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REVIEW ARTICLE

Comprehensive review on ideas, designs and current techniques in solar dryer for food applications

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Abstract

Due to the expansion of residents, the consumption of non-renewable energy increased enormously, thus indirectly increasing pollution and affecting the surroundings. To reduce pollutions in the surroundings, it is recommended to choose non-conventional energy sources. By satisfying this, we can probably decrease the non-renewable sources of energy, by consuming the solar power in day-to-day life in the application of food drying process. In this review article, we have discussed the classification of solar dryer and the impact of design modifications performed in the components of solar dryer and assessed the various types of solar dryer performance, cost estimations and designs performed in solar dryer of food applications which were not discussed in the earlier research. The primary and critical task in designing the solar dryer is to achieve higher efficiency at minimum cost. Hence, proper analysis of drying application, selection of suitable components and suitable design must be carried out to attain efficient dryer. Considering these characteristics, this paper primarily focuses on the effective design parameters incorporated with various efficiency enhancement processes of the solar dryer in the applications of food drying techniques. Thus, this review paper delivers the various classifications, design parameters, performance enhancement methods, properties and valuable assets of solar dryer, which helps to develop the sustainable green eco-friendly environment most primarily, in the application of food drying process. This review article concreted the way for upcoming considerations and provided the techniques for the studies to convey the work for promoting method enhancements.

Keywords Solar energy · Solar dryer · Design modification · Efficiency enhancement · Food application

Nomenclature

AHP	Analytic hierarchy process
ABF	Aluminium borate foams
Al_2O_3	Aluminium oxide
AWPFS	Active mix-mode wind-powered fan solar dryer
B_2O_3	Di-boron trioxide
$CaCl_2$	Calcium chloride
CFD	Computational fluid dynamics
CO_2	Carbon dioxide
COP	Coefficient of performance
CSAH	Concentrating solar air heater
CSP	Concentrating solar plants
$CuCr_2O_4$	Spinel copper chromite
$CuFeMnO_4$	Copper permanganate
DPISD	Double-pass indirect solar dryers
DPSC	Double-pass solar collector
DPSD	Double-pass solar dryer
DSD	Direct solar dryer
ECC	Energy consumption capacity
ETC	Evacuated tube collector
FA	Factor analysis
HIP	Hybrid indirect passive
HPD	Heat pump dryer
HTF	Heat transfer fluid
HAD	Hot air dryer
ICDC	Integrated collector drying chamber
ICSAH	Integrated concentrating solar air heater
INR	Indian rupees
ITSD	Indirect-type solar dryer

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LSM	Lanthanum strontium magnate
LPMO	Lytic polysaccharide monooxygenases
MMSCD	Multi-tray mixed-mode solar cabinet dryer
MPSAHC	Multi-pass solar air heating collector
NIFTEM	National Institute of Food Technology Entrepreneurship and Management
PV	Photovoltaic
PVC	Polyvinyl chloride
PVT	Photovoltaic thermal
PBTES	Packed bed thermal energy storage
SAC	Solar air collector
SAHPD	Solar-assisted heat pump dryer
SD	Solar dryer
SDS	Solar drying system
SHS	Sensible heat storage
SPE	Solar photovoltaic and electric
TES	Thermal energy storage
USD	United States dollar
UV	Ultraviolet
VWO_2	Vanadium dioxide
XRD	X-ray diffraction

Introduction

The heat from a solar dryer (SD) for food applications was twice as intense as the heat from the sun. While it is still 32 °C outside, a solar dryer may reach inside temperatures of up to 72 °C. This causes the dryers to quickly dry food goods by removing moisture, which is five times quicker than solar heating. Due to the shorter drying time, operational productivity will rise. Even on rainy days, solar dryers may be utilized. The drying technique is not ideal for a rainy climate. However, compared to a simple 26 °C ambient temperature, employing solar dryers may hold heat for up to 46 °C. Normal drying techniques cause problems during the rainy season as well as attract flies, dust and other germs. This is no longer an issue because solar dryers have enclosed spaces. A greater and higher-quality output will be received by farmers. Farmer income will finally rise as a result of this. Due to the one-time nature of the expenditure, unlike conventional dryers that use electricity, solar dryers are also less expensive to operate and maintain. Contrary to typical solar heating, where you need a lot of space to spread out the food goods for drying, solar dyers take up much less space since you can stack the products in trays and stack them on top of one another. Additionally, a distinct benefit of solar dryers is that they do not suffer from UV-induced colour fading. The colour and value of the food items are retained since there is a layer between them and the source of sunlight. Due to the above significant advantages, many recent improvisations were carried in the solar dryer for food drying applications. And these solar drying techniques were applicable to sub-tropical and tropical weather conditions. The drying mechanism depends on the solar thermal dryers, solar-assisted desiccant systems, geometrical parameters and different products. In desiccant system, the performance was affected by the properties of desiccant material, regeneration technique and dehumidifier design. Solar dryer performance is related to multiple drying chambers, optimization cum modelling and geometrical parameters. And it paved the way to enhance the characteristic performance of food product drying. It has been made evident how flow homogeneity affects how well a product dries. A new design strategy is suggested for a hybrid drying system to achieve greater flow uniformity (Husham Abdulmalek et al. 2018). Kamarulzaman et al. (2021) determined the existing dyers and collectors can produce a maximum efficiency of about 54% and 81% correspondingly, which is greater than the active solar drying method, and the payback period is up to 0.54–4.69 years. By using fossil fuel, the emission of CO_2 is reduced to 32% in the solar dryer system. Efficiency is enhanced by improving the auxiliary systems, solar collector and materials. An evaluation of the technologies can serve as a foundation for the successive creation of eco-friendly sun drying systems and aid in the formulation of plans for clean technology and sustainable development by policymakers. Getahun et al. (2021) elaborated the latest advances, opportunities and challenges in drying vegetables and fruits in solar dryer and also elucidated frequently used mathematical calculations for the models and design of solar dryer. The authors also explain about the factors affecting the performances of the system such as product quality, drying proportion, air velocity, product moisture and uniform drying temperature inside the DC. Computational fluid dynamics (CFD) is the best choice in the application of mathematical modelling technique and, also, in determining the optimum drying conditions of the product that can be retained with the dryer design. The authors also indicated that, however, the feature component or optimization studies were not included in the majority of CFD research. In addition to being able to forecast airflow, heat and moisture transfer characteristics, CFD-based assessment or optimization in dryers can be able to anticipate quality for the best results.

Bhaskara Rao and Murugan (2021) explained the variant solar drying methods and the factors affecting their performance. Also, the authors indicated that it is necessary to decrease or eliminate the moisture in herbs and other therapeutic plant components without compromising their efficacy. Drying provides longer shelf life, lower density and less expensive shipping. In the beginning of this study, several solar drying techniques and dryers, as well as the variables impacting their effectiveness, are reviewed and presented. Dake et al. (2021) illustrated the use of absorption substances to increase the efficiency of SD and highlighted the main characteristics concerning their use as dehumidification substances or TES. Furthermore, it shows that the solid adsorbent silica gel is mostly used as a composite material that is a combination of $Al_2H_2Na_2O_{13}Si_4$, Vrm, $CaCl_2$ and cement. The fusion of an absorption dehumidifier in the dryer commonly downgrades the aeration interval up to 15–30%. Introducing absorption materials as TES incorporated with solar dryer at the upper surface results in a drop of the interval in a span of 30–45%. Singh et al. (2018) explained that the solar radiant energy can be utilized by both straight and ancillary drying of agricultural food and non-agricultural products and that, in direct solar drying, the products were influenced by natural circumstances such as animals, insects and rain. To rectify the limitations of direct solar drying, several greenhouse dryers were proposed and data of already established greenhouses are provided so that new and modified greenhouse structures were developed. A greenhouse solar dryer should operate in dynamic mode rather than inactive mode, according to the authors. A PVT-integrated greenhouse dryer is the best option for remote places with limited availability to electricity. Gorjian et al. (2021) examined the destructive effect on food production in several regions due to political and climatic disasters; they also illustrated that these regions widely use agricultural greenhouses, and other drying technologies are deeply integrated. For future study, it is highly recommended that life cycle assessments (LCAs) and evaluations of the environmental effects of solar greenhouse projects be done. With further scientific and economic developments, the enactment of beneficial legislation and the creation of appealing mechanisms, modern solar greenhouses are anticipated to have a wonderful worldwide potential to promote sustainable growth in the agriculture sector in the near future.

Fudholi et al. (2010) analysed the categories of solar dryers constructed on the aspects of economic, the drying rate of products and technical aspects and also suggested to use water-based collectors rather than air-based collectors. The authors also emphasized that there are more systems than air-based solar collectors. Additionally, it is possible to use water-based collectors with a water-to-air heat exchanger. The hot water tank for the sun drying system functions as a heat storage mechanism. Tiwari et al. (2018) explored the photovoltaic thermal air collectors which are incorporated with the greenhouse solar dryer. The yearly production of electricity by using PVT air collectors is low in developed countries compared to developing countries. The output indicated that the overall performance is about 56.30% using PVT air collector. Lamidi et al. (2019) explained the involvements of drying and power, hybrid drying systems and PCM applications to agricultural products. Furthermore, the distribution of biomass-powered merged power and heat system is a better solution for drying. It is specified in this article that, in comparison, hybrid drying systems are competitive and promising. In order to optimize hybrid systems, modelling software that incorporates energy sources is crucial. In rural locations, a CHP system powered by biomass can be an excellent option for sustainable food drying. Lingayat et al. (2021) evaluated the solar-based dryer's utilization, in several marine, agricultural, tea, automobile, paper and pulp industries, and explained the usage of solar energy, lignite coal drying and sewage drying for the generation of power; variant types of dryers were used for assessing the performance. Finally, the environmental and economic features of dryers were also analysed. Raghavi et al. (2018) illustrated the impact of food drying quality in window drying methods which works on the underlying mechanism. This method provides economic way of drying methodology for mango pulp and result showed that the quality of drying is more efficient. Slices, purees and juices of exceptional quality can be dried using a refractive window. This method can retain the sensory and nutritional qualities of the active aromatic and pigment components, according to study. Mhd Safri et al. (2021) studied solar-assisted greenhouse dryers, such as active dryers, passive dryers and hybrid dryers, which depend on a collector's efficiency, the drying characteristics and the dyer performance of various paddies. By employing a solar-assisted greenhouse dryer consisting of PVC tubing covered in a UV film, the paddies may be protected from the wind, insects and rain. This approach significantly accelerates drying compared to natural convection. Fudholi and Sopian (2019) studied and examined the solar collector exergy and energy analysis based on certain efficiency levels of hybrid solar collectors and indoor testing; these models are established for the purpose of testing and evaluating other alterations. Some techniques are followed for improving the performance of solar collector, like extended surface, which uses fins, packed bed materials, artificial roughness and corrugated absorber. Mekhilef et al. (2011) studied the solar techniques in the application of industry integrated with solar energy systems. It is also highlighted how using solar energy may increase product quality and output while lowering greenhouse gas emissions. Both solar thermal and photovoltaic systems have been proven to be appropriate for use in several applications. However, the entire effectiveness of the system is dependent on the right system usage and solar collector design. Bal et al. (2010) elucidated the current and past investigation in the domain of TES technology for drying food products and explained the outcomes of storage division in which foods can be dried at twilight. The authors further mentioned that hybrid sun drying with thermal storage must be taken into consideration for the continuous drying of agricultural and food items at a regular and moderate temperature of 40–75 °C. Pirasteh et al. (2014) explained the enhanced technique to utilize solar resources in industrial drying sectors which incorporated the ECC, the need of energy for drying, the use of compatible dryers and also the economic and environmental features of solar dryer. Bennamoun (2011) found that the primary roles made in solar drying systems depends on the TES medium and indicates that the TES technology is very much suitable of storing heat. Kant et al. (2016) reviewed the functions of current dryers, incorporated with variant design terminologies and mathematical modelling for describing and predicting their behaviours. A PCM with a high surface area and huge heat of fusion for heat transmission is required for improved efficiency and is currently the subject of extensive research, according to the authors, who also illustrated significant challenges facing solar dryers based on the complexity of their practical application. Prakash et al. (2016) explained the modelling techniques that are essential for growth and increase the drying efficiency. By these modelling techniques, we found various activities of SD systems; in these drying methods, the airflow is constant and it also uses a heat transfer medium. By using these modelling techniques in solar drying systems, we could save time and save the long-term investment. Kumar and Rosen (2011) enumerated that the performance of thermal photovoltaic methodology and the photovoltaic thermal PVT air heater may be appreciable for air preheating. The combined PVT concentrators distribute higher energy per unit area of the collector than isolated thermal and PV systems. PVT requires further research in order to reduce costs, enhance performance characteristics and debug various technical problems correlated to collectors. Zarezade and Mostafaeipour (2016) analysed and determined the effect of several predominant risks and factors of the dryers. The analysis revealed that there were three risks and six predominant factors while constructing, designing and implementing the solar dryer system. As farmers become more aware of solar dryers, so will their desire to adopt them. This made it simpler to market these systems to both niche and general audiences.

