirement for the drying of onion. Renew Energy. 2007;32(15):2529–47. https://doi.org/10.1016/j.renene.2006.12.019.
58. El-Beltagy A, Gamea GR, Essa AHA. Solar drying characteristics of strawberry. J Food Eng. 2007;78(2):456–64. https://doi.org/10.1016/j.jfoodeng.2005.10.015.
59. Madhlopa A, Ngwalo G. Solar dryer with thermal storage and biomass-backup heater. Sol Energy. 2007;81(4):449–62. https://doi.org/10.1016/j.solener.2006.08.008.
60. Shanmugam G, Natarajan E. Experimental study of regenerative desiccant integrated solar dryer with and without reflective mirror. Appl Therm Eng. 2007;27(8–9):1543–51. https://doi.org/10.1016/j.applthermaleng.2006.09.018.
61. Zomorodian A, Zare D, Ghasemkhani H. Optimization and evaluation of a semi-continuous solar dryer for cereals (Rice, etc.). Desalination. 2007;209(1–3):129–35. https://doi.org/10.1016/j.desal.2007.04.021.
62. Forson FK, Nazha MAA, Akuffo FO, Rajakaruna H. Design of mixed-mode natural convection solar crop dryers: application of principles and rules of thumb. Renew Energy. 2007;32(14):2306–19. https://doi.org/10.1016/j.renene.2006.12.003.
63. Thanaraj T, Dharmasena NDA, Samarajeewa U. Comparison of drying behavior, quality and yield of copra processed in either a solar hybrid dryer on in an improved copra kiln. Int J Food Sci Technol. 2007;42(2):125–32. https://doi.org/10.1111/j.1365-2621.2006.01087.x.
64. Janjai S, Srisittipokakun N, Bala BK. Experimental and modelling performances of a roof-integrated solar drying system for drying herbs and spices. Energy. 2008;33(1):91–103. https://doi.org/10.1016/j.energy.2007.08.009.
65. Tarigan E, Tekasakul P. A small-scale solar agricultural dryer with biomass burner and heat storage backup heater. Proc ISES World Congr. 2007. https://doi.org/10.1007/978-3-540-75997-3_398.
66. Mohanraj M, Chandrasekar P. Drying of copra in a forced convection solar drier. Biosys Eng. 2008;99(4):604–7. https://doi.org/10.1016/j.biosystemseng.2007.12.004.
67. Sreekumar A, Manikantan PE, Vijayakumar KP. Performance of indirect solar cabinet dryer. Energy Convers Manage. 2008;49(6):1388–95. https://doi.org/10.1016/j.enconman.2008.01.005.
68. Janjai S, Srisittipokakun N, Bala BK. Experimental and modeling performances of a roof-integrated solar drying system for drying herbs and spices. Energy. 2008;33(1):91–103. https://doi.org/10.1016/j.energy.2007.08.009.
69. Smitabhindu R, Janjai S, Chankong V. Optimization of a solar-assisted drying system for drying bananas. Renew Energy. 2008;33(7):1523–31. https://doi.org/10.1016/j.renene.2007.09.021.
70. Aktaş M, Ceylan I, Yilmaz S. Determination of drying characteristics of apples in a heat pump and solar dryer. Desalination. 2009;239(1–3):266–75. https://doi.org/10.1016/j.desal.2008.03.023.
71. Boughali S, Benmoussa H, Bouchekima B, Mennouche D, Bouguettaia H, Bechki D. Crop drying by indirect active hybrid solar - electrical dryer in the eastern Algerian septentrional Sahara. Sol Energy. 2009;83(12):2223–32. https://doi.org/10.1016/j.solener.2009.09.006.
72. Fagunwa, A.O., Koya, O.A. and Faborode, M.O., 2009. Development of an intermittent solar dryer for cocoa beans,11 (1),1–14. https://cigrjournal.org/index.php/Ejounral/article/view/1292/1219.
73. Mohanraj M, Chandrasekar P. Performance of a forced convection solar drier integrated with gravel as heat storage material solar photovoltaic water pumping systems. J Eng Sci Technol. 2009;4(3):305–13.
74. Amer BMA, Hossain MA, Gottschalk K. Design and performance evaluation of a new hybrid solar dryer for bananas. Energy Convers Manage. 2010;51(4):813–20. https://doi.org/10.1016/j.enconman.2009.11.016.

75. Burnout J, Ehl P, Havlik J, Lojka B, Polesny Z, Verner V. Design and performance evaluation of a double-pass solar drier for drying red chili (*Capsicum annum* L.). Sol Energy. 2011;85(3):506–15. https://doi.org/10.1016/j.solener.2010.12.017.
76. Gatea AA. Design and construction of a solar drying system, a cylindrical section and analysis of the performance of the thermal drying system. Afr J Agric Res. 2011;6(2):343–51.
77. Ben Mabrouk S, Benali E, Oueslati H. Experimental study and numerical modeling of drying characteristics of apple slices. Food Bioprod Process. 2012;90(4):719–28. https://doi.org/10.1016/j.fbp.2012.02.001.
78. Jain D, Tewari P. Performance of indirect through pass natural convective solar crop dryer with phase change thermal energy storage. Renew Energy. 2015;80:244–50. https://doi.org/10.1016/j.renene.2015.02.012.
79. Singh S, Kumar S. Development of convective heat transfer correlations for common designs of the solar dryers. Energy Convers Manage. 2012;64:403–14. https://doi.org/10.1016/j.enconman.2012.06.017.
80. Seveda M, Seveda MS. Design of a photovoltaic powered forced convection solar dryer in NEH region of India Comparative multi-criteria life cycle and utility assessment analysis of different types solar energy. Int J Renew Energy Res. 2013;3(4):906–12.
81. López-Vidaña EC, Méndez-Lagunas LL, Rodríguez-Ramírez J. Efficiency of a hybrid solar-gas dryer. Sol Energy. 2013;93:23–31. https://doi.org/10.1016/j.solener.2013.01.027.
82. Dhanushkodi S, Wilson VH, Sudhakar K. Life cycle cost of solar biomass hybrid dryer systems for cashew drying of nuts in India. Environ Clim Technol. 2015;15(1):22–33. https://doi.org/10.1515/rtuect-2015-0003.
83. Afriyie JK, Rajakaruna H, Nazha MAA, Forson FK. Mathematical modeling and validation of the drying process in a chimney-dependent solar crop dryer. Energy Convers Manage. 2013;67:103–16. https://doi.org/10.1016/j.enconman.2012.11.007.
84. Şevik S. Design, experimental investigation and analysis of a solar drying system. Energy Convers Manage. 2013;68:227–34. https://doi.org/10.1016/j.enconman.2013.01.013.
85. Yassen TA, Al-Kayiem HH. Experimental investigation and evaluation of hybrid solar/thermal dryer combined with supplementary recovery dryer. Sol Energy. 2016;134:284–93. https://doi.org/10.1016/j.solener.2016.05.011.
86. Atalay H, Turhan Çoban M, Kıncay O. Modeling of the drying process of apple slices: application with a solar dryer and the thermal energy storage system. Energy. 2017;134:382–91. https://doi.org/10.1016/j.energy.2017.06.030.
87. Rabha DK, Muthukumar P, Somayaji C. Energy and exergy analyses of the solar drying processes of ghost chili pepper and ginger. Renew Energy. 2017;105:764–73. https://doi.org/10.1016/j.renene.2017.01.007.
88. Rabha DK, Muthukumar P. Performance studies on a forced convection solar dryer integrated with a paraffin wax–based latent heat storage system. Sol Energy. 2017;149:214–26. https://doi.org/10.1016/j.solener.2017.04.012.
89. Nabnean S, Janjai S, Thepa S, Sudaprasert K, Songprakorp R, Bala BK. Experimental performance of a new design of solar dryer for drying osmotically dehydrated cherry tomatoes. Renew Energy. 2016;94:147–56. https://doi.org/10.1016/j.renene.2016.03.0137.
90. Ibrahim AMH, Quick JS, Kaya R, Grandgirard J, Poinsot D, Krespi L, Nénon JP, Cortesero AM, Islam AU, Chhabra AK, Dhanda SS, Munjal R, Biosci IJ, Shaukat S, Khan AS, Hussain M, Kashif M, Ahmad N, Rehman SU. Evaluation of spring wheat genotypes for heat tolerance using cell membrane thermostability. Crop Pasture Sci. 2017;2(4):291–6. https://doi.org/10.1501/Tarimbil.