Mustayen et al. (2014) described about various kinds of solar dryers, direct, mixed and indirect mode dryers as well as passive-mode SD and active-mode SD, which shows conceivable in drying agricultural foodstuffs in sub-tropical and tropical countries. To overcome the performance reduction, several improvisations were carried out in recent years. Mugi and Chandramohan (2021) elaborately explained about the factors of shrinkage, mass and heat transfer coefficient like water, air velocity, geometry of food and air temperature. The values of shrinkage are determined by performing on different mathematical models throughout solar drying of foodstuffs. Furthermore, the rate of mass and heat transfer coefficient of different solar dehydrating processes are explained. Mat Desa et al. (2019) summarized the examination of solar drying system, incorporated with PCM for drying agricultural foodstuffs. Future studies should focus on ways to improve and alter this technology in order to achieve quicker drying periods and constant heat supply. Bal et al. (2011) explained the various potentials of solar thermal applications irrespective of geographical, agricultural preservation techniques and technological challenges. Drying is an economic conservation method for figs such as feasibility nutritional and technical quality, and the three major drying systems were found to be artificial drying, solar-assisted drying and natural sun drying. The main factor was determined for the successful drying of figs, and drying temperature and drying time are calculated for the similar condition. El-Sebaii and Shalaby (2012) elaborated the applications of solar energy which are divided into two different types, namely, the thermal applications and the electrical applications. The thermal applications comprise of cooking, cooling, solar heating and drying. Hedayatizadeh and Chaji (2016) conducted the study on plum drying which is categorized into three groups as follows: plum drying kinetics, stimulation of plum drying and mathematical modelling, which are chemical/mechanical methods with the aim of conservation of energies. It is also indicated that drying methods are required to minimize the water content (dehydration) of plums in order to increase their shelf life and reduce shipping expenses. Meanwhile, it was discovered that pre-treatments applied to plum products are particularly beneficial for shortening drying times while maintaining good quality and using less energy. The simulation and mathematical models for the plum drying process are also thoroughly examined and summarized in the current review, which aids in identifying crucial temperature points and accurately forecasting the processes.

According to the findings of the literature study, none of the review papers offers a comprehensive assessment on the evaluation on various ideas, classifications of several food products drying, design and selection aspects of components associated with the solar drying, current techniques to improvise the thermal and overall performance in solar dryer for food drying applications and also the economic aspects of solar dryer in food product drying application. Therefore, an effort was made in this review article to examine the new developments in the solar dryer, various modifications made to its components, improvements in thermal and overall efficiency and economic implications of the solar dryer's modifications for the application of food drying. This review article's goal is to offer a detailed framework for future considerations and research methodologies that will be used to carry out work on future improvements to solar dryer systems. In order to present an overview and recent advancements in solar dryer for food product drying applications, this review paper has been divided into eight chapters. The 'Introduction' section discusses the introduction of the solar dryer and application of solar dryer in food application, and reviews work conducted by several investigators. The 'Nomenclature' section listed the nomenclature used in the review article. The 'Categorization of solar dryer' section discusses the overview and categorization of solar dryer based on several aspects. The 'Components and design considerations' section discusses the various design modifications performed in the components of the solar dryer to enhance the performance. The 'Methods to assist solar drying' section indicates the various methods to assist solar dryer to increase the drying rate and reduce the drying time. The 'System analysis and performance of solar dryer' section describes the system analysis and performance of solar dryer pertaining to thermal and overall efficiency enhancement. The 'Economic analysis' section explains the economic analysis of various modified solar dryers. The 'Scope for future work' elucidated the scope for future work for the researchers towards the solar dryer for food applications. According to the outcome in the above chapters, the main findings about the solar dryer for food applications were revealed in the 'Conclusions' section. The range of years and number of journals are distributed in Fig. 1. The distribution of the percentage of the number of journals corresponding to different parameters of solar dryer for food application is shown in Fig. 2.

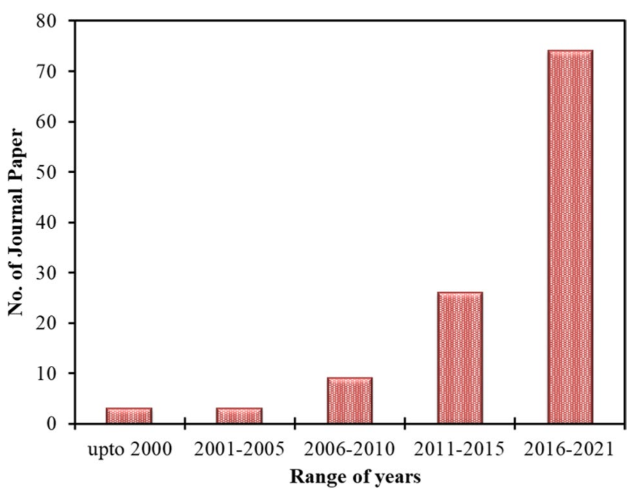


Fig. 1 Distribution of range of years and number of journal papers

Categorization of solar dryer

Various types of solar dryers had been used in the application of drying food products on the basis of design, material used for construction, energy standby methods and secondary heating units.

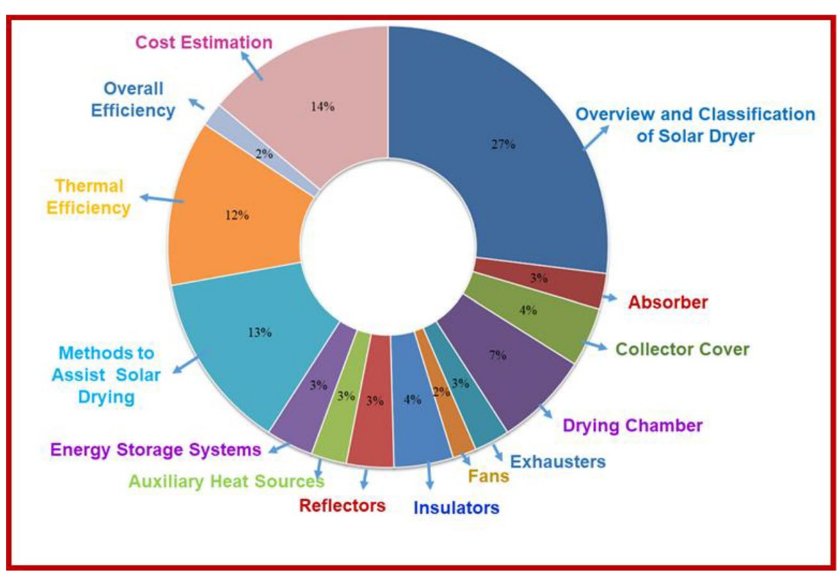
Categorization of solar dryer based on the movement of dried air

Solar dryer is classified into passive and active types depending on the various types of mobility of air used for drying.

Active mode

In this mode, the air movement is obtained through external technique by using a fan or pump and commodities like cabbage, papaya, tomato, kiwi, cauliflower and other commodities with moisture are dried using active mode. The drying rate of active mode is increased because of better air movement. Furthermore, nighttime drying can be performed with the help of this method and there are

Fig. 2 Percentage allocation of the several numbers of journal papers consequent to variant solar dryers in the application of food drying



minimum chances of loss. Chaouch et al. (2018) described indirect- and direct-type active solar dryer incorporated with a heat system, in the application of drying the camel flesh. Therefore, it is resulted that the thermal efficiency is enhanced by using heat storage system up to 28%, and the average drying efficiency is recorded for indirect- and direct-type active solar dryer as 18% and 7% respectively.

Passive mode

In this mode, the air movement strikes naturally by pressure variances or floating force or by combined. Passive mode is mostly used in many cabinets and greenhouse dryers (EL khadraoui et al. 2019). Fudholi et al. (2013) illustrated that within 33 h, red chillies have been dried from an estimated humidity content of 80–100%. When compared to direct air drying, the drying rate was reduced by 49%. It signifies that the environmental condition plays a major function in the efficiency characteristics of the passive-mode SD compared to other types. The low floating effect of air is reduced in passive-mode solar dryer (Chavan et al. 2021). Mohammed et al. (2020) indicated that the modified SD was a better variety of a traditional HSD that operated in the passive mode. An improved solar collector and a compromising food drying cabinet made up the improved solar dryer (ISD), and due to utilization of extra fans or accessories, it increases the initial and maintenance cost.

Categorization of solar dryer depends on the incident solar radiation on the product to be dried

Akamphon et al. (2018) explained that the solar dryer can be categorized into four different types as direct type, indirect type, mixed type and hybrid type.

This classification is examined by drying the products directly (or) indirectly under solar energy. The detailed classification of solar dryer is shown in Fig. 3.

Direct type

It is one of the traditional OSD where the material is covered with a transparent sheet and placed directly under the sunlight for drying (Ameri et al. 2018). The solar radiations pass through the transparent sheet; then, the material and its surrounding absorb the radiation. These dryers are also called as cabinet dryer. The temperature will get enhanced when the absorption rate of solar radiation gets increased. In this method, the temperature gets increased in the inner part of the chamber which dries the moisture content in the product (Kumar et al. 2016). Due to improper drying of the material, this method cannot be used for drying the products in a large scale.

Indirect type

When compared to direct-type solar dryers, this dryer's material characteristics and thermal performance are improved. In last few years, it is used for drying biodegradable food products like gooseberry, mango, meat, banana, chilli and tomato (Moses et al. 2013b). Shorter drying times, better product quality, fewer floor space needs, lower operational expenses, minimal heat losses, increased flavour compound retention and better rehydration qualities were included. Samples dried at 720 and 900 W had a better rehydration capability. The quality of traditionally dried coconut powder was found. The microwave approach can be utilized to produce higher-quality end results (Moses et al. 2013a, b). Mohanraj and Chandrasekar (2008) stated that forced convection type of SD is used for dehydrating copra in the tropical

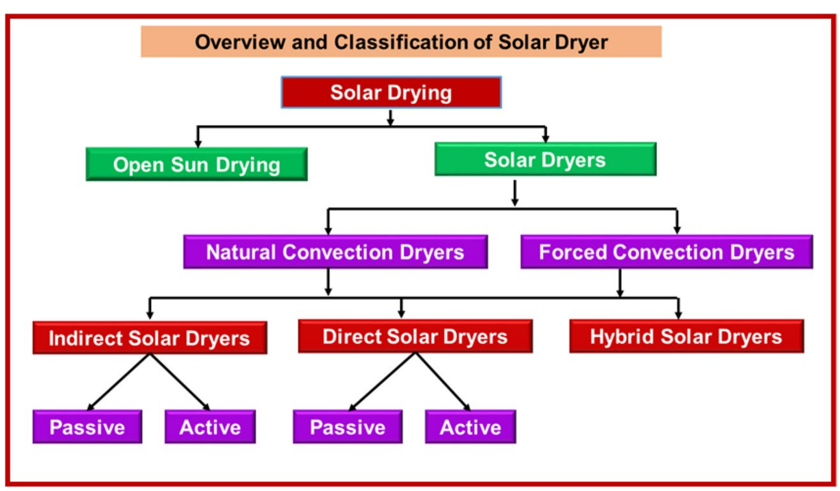


Fig. 3 Categorization of solar dryers (Udomkun et al. 2020)

climate. The thermal performance is increased by 24% and the removal moisture is enhanced by 7.8% and 9.8% in both the top and bottom trays, respectively, for 82 h. The dried copra is obtained in high quality. In order to dry the cashew nuts, an indirect type of SD is most suitable (Dhanushkodi et al. 2014).

Mixed type

The mixed-type solar dryer works on both indirect- and direct-type SD and is provided with an apparent chamber and also an air preheater (Shalaby et al. 2014). In this type of dryer, the food is dried based on the heat transfer from the air preheater and transparent sheet, which permits the solar radiation to dry the chamber (Dhalsamant et al. 2018). As a result, the mixed-type SD performs better in terms of thermal properties than the other kind of SD. The drying period for moisture is less in this sort of solar dryer than it is in other ways. Therefore, the overall drying efficiency and average energy efficiency are increased by 33.5% and 59.1%. Also, the quality of stevia leaves is better than any other conventional methods. For drying biodegradable food like tomato, beans, red pepper, banana, seafood and turmeric, mixed-type solar dryer can be used (Lakshmi et al. 2019).

Categorization of solar dryer based upon the design/construction

The water-based solar collectors were classified into four categories: hybrid PVT-greenhouse SDS, dehumidification system, chemical heat pump and mechanical heat pump with heat exchanger (Fudholi et al. 2015). Hot air technique works based on a complete solar PV collector and built in this research to improve comprehensive renewable power utilization efficiency (Kong et al. 2020). The condition to beneficially use the incident solar energy, the main wastage of solar fraction takes place from the northern wall is eliminated by using proper insulation (Chauhan and Kumar 2018). To control this wastage, researches have investigated the capability of utilizing the packed bed thermal method, mirrors (Singh and Sethi 2018) and PCM (Azaizia et al. 2020). Tunnel dryer is one type of greenhouse dryer; the drying cover and the walls of the tunnel dryer are fabricated with transparent materials like fibreglass and UV-stabilized plastics (El Hage et al. 2018). To dry huge number of commodities, tunnel solar dryers were chosen. Normally, to arrest the pollution in the product, this type of dryer is provided with a physical shelter. With small drying period, tunnel solar dryer can be able to produce a high-grade food product (Wilkins et al. 2018). Tent-type dryer is also one type of greenhouse dryer, which promotes good absorption of solar energy due to its triangular wooden structure enclosed with a black plastic sheet. An erected platform is provided high above the ground level to dry the food materials. Air inside the tent is drifted using the vent at the top (Mehta et al. 2018). On comparing with the passive mode, these solar dryers are affordable and take shorter time to dry equal amount of food to a stable humidity level. But these solar dryers did not retain their performance at higher speed winds. Hence, this solar dryer is not appreciable. In tent solar dryer, biodegradable items like vegetables, fruits, chicken, mutton and fish can be dried. Mishra et al. (2019) investigated and determined the common constrains implemented in evaluation along with testing of variant categories of solar dryers in the application of drying the foods and various types of solar dryer nearly 66 variants with their capacity, configurations, cost and the products dried. Various ranges of design and size were available and used for the application of drying the food products. Khaing Hnin et al. (2019) analysed that the majority of drying systems were primarily categorized into two such as low- and high-temperature dryers. Then, the basic types of solar dryers are categorized into various categories depending on the solar energy dryers and the heating sources into fossil fuel dryers. The result revealed that the efficiency is enhanced by using the auxiliary heating sources but it requires maintenance, capital and operational cost.

Hybrid solar dryers

López-Vidaña et al. (2013) described that the dryers have also been constructed with supplement element which acquires the solar energy through the daylight and uses the stored energy in the nighttime. The heat sources like solar-assisted secondary TES, mechanical heat pump or forced convection system are the other drying methodologies which are combined with the solar dryers. Leon et al. (2002) studied the characteristics of solar dryer works on the solar radiation which acts as primary heat source. Ekechukwu and Norton (1999) declared that using solar liquefied petroleum gas (LPG), the drying characteristics of tomato are detailed. Solar, LPG and hybrid modes are the three modes in which hybrid dryer is operated; the result proclaimed that drying performance of the combined systems was lesser when compared to LPG mode. Misha et al. (2015) explained that the hot water was used in the application of solar drying system (solar desiccant). The thermal energy storage reserve was served by hot water which is a desiccant. For the supplement of heat required, electrical heating arrangement was provided. Results revealed that drying time was diminished prominently by 24% by using thermo-electrical combined solar dryer. Amer et al. (2018) mentioned that the dryers for the purpose of drying of cashew nuts, peppermint, mushrooms and banana can ensure for the safety precautions of the food products. Soto-Gomez et al. (2000) designed, operated, constructed and energetically evaluated the solar dryer which does not affect the ozone layer and does not contain chlorine for the application of drying the grains.

Components and design considerations

The solar dryer comprises of basic parts like absorber, collector cover, drying chambers, exhausters, fans, insulators, reflectors, auxiliary heat source and energy storage systems. To enhance the characteristic of the SD, several designs were evolved to produce the higher quality of dried food products.

Absorber

Solar absorber is a vital component in the solar dryer. Solar absorbers are designed by metallic alloy tubes. Kim et al. (2016) evaluated the bi-layered tandem construction of solar absorber surface made of a spongy $CuFeMnO_4$ and a dense $CuCr_2O_4$ as top and bottom layer, which is a nanoparticle. This layer is used to enhance the absorption rate in the infrared and visible regions. The tandem construction laid out a best flavour of month value which is about 0.903 and the solar to conversion efficiency about 90.3%. Nwosu (2010) assessed the heaters with a non-porous absorber, which prevents air steam from passing through it and allows air to flow above or below the absorber plate. In order to determine the efficiency of an indirect solar dryer for drying various materials under varied operational conditions, Madadi et al. (2023) did a CFD analysis. A solar air collector (SAC), a V-corrugated absorber plate and a drying chamber with four perforated plates make up the system. A useful computational fluid dynamics (CFD) model is provided to the system. With the use of available experimental data, the model is verified. The obtained findings show that the moisture ratio for potato, carrot and apple at the conclusion of the process rises up to 11%, 127% and 119% as the input airflow rate increases from 100 to 400 m^3/h. Moghimi et al. (2021) conducted numerical analysis in a low-cost solar fruit and vegetable dryer. An optimization process was utilized to transform a typical frequently used data from experiments and computer models; a direct cabinet dryer was converted into a new indirect dryer. Researcher conducted a number of well-planned tests and CFD simulations using the finite volume approach. An additional tray might be added to the optimized dryer, increasing its drying capacity by more than 50% in contrast to the direct type and according to estimates of 16.4% thermal efficiency by Ozge et al. (2020). Experimental findings and numerical modelling demonstrated that employing mesh modification has a favourable impact on the collector's performance. In DPISDMA, the thin sample thickness had the highest average drying efficiency at 23. The objective of Lingayat and Chandramohan's (2021) groundbreaking study was to develop a numerical model that could be used to choose the best solar collector (SAC) and to use the recommended SAC model in an experimental scenario. The use of corrugated absorber surfaces enhanced the rate of heat transfer between the absorber and the air. The drying behaviour and drying characteristics of banana slices were assessed by completing the tests in an indirect sun dryer (ISD) that was built using the findings of a numerical analysis. The enhanced performance of triangular corrugated SAC led to the development of a triangular corrugated SAC-based ISD. Lingayat et al. (2020) analysed the specifications and benefits of indirect-type SD, and the analysis revealed that the higher amount of insulation levels allows the economic absorption of energy and the selection of suitable absorber material characteristics based on the efficient emitting properties which can enhance the temperature of air.

Collector cover

The solar collector attracts the radiation from the sun and thus creates the heating effect. The absorption level is reliable to climate condition and varies throughout the day. Based on the method of procedure, the collectors were categorized into concentrating and non-concentrating types, i.e. the wide area of incident radiation is gathered and focused to one certain region. There are various kinds of collectors such as cubical, parabolic, evacuated tube, flat plate or double pass. Zulkifle et al. (2018) implemented and studied the thermal efficiency characteristics of SPSAC incorporated with a V-groove absorber and its cover. By using the theoretical model and Excel sheet, the evaluation was conducted. The evaluation reported that the covers with V-groove absorber had increased the performance characteristics like convective heat transfer of the collector than in the flat plate collectors. Choudhury and Garg (1991) theoretically examined performance constrains of single-pass solar air heater consists of flat plate collector incorporated with single cover of plane glass and corrugated glass. It was found that the HTF air running overhead the collector through the channel between collector and the cover. Jin et al. (2020) presented the glass tube flow channel acts as an absorber or collector cover. The analysis revealed that the addition of glass cover plate enhances the reflective nature of CSAH particularly for larger aperture width, and it acts as the preventive surface for the collector from the rain, dust, snow and the corrosion during long-term operation which decreases its optical performance. Nowzari et al. (2014) experimentally investigated the thermal performance of quarter perforated cover used in double- and single-pass SAH with standard glazing. The schematic assembly of SAH is shown in Fig. 4. The inspections were made with two variant covers: one type of cover is hole on one cover that had the centre-to-centre distance of 10 D (0.3 mm), where D (0.03 mm) was the hole diameter, and the another cover is hole on one cover had the centre-to-centre distance of 20 D (0.6 mm). It is found that the mass airflow rate alters between 37 and 11 g/s. The result analysis reported that the average efficiency of

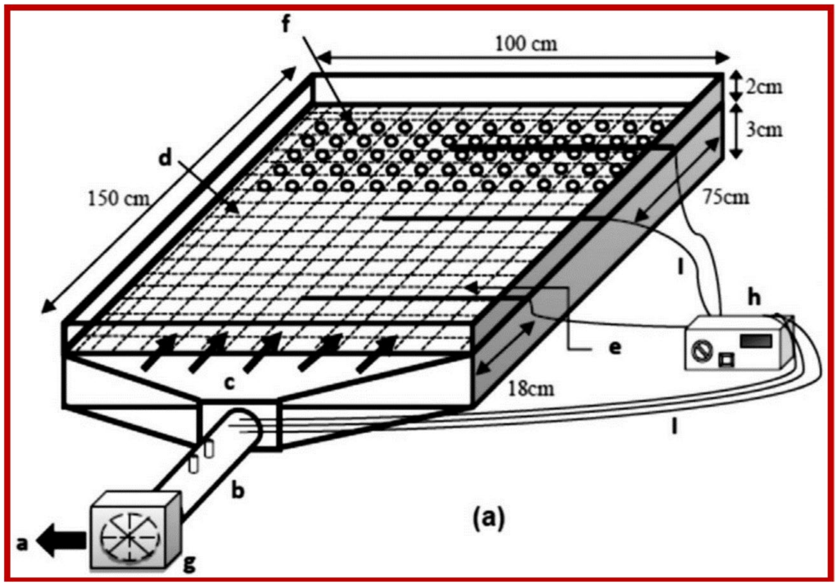


Fig. 4 Schematic assembly of solar air heater. a Outlet air, b orifice meter, c inlet air, d glass cover, e wire mesh layers, f perforated Plexiglas cover, g centrifugal fan, h thermometer, I thermocouples (Nowzari et al. 2014)

double- and single-pass SAH is found to be 53.67% and 49.98% respectively; thus, for the equivalent rate of flow, the performance of SD is always higher in double-pass SAH than in single-pass SAH. Verma et al. (1991) theoretically analysed the grooved solar air heater incorporated without and with the cover and found that the flow is above and the below the absorber in single cover design. The result showed that the efficiency reduction is only about 13% for single cover collector.