91. Wang W, Li M, Hassanien RHE, Wang Y, Yang L. Thermal performance of indirect forced convection solar dryer and kinetics analysis of mango. Appl Therm Eng. 2018;134:310–21. https://doi.org/10.1016/j.applthermaleng.2018.01.115.
92. Komolafe CA, Ojediran JO, Ajao FO, Dada OA, Afolabi YT, Oluwaleye IO, Alake AS. Modeling of moisture diffusivity during solar drying of locust beans with thermal storage material under forced and natural convection mode. Case Stud Thermal Eng. 2019;15:1–11. https://doi.org/10.1016/j.csite.2019.100542.
93. Abdul Razak A, Tarminzi MASM, Azmi MAA, Ming YH, Akramin M, Mokhtar N. Recent advances in solar drying system: a review. Int J Eng Technol Sci. 2021;8(1):1–13. https://doi.org/10.1528/ijets.8.1.2021.1001.
94. Davidson SJ, Gunasekar JJ, Prasanthkumar K. Drying performance of beans using natural convective step type solar dryer. Curr J Appl Sci Technol. 2020;38:1–7. https://doi.org/10.9734/cjast/2019/v38i630490.
95. Bhardwaj AK, Kumar R, Chauhan R. Experimental investigation of the performance of a novel solar dryer for drying medicinal plants in the western Himalayan region. Sol Energy. 2019;177:395–407. https://doi.org/10.1016/j.solener.2018.11.007.
96. Zoukit A, El Ferouali H, Salhi I, Doubabi S, Abdenouri N. Fuzzy modeling of a hybrid solar dryer: experimental validation. J Energy Syst. 2019;3(1):1–12. https://doi.org/10.3052/jes.457645.
97. Atalay H. Performance analysis of a solar dryer integrated with the packed bed thermal energy storage (TES) system. Energy. 2019;172:1037–52. https://doi.org/10.1016/j.energy.2019.02.023.
98. Ouaabou R, Nabil B, Ouhammou M, Idlimam A, Lamharrar A, Ennahli S, Hanine H, Mahrouz M. Impact of solar drying process on drying kinetics, and on bioactive profile of Moroccan sweet cherry. Renew Energy. 2020;151:908–18. https://doi.org/10.1016/j.renene.2019.11.078.
99. Nabnean S, Nimnuan P. Experimental performance of direct forced convection household solar dryer for drying banana. Case Stud Thermal Eng. 2020;22:100787. https://doi.org/10.1016/j.csite.2020.100787.
100. Nukulwar MR, Tungikar VB. Evaluation of drying model and quality analysis of turmeric using solar thermal system. Appl Sol Energy. 2020;56(4):233–41. https://doi.org/10.3103/S0003701X20040088.
101. Aukah J, Muvengei M, Ndiritu H, Onyango C. Optimization of the performance of hybrid solar biomass dryer for drying Maize using ANSYS workbench. J Energy Res Rev. 2020. https://doi.org/10.9734/jenrr/2020/v4i130119.
102. Babar OA, Tarafdar A, Malakar S, Arora VK, Nema PK. Design and performance evaluation of a passive flat plate collector solar dryer for agricultural products. J Food Process Eng. 2020. https://doi.org/10.1111/jfpe.13484.
103. Roy D, Saha CK, Alam MA, Sarker TR, Alam MM. Evaluation of s4s solar grain dryer for drying paddy seeds. Agric Eng Int CIGR J. 2020;22(4):200–10.
104. Singh S, Gill RS, Hans VS, Singh M. A novel active-mode indirect solar dryer for agricultural products: experimental evaluation and economic feasibility. Energy. 2021;222:1–10. https://doi.org/10.1016/j.energy.2021.119956.
105. Malakar S, Arora VK, Nema PK. Design and performance evaluation of an evacuated tube solar dryer for drying garlic clove. Renew Energy. 2021;168:568–80. https://doi.org/10.1016/j.renene.2020.12.068.

106. Kondareddy R, Sivakumaran N, Radha Krishnan K, Nayak PK, Sahu FM, Singha S. Performance evaluation and economic analysis of modified solar dryer with thermal energy storage for drying of blood fruit (*Haematocarpus validus*). J Food Process Preserv. 2021;45(9):1–16. https://doi.org/10.1111/jfpp.15653.
107. Nabnean S, Nimnuan P. Experimental and modelling performances of a household solar dryer for drying banana. Appl Sol Energy. 2021;57(1):34–43. https://doi.org/10.3103/S0003701X21010059.
108. Roratto TB, Monteiro RL, Carciofi BAM, Laurindo JB. An innovative hybrid-solar-vacuum dryer to produce high-quality dried fruits and vegetables. Lwt. 2021. https://doi.org/10.1016/j.lwt.2020.110777.
109. Huddar VB, Razak A, Cuce E, Gadwal S, Alwetaishi M, Afzal A, Saleel CA, Shaik S. Thermal performance study of solar air dryers for cashew kernel: a comparative analysis and modelling using response surface methodology (RSM) and artificial neural network (ANN). Int J Photoenergy. 2022. https://doi.org/10.1155/2022/4598921.
110. Abedini E, Hajebzadeh H, Mirzai MA, Alahdadi AA, Ahmadi HM, Salehi MA, Zakeri M. Evaluation of operational parameters for drying shrimps in a cabinet hybrid dryer. Sol Energy. 2022;233:221–9. https://doi.org/10.1016/j.solener.2022.01.045.
111. Nazarova NM, Nazarov MR, Juraev TD. Experimental validation of the mathematical model for a recirculating solar dryer. Appl Sol Energy. 2022;58(2):264–72. https://doi.org/10.3103/S0003701X2202013X.
112. Kondareddy R, Natarajan S, Radha Krishnan K, Saikia D, Singha S, Nayak PK. Performance evaluation of modified forced convection solar dryer with energy storage unit for drying of elephant apple (*Dillenia indica*). J Food Process Eng. 2022;45(1):1–18. https://doi.org/10.1111/jfpe.13934.
113. Behera DD, Mohanty RC, Mohanty AM. Performance evaluation of indirect type forced convection solar mango dryer a sustainable way of food preservation. Therm Sci. 2023;27(2):1659–72. https://doi.org/10.2298/TSCI220621154B.
114. Veeramanipriya E, Umayal Sundari AR. Performance evaluation of hybrid photovoltaic thermal (PVT) solar dryer for drying of cassava. Sol Energy. 2021;215:240–51. https://doi.org/10.1016/j.solener.2020.12.027.
115. Gupta A, Biswas A, Das B, Reddy BV. Development and testing of novel photovoltaic-thermal collector-based solar dryer for green tea drying application. Sol Energy. 2022;231:1072–91. https://doi.org/10.1016/j.solener.2021.12.030.
116. Gupta A, Das B, Biswas A, Mondol JD. An environmental and economic evaluation of solar photovoltaic thermal dryer. Int J Environ Sci Technol. 2022;19(11):10773–92. https://doi.org/10.1007/s13762-021-03739-8.
117. Zachariah R, Maatallah T, Modi A. Environmental and economic analysis of a photovoltaic assisted mixed mode solar dryer with thermal energy storage and exhaust air recirculation. Int J Energy Res. 2021;45(2):1879–91. https://doi.org/10.1002/er.5868.
118. Poonia S, Singh AK, Jain D. Design development and performance evaluation of photovoltaic/thermal (PV/T) hybrid solar dryer for drying of ber (*Zizyphus mauritiana*) fruit. Cogent Eng. 2018;5(1):1–18. https://doi.org/10.1080/23311916.2018.1507084.
119. Gupta A, Das B, Biswas A, Mondol JD. Sustainability and 4E analysis of novel solar photovoltaic-thermal solar dryer under forced and natural convection drying. Renew Energy. 2022;188:1008–21. https://doi.org/10.1016/j.renene.2022.02.090.
120. Gupta A, Das B, Biswas A, Deb Mondol J. Assessment of performance and quality parameters for drying neem leaves in photovoltaic-thermal solar dryer. Thermal Sci Eng Progress. 2023;43(June):101989. https://doi.org/10.1016/j.tsep.2023.101989.