Drying chamber

The drying chamber is made of transparent materials or opaque material and typically invented in two shapes such as cubical or triangular prism. The chamber absorbs additional solar radiation and enhances the heat transfer. The thermal loss is negotiated by using transparent materials or opaque material along the drying chamber sides. Amer et al. (2010) found that the solar dryer comprised of HE with heat SU, reflector, absorber and DC. The location of the drying chamber is 200 mm below the absorber plate. The chamber's height, insulation thickness, material of the tray, number of trays and the area is found to be 20 cm, 50 mm, aluminium meshed (90–70 cm), 16 and 5.04 m^2 respectively. The drying chamber is categorized into eight parts with uniform dimensions; furthermore, each part comprised of two trays for drying. Thus, the chamber has 16 trays for drying in the drying chamber. In their 2009 study, Cakmak and Yildiz looked at the effects of increasing drying air velocity, placing swirl elements at the dryer's input and installing directing elements inside the drying chamber, all of which increased drying speed and decreased drying time. The entire drying process took place over a time of decreasing velocity. The drying process moves at a speed of 1.5 m/s, and is then followed by phases of drying at velocities of 0.5 m/s and 1 m/s. The outcome showed that the drying time is slower using the natural drying approach. In the drying room, new cocoons are arranged in a thin layer, according to Singh's (2011) analysis. For optimal cocoon drying, with temperatures between 60 and 80 °C, a higher starting temperature scheme is used in the electrical dryer for quicker drying activities. Hernandez et al. (2021) used CFD research to assess the effect of the swirl generating chamber's shape. The wall that is integrated with the governor's vortex can see how the swirl's intensity is waning. Chan et al. (2015) investigated the design and construction of the recirculated kind of integrated solar collector drying chamber, which was used to dry granular materials like rice, wheat and maize. The drying chamber's upper layer was a hopper with a vortex. The analysis showed that the sun radiation received was 8.724 kJ and the hopper temperature was 54.5 °C. Eltief et al. (2007) examined the performance parameters of a solar-assisted drying system that included a drying chamber. This system includes a drying chamber, two variable-speed centrifugal fans, a V-groove collector with a surface area of 13.8 m^2 and an auxiliary heater. The outcome showed that the drying chamber's efficient and well-insulated structure improved the solar dryer's performance. Al-Kayiem and Gitan (2021) used a variety of studies to investigate the performance traits of different drying chambers. CFD is used to enhance and stimulate the various drying chambers. One movable tray with edges that are hinged makes up the death chambers. The findings indicated that the turbulence intensity of the velocity field will be lower in the centre of the drying chamber and significantly greater at its outskirts. Xiao et al. (2019) found that the simulation of both drying and dispersion chamber as a single unit is not practically possible and its efficiency is not appreciable. Based on the rate of flow of injection of droplets, the continuous source of droplets to the chamber was ensured.

Exhausters

Moisture air from the drying chamber can be vent out using fans, air vents and chimneys in order to overcome the cause of an inefficient drying due to the very high amount of relative humidity. Zhang et al. (2021) revealed that in controlling the segregated flue gas exhaust system, the top layer of flue gas exhaust plays a vital role and the flue gas is spread vastly, if it is started late. The portable FG Analyser System Test 350 with an O_2 measuring cell was employed as a standard by Kamal et al. (2017) for the examination of the flue gas, which needs to be vented by an exhauster. The normal gas-sampling probe's length is determined to be 700 mm, which corresponds to a maximum temperature of roughly 1000 °C. Ononogbo et al. (2021) evaluated the convective crop solar dryer drove by flue gas waste heat for the application of drying the corn. The schematic diagram of the waste heat recovery dryer is shown in Fig. 5, and it also indicates the significant component associated in the dryer. To conform the temperature of drying air and ambient temperature and humidity, a temperature sensor is placed in and out of the drying tray.

Fans

In order to enhance the pressure differentials, the fans were incorporated with collector cover under the ambient conditions, i.e. the drying efficiency is getting reduced due to convection currents. Poblete et al. (2018) analysed the solar dryer with forced convection. This moderation in velocity and turbulence is converted into enhanced vapour which gets eliminated through the drying process and a best drying time. Moses et al. (2015) found that the higher amount of deep grain beds was caused by the resistance to airflow offered and rectified by natural convection. It is essential to carefully note that there is a proper airflow distribution process within the systems.

Insulators

The thermal defeats due to convection and conduction currents are reduced by placing the insulator at the bottom and the sides of the solar collector and also due to radiation from absorber. Air is a good insulator by nature, and under static conditions, heat transfer between the absorber and transparent cover is limited. Babalola et al. (2020) brought back natural-based nano-composite from chicken feather fibre as thermal insulator and bentonite as nano-filler respectively Lee's disc method at static state was used to measure the thermal conductivity of insulators. The well-suited highest insulation property and highest thermal conductivity are 114.63 m^2 k/W and 0.0549 W/mK respectively. The

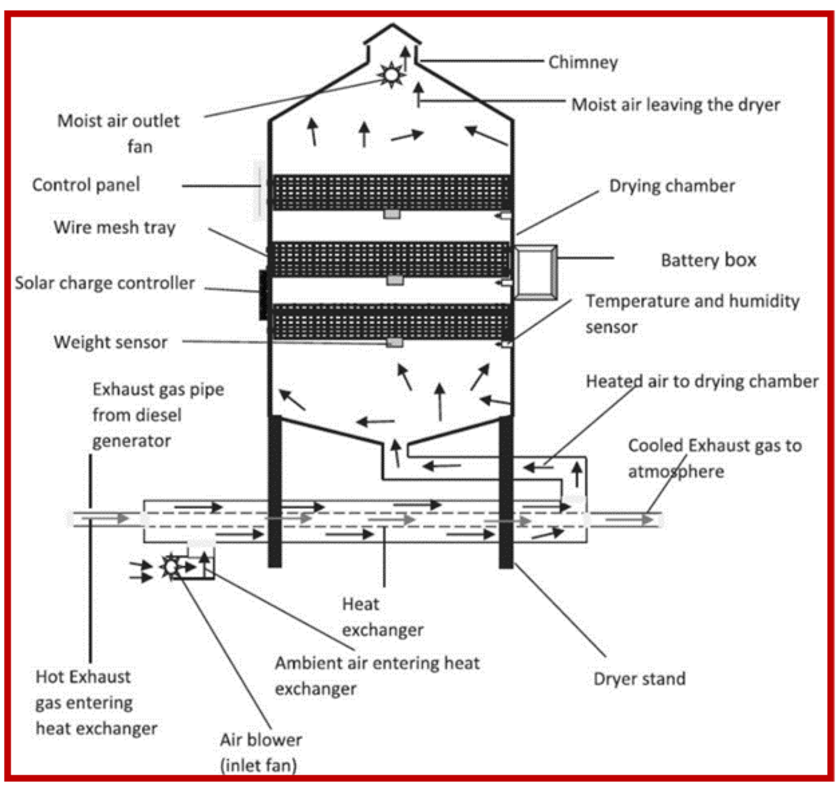


Fig. 5 Schematic diagram of the waste heat recovery dryer (Ononogbo et al. 2021)

result revealed that the effective insulator with lowest thermal conductivity is suitable for the solar dryer. Cozzarini et al. (2020) established the application of life cycle analysis methodology in comparison with traditional method. In this cycle, innovative insulating foam was produced by freeze drying process by two mixtures via recycled glass powder and green chemical reagent. The quality of product life cycle was based on the thermal resistance $R = 1$ m^2 k/W. Thus, the result mentioned the performance of life cycle by thermal resistance. Salomao et al. (2021) discovered that an efficient thermal insulator has an average size range between 0.5 and 1.0 m to increase the phonon and photon scattering that aids in preventing heat transfer throughout the solid phase; the surface of the insulator must reduce air convection, should possess lower interconnection among the pores and should have a 50–80% volumetric fraction of pores. Luo et al. (2020) presented the controllable performance of innovative aluminium borate foams (ABFs) as thermal insulators which is prepared by the technique of manageable foam-casting. The aluminium borate foams are fabricated by $2Al_2O_3{\cdot}B_2O_3$ and $\alpha = Al_2O_3$ with incorporation of several quantities of slurry solid contents, foaming agents and thickening agents. Ueno et al. (2021) described the metal insulator transition fabrication and temperature measurement dependency. The evaluation of multifunctional thermal control devices by dependent properties such as thermal conductivity, specific heat and total hemispherical emittance are carried out. The result of confirmed experimental verification showed that the thermal conductivity of LSMO and LPMO decreases, with increases in thermal conductivity of VWO_2 and with gradual increase in temperature.

Reflectors

Reflectors can be neither integrated within the dryer or separately. Spall and Sethi (2020) determined the impact and performance of reflected north wall of modified global solar radiation capture model. The analysis reported that the radiation capture rate enhanced by the use of reflected north wall and the rate is about 31.57%, 23.24% and 37.58% at 50°, 40° and 30°N latitude respectively in winter, and the average efficiency with reflected north wall is 5% and 4.35% larger under forced and natural convection methods correspondingly as compared to without using reflected north wall. For the purpose of drying the moisture content present in the grapes, Leon Dharmadurai et al. (2022) experimentally evaluated and thermally compared the sun dryer integrated with an external reflector and open solar dry technology. The outcome showed that the external reflector improves energy input and shortens drying time compared to open-sun drying (Maiti et al. 2011). The outcome shows that using efficient reflectors without regard to load characteristics at the highest solar irradiance conditions on a typical day in January increased absorber efficiency from 40.0 to 58.5%. Tiwari et al. (1994) analysed the impact of reflector placed above the chimney wall and derived the energy balance equation in terms of climatic and design considerations for passive-type solar dryer incorporated with shallow bed. The result shows that the absorber has enhanced thermal energy from the reflector, and the time of drying is considerably reduced.

Auxiliary heat sources

Additional heating sources help to enhance the drying performance and allow extreme usage in all weather conditions. The common heat sources are electrical heaters, LPG-based burners and biomass. According to Sevik et al. (2013), the dryer's solar heat exchanger and heat pump condenser are both necessary to deliver the necessary quantity of heat. Heat is generated using SCS. This serves as a heat source and a drying process for heat pumps, respectively. Aktaş et al. (2009), looked at the diffusion rate of effective moisture removal for apple slices that were 4 mm thick in a conventional heat pump dryer operating at 40 °C and 2.5 m/s air velocity. The solar dryer's schematic design (Fig. 6) shows the various parts and their locations. For apple slices that were 4 mm thick and dried in a sun dryer at a temperature that varied between 16 and 30 °C, the average effective moisture diffusivity was 1.03×10^{-8} m^2/s. Mohajer et al. (2013) examined the efficiency of the solar dryer for the application of drying a mixture of vegetables at a constant water and airflow. Based on low-cost availability in rural areas, if fast drying rate is required or when there is no sunshine, the usage may become compulsory during hours and the electric heaters are used, and the analysis reported that the system generates hot water and simultaneously dries vegetable.

Energy storage system

Solar heating system (SHS) helps to store the solar energy and can be used for various drying applications. While charging process, the latent heat of melting is attained and PCM absorbs the heat energy. During discharging process, the heat gets liberated to the environment until the warmth of the product drops to the melting point. According to Das et al. (2020), warm air from the solar collector's output went through the shell and tube-type thermal energy storage system. Four copper tubes, each measuring 25 mm in diameter and 300 mm in height, were joined to the shell side, which was filled with the bio-composite material. Using actual data from the literature, Chaatouf et al. (2022) utilized the CFD approach to model a solar dryer; the data gathered revealed that, compared to the scenario without storage, the efficiency of the solar dryer with sensible heat storage increased by 2.47% at night. Esakkimuthu et al. (2013) substituted a series of absorber tubes filled with the TES for the standard

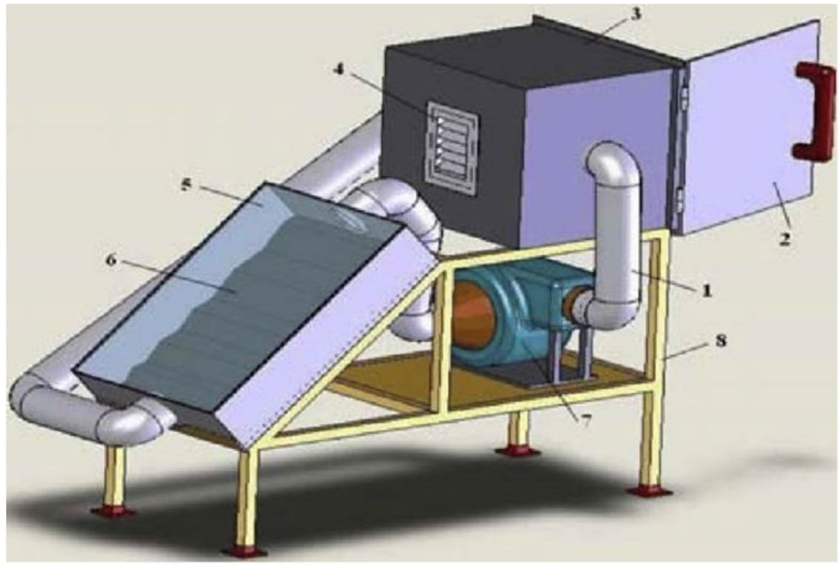


Fig. 6 1 Solar dryer fan ventilation canal, 2 drying chamber lit, 3 drying chamber, 4 air adjustment flaps, 5 solar air collector, 6 absorber plate, 7 system fan, 8 platform (Aktaş et al. 2009)

flat plate absorber. According to the result analysis, where the mass flow rate is 20 g/s for both kinds, the drying time increased to 16 h in a set of tubes packed with the thermal storage material type as opposed to 9 h for the typical type flat plate collector. Arun et al.'s (2019) investigation focused on the distinct metallic cylindrical macro-encapsulate unit housing paraffin wax, which frequently serves as a temporary storage container for the MMSCD. At reduced solar power levels, the thermal energy storage helps to continually deliver warm air to the multi-tray mixed-mode solar cabinet dryer. According to the obtained data, the concentrator's usable heat gain and the heat that was reserved were 9160 W and 4400 W at 30 g/s and 7520 W and 3700 W at 15 g/s, respectively. According to Baniasadi et al. (2017), the bottom of the DC is enclosed by an energy storage unit constructed with a copper coil packed with powered paraffin. Its melting point is around 70 °C. To compare the results of tests with and without TES, the energy storage device might be dissimulated. El-Sebaii et al. (2002) investigated to see whether a flat plate SAH is connected to a cabinet that acts as a DC in this configuration. The air heater is made to allow different storage materials to be installed beneath the absorber plate in order to enhance the drying processes. Different spherical fruits like figs have been dried both with and without preservation agents, as have vegetables including onions, green peas, apples, tomatoes and seedless grapes.

Methods to assist solar drying

Enhancing of overall improvement of product quality and acceptability and drying rate and reduction in drying time is a combination of the conventional solar drying with various methods. The reduction of drying rates and drying time can be enhanced by using hybrid methods. The performance efficiency of the dryer and solar energy utilization can be increased by integrating solar collectors and heat pump dryers, from the design aspects. Ssemwanga et al. (2020) have built an enhanced HIP solar dryer with a redesigned drying cabinet and solar collector plate for better drying of foods than the old-style OSD method. A conventional active-mode SPE dryer is also built with a supplementary thermal-backup system. The photographic view of an improved HIP dryer and the various modified components to enhance the performance are indicated in Fig. 7. Using fruits like mangoes and pineapples, the drying performance of the SPE and HIP dryers was evaluated and contrasted with the traditional open-sun drying approach. Drying efficiency of the improved HIP dryer was comparable to the SPE dryer and was 18% higher than the open-sun drying (OSD) method. Atalay (2019) has published research on the drying kinetics of orange slices using a solar dryer with a built-in packed bed as the TES medium. The author in this study presents the energy and exergy-based performances of a solar dryer integrated with packed bed as thermal energy storage medium. The drying system was conducted two times a day, and to determine the solar dryer's thermal efficiency to dry orange slices, it is compared with solar dryer without packed bed. Benhamza et al. (2021) emphasized the ideal design and operating circumstances in the current research through a parametric analysis that makes use of an experimentally verified CFD model and image processing methods in solar dryer for food drying application. The effect of three mass flow rates and the inclusion of a passive chimney on the drying air distribution are tested using the Ansys Fluent programme. The average temperature increased by 16 K, 11 K and 8 K for the corresponding mass flow rates of $m = 0.0141$, 0.0636 and 0.0872 $kg.s^{-1}$. The air temperature uniformity was

Fig. 7 Photos of an improved hybrid indirect passive (HIP) dryer: **A** a modified solar collector plate consisting of multiple metallic solar collectors; **B**, **C** the physical prototypes of the HIP without and without a non-perforated greenhouse plastic cover enclosing the dryer cabinet (Ssemwanga et al. 2020)

significantly increased by 22% and 20% for the mass flow rates of $m = 0.0141$ and 0.06 kg.s^{-1}, compared to a hardly detectable increase for $m = 0.08$ kg.s^{-1}.

A solar dryer with an improved flat plate collector was created by Ebrahimi et al. (2021) utilizing a PCM as a result of low thermal efficiency in the solar collector in diverse sectors. Figure 8 shows the schematic for the solar drying system that is coupled to a drying cabinet and a flat plate collector with numerous essential parts. The phase change materials inside the solar collector were taken into consideration in four distinct configurations, with the PCM tube aligned with equal distances in position (a), different distances in position (b), equal distances in position through two-thirds of the plate (c) and equal distances through one-half of the plate (d). So, using tomato slices as a comparison tool, the thermal efficiency and general efficiency of phase change materials with flat plate collector and those without were studied. The drying time of the slices was decreased by around 21.87% when the collector with PCM was used at the end portion. Depending on the position of the PCM, the thermal efficiency of FPC increased by around 5.02–10.13%. Numerical study was done by Lad et al. (2023) to create a solar dryer with integrated latent heat storage that maintains the drying chamber between 50 and 55 °C. The usage of phase change material (PCM) in various configurations is also evaluated in this study to determine how it impacts drying temperature. The PCM-integrated solar dryer's performance in hot and dry conditions is thoroughly evaluated once the model has been verified. Products dried include tomato, ginger, hot yellow pepper, onion and sweet green pepper. The traditional indirect dryer (case 1), the modified solar dryer with PCM within the collector (case 2) and the modified dryer with PCM incorporation inside the drying chamber (case 3) are the three separate PCM incorporation configurations examined in this study. The results show that case 3 outperformed the other examples in terms

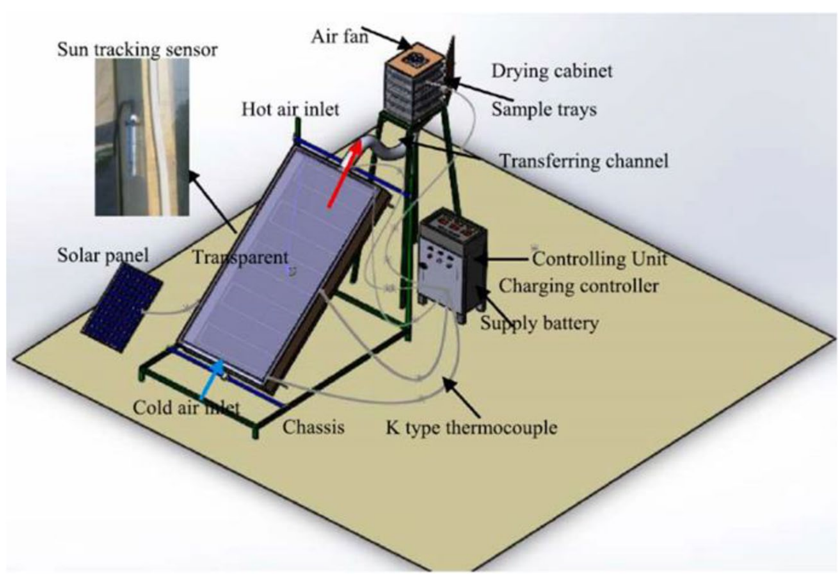


Fig. 8 The schematic of solar drying system coupled to a flat plate collector and drying cabinet (Ebrahimi et al. (2021)

of preserving the required temperature conditions for a variety of crops. The PCM and fluid type's impact on the thermal efficiency of the parabolic trough solar collector (PTSC) were investigated by Alimohammadi et al. in 2020. To predict heat changes in the storage tank and receiving tube using CFD, a modelling approach was conducted. The testing employed an airflow rate of 0.025 kg/s. Four fluid types—nanofluid (Al_2O_3, 4%), engine oil (10W-40), glycerin and water—were considered for the performance evaluation. The drying process of the solar dryer was also considered when drying apple slices that were 5 mm thick. The results showed that the dryer's total input thermal energy for water, oil, glycerin and nanofluid was approximately 17.36 MJ, 18.46 MJ, 17.76 MJ and 16.80 MJ, respectively. A self-sustaining renewable energy food drying system, the hybrid geothermal PCM flat plate solar collector proposed in this study by Ananno et al. (2020), has a precise design and a complete numerical analysis. The outcomes of the numerical investigation demonstrate how effective and efficient this near-zero hybrid energy technology. When the mass flow rate is 0.02 kg/s, numerical modelling indicates that the hybrid geothermal PCM flat plate solar collector dryer's efficiency is 20.5% higher than that of the conventional flat plate solar collector. A novel concept for an indirect hybrid solar-electrical wood dryer coupled with a thermal energy storage system was statistically examined by Lamrani and Draoui (2020), and for the thermal energy storage system and drying chamber, two numerical models are developed and put to the test using historical experimental data. According to the data acquired by using the thermal storage system in the dryer system, the temperature of the drying chamber is regularly 4 to 20 °C higher than the temperature of the surrounding air throughout the night.

A solar dryer for drying fruits and vegetables has been constructed by Islam et al. (2019). The induced attic space-type chamber, the natural draught type chamber and the draught type chamber were designed for the solar dryer's natural convection cabinet chamber, and their performances were tested in real-world settings. The total moisture removed in 6 h by the thin tube chimney type chamber was 44.5%, the attic space-type chamber was 33.3%, and the natural draught type chamber was 58.9%, according to an analysis of the rates of moisture removal in the three different chambers. According to Teshome et al. (2022), the drying air's flow parameters significantly affect the product's ultimate quality. The results show that using vertical air distribution tubes to increase the homogeneity of the drying air distribution can improve the drying process. Atalay et al. (2017) have built a solar air heater with a thermal energy storage system in a packed bed to assist continuous drying process, so as to inspect the drying rate of the apples. In addition, the waste heat is recovered using a recuperator unit. In recuperator unit, the drying air mixes with fresh air which increases the moisture content, at a definite rate. The drying system was repeated two times a day to determine the thermal efficiency of a solar air heater to dry apple slices at a constant temperature ranging from 50 to 60 °C. In order to calculate the drying time and drying rate, Mokhtarian et al. (2017) analysed the drying of fresh pistachio using the sun, solar energy, shade drying with air recycling and solar dyer without air recycling. Due to its ability to increase the ambient air temperature by 17 °C above the other strategies, the new strategy had the highest drying rate of any of them. Sharma et al. (2021) have analysed the drying kinetics of turmeric using the HAD and DSD. The drying time of turmeric is compared between HAD and DSD. Curcuminoids often lose less weight in DSD samples (42.60%) than in HAD (44.77%). Our research suggests DSD as a feasible method for producing turmeric that is of higher quality than HAD. According to Veeramanipriya and Umayal Sundari (2021), for drying cassava slices, a prototype hybrid photovoltaic thermal solar dryer with evacuated tube collector has been shown. The drying kinetics are investigated and compared to sun drying, and non-linear regression analysis is performed. 'A'-type crystalline patterns were shown on XRD results indicating semi-crystalline nature of both sun-dried cassava and hybrid. It is revealed that the physical and chemical components of hybrid cassava are superior to those of sun-dried cassava. The suggested hybrid dryer can create high-quality dried items that may be exported for a profit.

Babar et al. (2021) tested the green chillies lightened at 194 °F and 158 °F and solar dried for 3 min without and with PCM under forced and natural convection conditions, and the modified components of the flat plate collector-solar dryer are shown in Fig. 9. The solar drying effects without and with PCM on the level of aflatoxins and colour bioactive compounds were compared in chillies. The whole drying process might be improved and the drying rate increased as a result of the usage of PCM. It helped retain the green colour of chilli to an extent. The chilli dried at 70 °C in forced convection resulted better retention of total phenols. Rashidi et al. (2021) presented a desiccant wheel and flat plate collector with reflecting systems for drying the oleaster fruit. It was tested with three airflow rates in different drying conditions, without reflectors desiccant wheel and with reflectors desiccant wheel. The results showed that the effect on moisture extraction is significant. Due to high thermal energy, the solar thermal fraction rate with reflectors desiccant wheel was reduced by 15%. The oleaster dried with reflectors desiccant wheel is better than without reflectors desiccant wheel and sun drying samples. Kasaeian et al. (2020) indicated that energy-efficient systems called polygeneration may provide a number of useful energy outputs, such as electricity, cooling, heating, fresh water and hydrogen. As a consequence, the most effective way to utilize a clean energy source while simultaneously producing a lot of valuable outputs

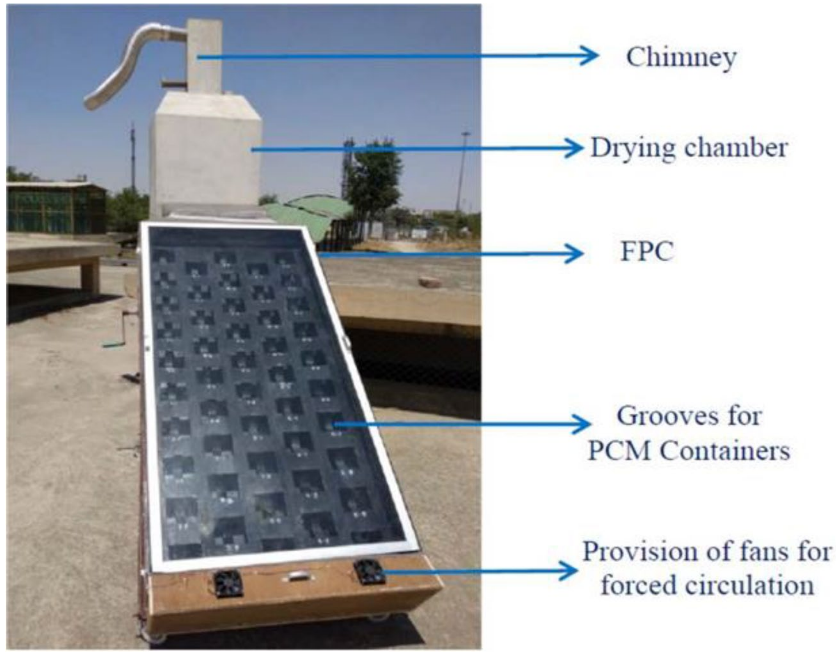


Fig. 9 Photographic view of flat plate collector-solar dryer (Babar et al. 2021)

is to combine solar energy systems with polygeneration units. In a comparison study using sliced potatoes, Ndukwu et al. (2020) showed PNWPS and AWPFS, with the goal of developing a non-electricity-driven active solar dryer and two dryers, one without glycerol and the other with glycerol, were tested. The results showed that drying with AWPFS combined with glycerol required less time than drying with AWPFS alone or PNWPS. So with low electricity diffusion across Africa, the fan will be naturally powered, and their product dried faster with the help of crop processors.

Using a sun tracking system, Samimi-Akhijahani and Arabhosseini (2018) investigated the outcome of solar drying kinetics. To study the drying behaviour of tomato slices, a sun tracking unit with a solar drying system supported by PV was built and constructed. Drying time, effective moisture diffusivity and activation energy are taken into account when calculating the impact of the solar monitoring system on tomato slices. The drying time was significantly reduced by the solar monitoring system from 16.6 to 36.6%, according to the data. Thus, sun tracking system might be a potential strategy for not only speeding up the solar drying process but also moving this drying technology closer to industrial applications. Stiling et al. (2012) elaborated that the process of solar drying Roma tomatoes is improved by concentrating solar panels. The performance of two mixed-mode solar dryers is compared. It was built identically, and one of the dryers employed movable and flat concentrating solar panels to enhance solar energy on the dryer, which raised temperature and resulted in faster Roma tomato drying periods using CSP. The solar concentrators made the drying rate faster under both conditions which reduces postharvest loss and prevents spoilage. On sunny days, the concentrating solar panels showed a considerable improvement in drying rate, requiring 27% less time overall to dry the material to the target. Lingayat et al. (2017) concentrate on the importance given to solar energy sources as the prices of fossil fuels are higher, and they also reduce fuel consumption during the drying process. A solar dryer of indirect type is designed for drying agricultural products. It consists of an absorption plate, solar flat plate air collector, chimney and insulated drying chamber. The drying characteristics of bananas are studied. During drying, the drying air temperature and the effective factor are important. The moisture of air and air velocities are also important factors that improve the drying rate, and the drying chamber's thermal efficiency was discovered to be 22.38%.

System analysis and performance of solar dryer

Solar drying is environmentally friendly and cost-effective as compared to conventional methods of drying. The emission of CO_2 is limited with solar dryer for food processing, such as the characteristic of high carbon footprints, which is neglected in conventional electrical dryers. A well-designed solar dryer may be used to evaluate higher drying properties with greater heat and mass transmission. Utilizing photovoltaic thermal-driven fans and ventilators, corrugated and roughened collectors, thermal storage systems with latent or sensible heating units for drying and double- or triple-pass solar air collectors may all help enhance the efficiency of solar dryers. Basically, the feasibility and applicability also include the selection of components.

Thermal efficiency

Ssemwanga et al. (2020) have analysed a redesigned solar collector plate with the enhanced HIP solar dryer and drying cabinet for better drying of foods than the traditional OSD method. An additional thermal-backup mechanism is also included into a conventional active-mode SPE dryer. The author examined the drying performance of the SPE and HIP dryers using fruits such as mangoes and pineapples, and related with the conventional OSD method. The drying times of SPE, enhanced HIP and OSD for drying fruits are 600 min, 1080 min and 1800 min respectively. Therefore, the drying efficiency of SPE and enhanced HIP is 18% greater than the OSD method. Atalay (2019) has analysed the drying kinetics of orange slices using a solar dryer with a built-in packed bed as the TES medium and indicated that the thermal efficiency of a solar dryer combined with packed bed to dry orange slices is 54.71–68.37%, which is greater than the solar dryer without packed bed.

According to Ebrahimi et al. (2021), a solar dryer with an improved FPC plate collector using a PCM has been developed due to the low thermal efficiency of solar collectors in various sectors. We compared a flat plate collector with phase change material to a flat plate collector without phase change material using tomato slices to measure the thermal efficiency and total efficiency of each. Utilizing the flat plate collector with PCM as opposed to the flat plate collector without PCM reduced the drying time for tomato slices by a comparative 21.87%. The thermal efficiency of the flat plate collector with PCM was 5.02–10.13% greater than the flat plate collector without PCM, depending on the location of the PCM. A solar dryer for drying fruits and vegetables has been constructed by Islam et al. (2019). The sun dryer was built using three different types of natural convection cabinet chambers, including natural draught chambers, induced draught chambers and attic space-type chambers. Different foods were dried in their natural state. Foods were dried at rates of 44.5% in an induced draught room, 33.3% in an attic space-type chamber and 58.9% in a natural draught chamber over the course of 6 h. Solar dryer with natural draught provides better drying capabilities than dryers with the other two types of chambers. In order to investigate the pace of drying of the apples and to aid in the continual drying process, Atalay et al. (2017) built a solar air heater. A recuperator device is also used to recover the waste heat. In recuperator unit, the dry air mixes with fresh air which increases the moisture content at a definite rate. The drying system was repeated two times a day and the thermal efficiency of a solar air heater to dry apple slices was 50–60% higher at constant temperature of 50–60 °C. The rate of energy consumption is 76.8% lesser than other drying technologies, which is the main advantage. Through the addition of triangular corrugations above the solar air collector (SAC), Prajapati et al. (2022) improved the heat transfer phenomena of the SAC through numerical analysis utilizing the for-profit programme Ansys Fluent. The flow parameters included velocity, temperature, turbulent kinetic energy, turbulent intensity and performance parameters including Nusselt number (Nu), Nu ratio, friction factor (f) and f ratio. The highest Nu and THPP were 124.75 and 1.726, respectively, at $Re = 18{,}000$ and $p = 135$ mm. The best pitch was determined to be 135 mm since further increases or reductions in p led to low Nu and THPP. Using three different methodologies (experimental, computational fluid dynamics (CFD) and thermo-graphical), Motahayyer et al. (2019) investigated the heat transfer mechanism of the solar dryer under three distinct conditions: non-porous system, porous system and porous and recycling system. The flat plate collector was separated into four equal parts in order to calculate the amount of heat transfer coefficient, heat flux and overall heat transfer from the collector over time for each area. The performance of the dryer was also evaluated using a heat exchanger that was installed at the input of the collector. The air velocity distribution and temperature counters inside the collector were also modelled using computational fluid dynamics. According to the findings, compared to non-porous systems, overall heat transmission increased by roughly 16.50% in porous systems and by 21.19% in porous and recycling systems.

In order to calculate the drying time and drying rate, Mokhtarian et al. (2017) assessed the drying of fresh pistachios using sun drying, solar drying, shade drying with air recycling and solar dyer without air recycling. The rise in ambient air temperature and the pistachio drying duration for each drying method is as follows: 1, 1, 14 and 17 °C and 48, 19, 16 and 13 h, respectively. Therefore, solar dyer with air recycling (13 h) has a lesser drying time than the other three drying methods, a higher ambient air temperature of 17 °C and a higher drying rate than other methods. Sharma et al. (2021) have analysed the drying kinetics of turmeric using the HAD and DSD. The drying time of turmeric in HAD is 3.5 h lesser than in DSD. Direct solar drying has a higher potential technique to produce turmeric with better quality as compared to hot air drying. Veeramanipriya and Umayal Sundari (2021) elucidated that for drying cassava slices, a prototype hybrid photovoltaic thermal solar dryer with evacuated tube collector was shown. The drying kinetics are studied and compared with sun drying, and non-linear regression analysis is performed. 'A'-type crystalline patterns shown on X-ray diffraction results indicate semi-crystalline nature of both sun-dried and hybrid cassava. It is revealed that sun-dried cassava's physical and chemical compositions are inferior to hybrid cassava's. The suggested hybrid dryer can create high-quality dried items that may be exported for a good profit. The moisture content is reduced from 91.5 to 10.67%. It is verified to be the appropriate manner for predicting with $R_2 = 0.982$ and $\chi^2 = 0.017553$ for hybrid dryers and $R^2 = 0.998$ and $\chi^2 = 0.001247$ for open-sun drying. Babar et al. (2021) tested the green chillies lightened at 194 °F and 158 °F and solar dried for 3 min without and with PCM under forced and natural convection conditions. PCM reduced the drying time by 17–20% (natural convection) and 35–38% (forced convection). The solar drying effects with and without PCM on the level of aflatoxins and colour bioactive compounds were compared in chillies. The average drying is improved to 0.40–0.51 kg/kg-h from 0.40–0.44 kg/kg-h. The overall drying process could be accelerated and the drying rate increased as a result of using PCM. It helped retain the green colour of chilli to an extent. In NC solar drying, the greatest preservation of green colour with ΔE value 0.47 ± 0.03 was compared. When the PCM was utilized, aflatoxin B_1 levels in solar dried chilli were kept below 0.25 ppb, but when it was not, they ranged from 4.05 to 6.85 ppb.

A research on a sun dryer with an exterior reflector that reduces the moisture content in grapes was published by Kasaeian et al. (2020). The energy input was raised, while the thermal behaviour was contrasted with external reflector and open-sun drying procedures. The exterior reflector accelerated drying and increased thermal efficiency. When compared to open-sun drying, the temperature of the dryer employing exterior reflectors was raised by 20%. The results showed that drying with AWPFS combined with glycerol required less time than drying with AWPFS alone or PNWPS. When a potato is dipped in salt solution and blanched for 30 s before drying, the drying rate increases faster. The energy consumption ranged from 4.10 to 4.98 MJ. The exergy efficiency ranged from 14.5 to 80.9%, while the drying efficiencies ranged from 25.031 to 31.5%. Samimi-Akhijahani and Arabhosseini (2018) investigated how the sun tracking system affected the kinetics of solar drying. A sun tracking device with a photovoltaic-assisted solar drying system was conceived and constructed to analyse the drying behaviour of tomato slices during the process. It was tested with and without the sun tracking system at various air speeds (0.5–2 m/s) and thicknesses (0.3–0.5 cm). The influence of the solar monitoring system on tomato slices is assessed using the effective moisture diffusivity, activation energy and drying time. According to the data from the sun monitoring system, the drying time was cut from 16.6 to 36.6%, and the moisture diffusivity was raised by 9.1–64.6%. As a consequence, the sun tracking system may be a viable tactic for advancing the industrialization of solar drying technology while simultaneously accelerating the solar drying process. Stiling et al. (2012) illustrated that the process of solar drying Roma tomatoes is improved by concentrating solar panels. The two mixed-mode solar dryer's performances were compared. It was built identically, and one of the dryers employed movable and flat concentrating solar panels to enhance solar energy on the dryer, which raised temperature and resulted in faster Roma tomato drying periods using CSP. During the sunny day testing period, the temperature was 10 °C higher. The concentrating solar panels resulted in increased drying rate on sunny days and 27% decrease in total drying time. When the dryer was tested in simulated cloudy conditions, there was a significant increase in the drying capacity. The solar concentrators made the drying rate faster under both conditions which reduces postharvest loss and prevents spoilage.

Lingayat et al. (2017) focus on the value placed on solar energy sources due to the increased cost of fossil fuels and the fact that it uses less fuel throughout the drying process. Agricultural items were intended to be dried using an indirect-type sun dryer. It is made up of a solar flat plate air collector, an absorption plate, a chimney and an enclosed drying chamber. The collector's surface area is 200 cm^2, and the drying cabinet is 100 cm by 40 cm by 100 cm. Banana drying features are researched. Bananas humidity content dropped from 356% (db) to 16.3292%. During drying, the effective factor and the temperature of drying air are important. The drying chamber's average thermal efficiency was 22.38%, and collector average thermal efficiency was 31.50%. The humidity of air and air velocities are also important factors which improve the drying rate.

Overall efficiency

Ebrahimi et al. (2021) have established a solar dryer with an improved flat plate collector using a PCM because of low thermal efficiency in the solar collector in various fields. The PCM inside the solar collector were taken into consideration in four distinct configurations, with the PCM tube aligned with equal distances in position (a), different distances in position (b), equal distances in position through two-thirds of the plate (c) and equal distances through one-half of the plate (d). To evaluate flat plate collectors with and without phase change materials, tomato slices were used to examine the overall efficiency and the thermal efficiency of the phase change material in flat plate collectors. Utilizing the flat plate collector with PCM as opposed to the flat plate collector without PCM reduced the drying time for tomato slices by a comparative 21.87%. According to the PCM location, the flat plate collector with PCM had an overall efficiency that was 21.92–25.72% greater than the flat plate collector without PCM. Rashidi et al. (2021) presented the reflecting systems in a flat plate collector and desiccant wheel for drying the oleaster fruit. It was tested with three airflow rates in different drying conditions and desiccant wheel (WRD) (WORD), with reflectors (WR) and without reflectors. By using WRD, the energy consumption was reduced by 11.32–30.15%. WRD's overall efficiency varied from 33.21 to 39.64%, which was greater than it would have been without the reflectors and desiccant system. The results showed that the effect on moisture extraction is significant. Due to high thermal energy, WRD has a low solar thermal fraction rate, 15% of the total. The analysis resulted in the maximum exergy efficiency of the drying system for WORD, WR and WRD being 32.1%, 38.8% and 56.7%, respectively. The quality of oleaster dried by WORD and sun drying samples is poor when compared to WRD.

Economic analysis

The payback period is known as the total time needed to retrieve the initial cost and also resolves the tolerability of the refurbished system over a long period. Therefore, factors such as the cost of dryer components, drying period, miscellaneous cost, labour cost and climatic conditions are to be considered for economic cost calculations. Thus, the payback period can be calculated from the material cost, dryer's capacity, maintenance cost, electricity cost, labour cost, dryer life and depreciation cost. With the use of a conventional payback time, Boughali et al. (2009) assessed the economic properties of the solar dryer used for drying tomato slices, such as the cost of maintenance, cost of the dryer, total cost and net revenue. The analysis also showed that the solar dryer's maintenance costs, dryer costs, total costs and net income were found to be 2100 Da, 80,000 Da, 192,319 Da and 62,681 Da, respectively (US $1 = 70 Da). Sreekumar (2010) focused the economic characterization like total electricity cost per year, payback period, life of system and the total cost of the roof-incorporated solar dryer for the application of drying pineapple fruit. The result showed that the total electricity cost per year, payback period, life of system and the total cost are found to be Rs 12,000, 6 month and 4 days, 240 months and Rs 55,990 respectively (45 Rs = US $1).

Condorí et al. (2017) evaluated the economic performance of the large sized solar air collector. The result analysis revealed that the investment cost for solar and electric dryer, annual cost for solar and electric dryer, total cost for electric and solar dryer and labour costs were $5.333 and $8.000, $33.000 and $33.000, $180 and $190.70 and 8000 USD respectively. Red chillies are dried using a double-pass solar dryer, and economic performance is related with a cabinet dryer in Banout et al.'s (2011) analysis. The traditional method of drying used in Central Vietnam is the open-air sun dryer method. The results revealed that using the DPSD technique to dry 1 kg of chilly costs 39% less ($0.077/kg) than using a cabinet dryer ($0.126/kg). For cabinet dryers, the solar dryer's lifespan was 50 months, and for DPSD, it was 10 years. DPSD method has two times higher drying efficiency compared to cabinet dryer. The yearly cost for DPSD is 290 (US $) and for cabinet dryer is 33 (US $). Payback period for DPDA is 40 months and for cabinet dryer is 30 months. The comparison revealed that the yearly costs of double-pass solar dryer were higher than those of cabinet type of dryer. The usefulness of a multi-pass solar air heating collector with granite as a practical energy storage matrix was identified by Kareem et al. (2017) for drying the hibiscus sabdariffa, and its photographic perspective is shown in Fig. 10. This study was carried out in an environment with daily averages of 635.49 W/m^2, 64.5% relative humidity,

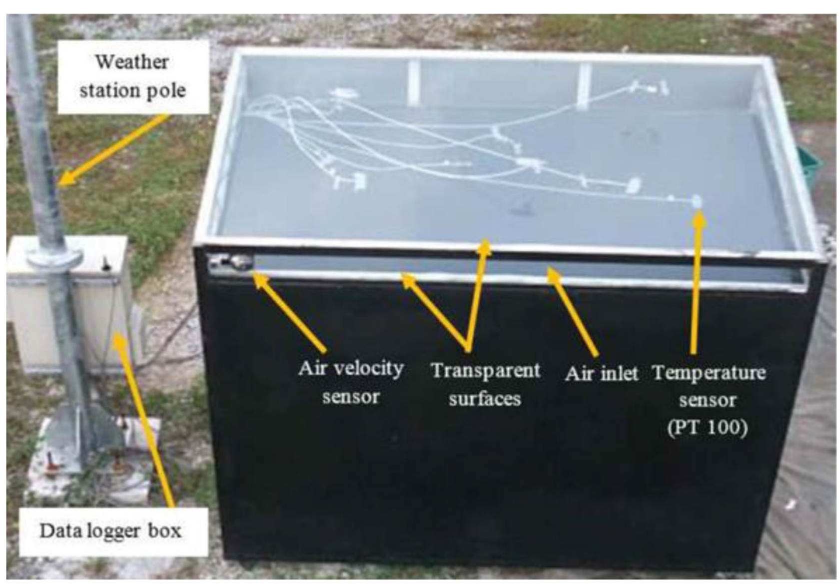


Fig. 10 Photographic view of the MPSAHC system (Kareem et al. 2017)

0.81 m/s wind speed and 32.24 °C ambient temperature. The outcome showed that the 33.57 g MPSAHC dryer's average drying rate was 1260 min quicker than the open-sun drying method. Jain and Tewari (2015) created and examined an economic analysis of a continuous method for drying herbs using a solar crop dryer integrated with thermal energy storage, with a flat plate solar collector as the collector. The estimation showed that the procedure costs $100,000. Raw materials cost $20/kg, whereas finished goods cost $400/kg. The evaluated yearly profit was ₹66,000 and the payback period for this method was 1 year and 6 months. The total value obtained ₹400,000 with a yearly profit of ₹66,000.

Vijayan et al. (2020) conducted a test and evaluated the impact of mass airflow rate on a solar collector with a drying chamber for drying bitter gourd slices, and to force the air, a centrifugal blower is used. The result showed that the mass decreased to 723 g in 7 h with a mass flow of 3.816 kg/min. Ecological studies represented that the energy of indirect solar dryer is 26 months. In advanced system, the CO_2 moderation and carbon 33 credit values are 33.52 tons and INR 10,894 to 43,576 for 420 months. In order to dry the sultana grape and red pepper utilizing forced convection technology, Elkhadraoui et al. (2015) tested and analysed the economic performance of a mixed-mode solar greenhouse dryer made up of a flat plate and a chapel-shaped greenhouse collector. In August and September, the dryer was used to dry grapes, and in June, July and August, it dried red pepper. The examination revealed that the drying rate is significantly higher than that of open-air solar drying, and the payback period was 18 months, which is less than the system's 240-month lifespan. The total cost is 2000 DT. Electricity costs for fans were 15 DT/year in earlier times. The price of grape is 1 DT/kg and dried pepper is 10 DT/kg (US 1$ = 1.6 DT).

Udomkun et al. (2020) found that the cost of parabolic dryer comprising with concrete floor construction, landfilling materials and labour depends on the dryer's size; 49 and 166 m^2 sizes cost US $237 and 170/m. Two hundred forty-three households use solar dryer to dry banana, mango, rubber and stevia leaves. The use of parabolic dryer gave a yearly income of US $70,075 which is US $290/year. The training costs for 2 days are US $500–800, and without training, it costs US $2040. The solar drying process is reasonable and profitable compared to sun drying in low-revenue countries.

Babar et al. (2021) compared the solar dryer performance incorporated with and without the PCM for the application of drying green chillies balanced at 194 °F and 158 °F, for 3 min. The impacts on drying without and with phase change material on colour, aflatoxins levels and bioactive compounds were related. The result revealed that the PCM helps in reducing the drying time to 4 h compared to without PCM. No specific grant from public and commercial funding agencies was received except NIFTEM's research fund. Srinivasan et al. (2021) drying process utilized the solar radiation in order to dry the agricultural products and the food. A photographic view of a solar dryer with forced convection of mixed mode is shown in Fig. 11. The solar dryers accomplish constant drying during off-sunshine hours. Drying in open air resulted in more labour cost, drying area and drying time. The analysis showed that the standard paraffin wax is suitable for storage of heat as it is nontoxic, accessible at low cost and chemically inert. Fins, metal matrices and encapsulates were used. Lately, nano-materials have been added to phase change material (PCM) to expand the rate of heat transfer. For the purpose of drying banana chips, Singh et al. (2020) investigated and experimented with the collection of solar-assisted heat pump

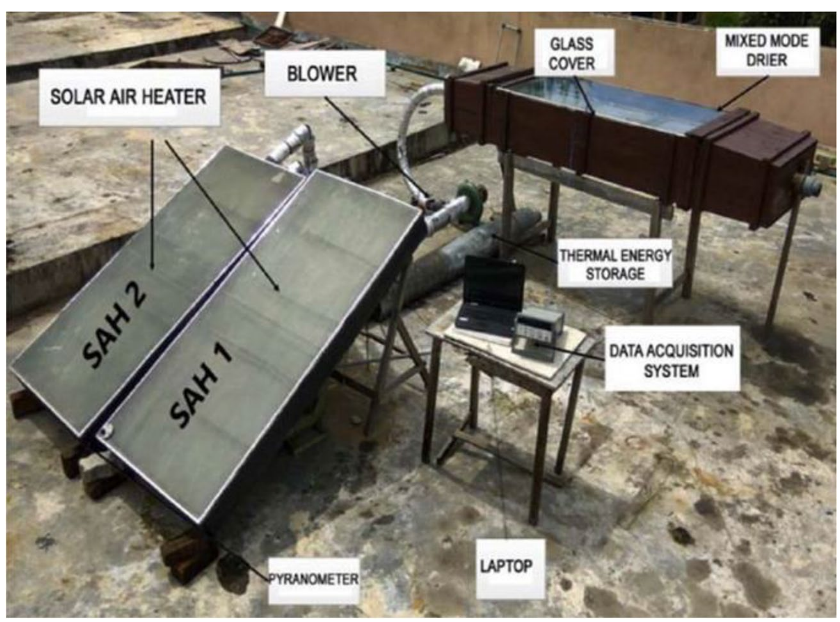


Fig. 11 Photographic view of mixed-mode type solar dryer with forced convection (Srinivasan et al. 2021)

dryers in both sun-assisted heat pump dryers and heat pump dryers. The outcome showed that the overall energy cost was lowest for the expansion device for the basic heat pump dryer and the SAHPD, at $0.001067/h and $0.00129/h separately, and highest for both heat pump dryer and SAHPD, at $0.0336/h and $0.05017/h individually. Simple HPD ($521.31) originally cost more than SAHPD ($892.94). SAHPD has a lower operating cost than a heat pump dryer. The heat pump dryer's annual cost was $1560, whereas the SAHPD's was $1462. So, on exergoeconomic factor, the SAHPD is improved as 528 compared to heat pump dryer, and the payback period is 24 months for both. Atalay (2020) assessed the binary energy storage system's economic characteristics. The investigation showed that the gain values for day, month and year were $8.9317, $270 and $3215.41 for both packed bed thermal energy storage (PBTES) and PCM. The annual maintenance cost is $188.74, and the total sale was $13,452.48.

Nabnean and Nimnuan (2020) conducted the experiment for drying the banana by using the direct forced convention. It was built as a solar dryer with polycarbonate plates. The outcome showed that the material cost, which included heat losses as solar radiation diffused into the dryer, was 390 USD. Repair and maintenance cost was 1% of the capital. The life of dryer is 60 months and the payback period is 13.4 months approximately. According to Vigneshkumar et al. (2021), the sun dryer is essential for drying and preserving grains, vegetables and fish in the food industry. The indirect solar dryers include a PCM-equipped area for sliced potatoes and a solar collector. The experiment was carried out in a sun dryer for 9 h both with and without PCM. The photographic view of flat plate single-pass solar dryer with various modifications is shown in Fig. 12. With paraffin-based PCM, moisture exclusion from potatoes was enhanced to 5.1% per day, and the presence of PCM improved the room temperature for two additional hours after the sun period. Nabnean et al. (2016) evaluated the economic characterization of solar dryer's new design for the application of cherry tomatoes which is dehydrated. The cabinet is 4.2 m long with a load capacity of 100 kg, and with a hybrid solar dryer, drying may be maintained even when the sun is not shining since backup heat energy is stored. With backup heat energy is stored in a hybrid solar dryer, drying can be continued without sun. This process has drawbacks like loss of material due to birds and animals and then spoilage due to climatic conditions. The process is labour concentrated, consumes time and requires huge area. The result showed that the payback period is 17 months and the material cost is found to be 5370 USD. The price of tomatoes is 0.8 USD/kg and the dryer life is expected to be 180 months.

Scope for future work

- The solar to thermal conversion ratio can be enhanced by using the tandem-structured solar absorbing layer incorporated with silica nanoparticles. By applying black coat on the fins, the heat absorption is increased and also reduces the loss of conventional energy.
- The quality of the dried products and the overall efficiency can be enhanced in collector with reflector and forced convection ITSD with double-pass or triple-pass facility.
- Introduction of toughen glass in collector cover and sepra mesh in single- and double-pass solar air heaters can be envisaged in future.
- Drying system with irrational flow supported by solar energy and artificial drying of various fruits can be designed.
- The angle of the dryer can be adjusted or the ratio at the hip can be enhanced to prevent low swirl instability in unrestricted areas. In the future, the deployment of a flue gas treatment system with ultra-low dust emission might be beneficial in reducing exhaust-related dangers.
- Various regional crops can be processed at varying process conditions using exhaust gas waste heat system to motorize the hot air dryer and the specific energy demand must be improvised in future.
- In the future, a direct forced convection batch-type solar dryer will be integrated with north–south reflectors. The optimal tray sequencing for drying various tropical agro-products has been identified.

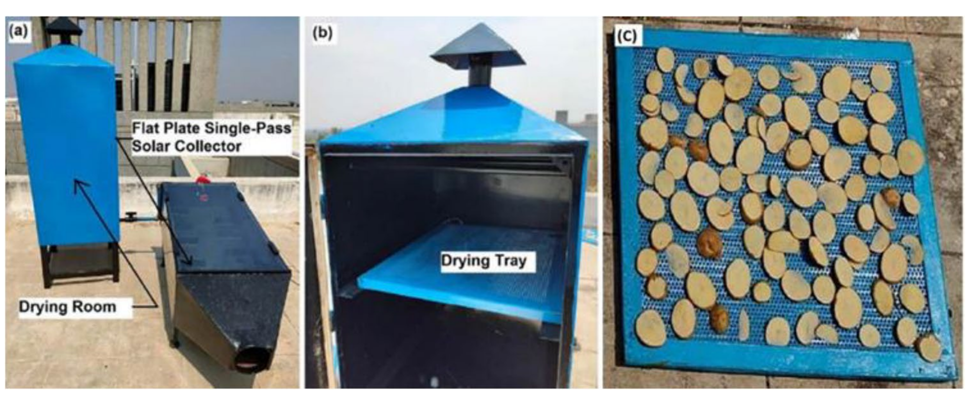


Fig. 12 Flat plate single-pass solar dryer: **a** complete set-up, **b** inside drying room, **c** sliced potatoes on the tray (Vigneshkumar et al. 2021)

- The drying air temperatures can be enhanced in the hybrid indirect passive (HIP dryer) and toughen glass may be used in the drying chamber covering to increase durability.
- Improvisation of ambient air fluctuation during high windy and cloudy conditions while drying fresh pistachio in the solar dryer.
- Evaluation of various chemical compositions in turmeric drying by using both hot air drying (HAD) and direct solar drying (DSD) methods can be considered in the future.

Conclusions

The major goal of this review article is to provide a consistent framework by presenting several designs and the effects of various parameters and components in solar dryers for food applications. The most important findings of this review article are as follows:

- The black oxide nanoparticles are of two types that include Cu-Cr oxides and Cu-Fe–Mn oxides in it; the reflectance data and flavour of month evaluation were improved by the help of compositions and crystallization conditions. With the help of a non-porous, flat plate, rear flow, only absorber plate design is considered simple and has less cost of maintenance, by which the material is capable of emitting infrared wavelengths which can raise the air temperature which is in contact.
- Solar air collector with a V-corrugated absorber plate and a drying chamber with four perforated plates shows that the moisture ratio for potato, carrot and apple at the conclusion of the process rises up to 11%, 127% and 119% as the input airflow rate increases from 100 to 400 $m^{3/}h$.
- It was determined that a blackened absorber plate, an air circulating unit and a honeycomb air manifold in solar air collector increase its drying capacity by more than 50% in contrast to the direct type.
- The final report says that the covers with V-groove absorber had increased the performance characteristics like convective heat transfer of the collector higher than the flat plate collectors. And the process of adding glass cover plate that enhances the reflective nature of CSAHs for larger space which prevent the surface for the collector from the rain, dust and snow for long time operation which decrease optical performance. In a solar dryer it was found that if the flow is above and below the absorber in single cover design there will be less efficiency.
- The result analysis reported that the average efficiency of double- and single-pass SAH is found to be 53.67% and 49.98% respectively; thus, for the equivalent rate of flow, the performance of solar dryer is always higher in double-pass SAH than in single-pass SAH.
- When it comes to dryers and drying chambers, the system's efficiency is improved if the drying chamber is well-built and well-insulated, allowing it to work as a solar dryer on sunny days and as a hybrid solar dryer on overcast days. In integrated solar collector drying chamber, a solar radiation of 8.724 kJ, a hopper temperature of 130.1 °F and a drying chamber RH at 21.73% were received, and the drying temperature of air was 50 °C.
- With the help of a Portable FG Analyser System, we discovered that controlling the segregated smoke exhaust system, the top smoke exhaust plays a major role and the smoke is spread widely if the convective crop dryer is driven by exhaust gas waste heat for the application of drying the corn from the dryer.
- To generate a forced convection with the help of air fan that increases the amount of air turbulence and air velocity which enhanced vapour removal during the drying process and a best drying time.
- The chicken feather fibre is best suited for highest insulation property and highest thermal conductivity which are 114.63 m^2 k/W and 0.0549 W/mK; the effective insulator with lowest thermal conductivity is suitable for the solar dryer. The modern aluminium borate foams (ABFs) as thermal insulators were prepared by the technique of manageable foam-casting.
- The addition of reflected north wall in the modified global solar radiation capture model reported that the radiation capture rate enhanced about 31.57%, 23.24% and 37.58% at 50°, 40° and 30°N latitude in winter. And the average efficiency with reflected north wall is 5% and 4.35% larger under forced and natural convection methods correspondingly as compared to without using reflected north wall.
- The solar dryer incorporated with an external reflector and open solar dry technique that has external reflector enhances the energy input and reduces the drying time than the OSD technique, the absorber has enhanced thermal energy from the reflector and the time of drying is considerably reduced. In natural convective solar dryer, the absorber efficiency is enhanced from 40.0 to 58.5% by the use of effective reflectors without load parameters under the uttermost solar irradiance circumstances during a north and south in January.
- Solar dryer with a sensible heat storage system indicates that the research is primarily concerned with the quantity of material needed, the appropriate porosity of the packed bed and the overall effectiveness of the solar dryer for many kinds of SHS materials. The collected

data showed that the efficiency of the solar dryer with sensible heat storage enhanced by 2.47% at night when compared to the case without storage.

- The SAHP system's practise is beneficial for thermal efficiency. Due to the assistance of solar energy, SAHP systems have greater COP values than HP systems. As a result, the drying process is simpler than it would be in nature. Apples may be dried quickly by combining a heat pump and sun dryer using this technique. Both dryers working together are said to be more effective. The DPSC system may be used as a household hot water supply as well as a drying system for homes.
- Using four fluid types say nanofluid (Al_2O_3, 4%), engine oil (10W-40), glycerin and water in parabolic trough solar collector for drying apple slices with a 5-mm thickness, the findings indicated that for water, oil, glycerin and nanofluid, the total input thermal energy for the dryer was around 17.36 MJ, 18.46 MJ, 17.76 MJ and 16.80 MJ.
- According to numerical modelling, the efficiency of the hybrid geothermal PCM flat plate solar collector dryer is 20.5% more than that of the traditional flat plate solar collector when the mass flow rate is 0.02 kg/s.
- The drying performance of the SPE and HIP dryers using fruits such as mangoes and pineapples was compared with the conventional open-sun drying (OSD) method, and the results indicated that the drying times of SPE, enhanced HIP and OSD for drying fruits are 600 min, 1080 min and 1800 min respectively. Therefore, the drying efficiency of SPE and enhanced HIP is 18% greater than the OSD method.
- Testing the green chillies lightened at 194 °F and 158 °F and solar dried for 3 min without and with PCM under forced and natural convection conditions. PCM reduced the drying time by 17–20% (natural convection) and 35–38% (forced convection).
- External reflector improved the thermal efficiency and reduced the drying time in solar dryer. The temperature of the dryer using external reflectors was increased to 20% when compared to open solar drying.
- The impact of the sun monitoring system on tomato slices is assessed using the effective moisture diffusivity, activation energy and drying time. According to the data from the solar monitoring system, the drying time was cut in half to 36.6%, and moisture diffusivity was raised to 9.1–64.6%. As a consequence, the sun tracking system may be a viable tactic for advancing the industrialization of solar drying technology while simultaneously accelerating the solar drying process.
- PCM helps to increase the dryer's performance; the process of drying agricultural and food produce with solar dryers may reduce the cost of fossil fuel by 27–80%. The cost of drying 1 kg of dried goods was $0.35, according to the profitable analysis. In comparison to the MMSCD's total lifetime, the MMSCD's payback period was shown to be short (9 months) (15 years). The thermal efficiency and pick-up efficiency of the solar dryer were improved employing the energy storage system in a mixed-mode solar dryer. The drying processes in packed bed thermal energy storage systems would gradually enhance energy and exergy efficiency, and a mathematical model was constructed to estimate the moisture evaluation.
- The performance of the dryer is enhanced by using phase change material (PCM). Twenty-seven to eighty percent of the drying process can be reduced through solar dryer for agriculture and food products. The drying time can be minimized up to 48% when compared to natural sun drying in the solar dryer. The annual payback period is too short which is found to be 15.24 months compared to the lifetime of the dryer which is 180 months. The double-pass solar dryer had greater yearly expenditures than the other cabinet kinds of dryer, according to the study.
- A multi-pass solar air heating collector with granite as a practical energy storage matrix was employed to dry the *Hibiscus sabdariffa*. The findings of this study showed that MPSAHC dryer was 1260 min quicker than open-sun drying strategy under conditions of daily average solar irradiance, relative humidity, wind speed and ambient temperature of 635.49 W/m^2, 64.5%, 0.81 m/s and 32.24 °C.
- The solar drying systems can reduce drying time by up to 86% savings; are cost-effective; and improve performance efficiency.

Author contribution Rasaiah Naveenkumar: conceptualization; Manickam Ravichandran: supervision; Ravikumar Harish: methodology; Jegan Joywin Ruskin, Annadurai Kolanjinathan: investigations, writing; Rasaiah Naveenkumar, Nagarajan Pozhingiyarasan, Manickam Ravichandran: original draft; Rasaiah Naveenkumar: writing—original draft; Manickam Ravichandran: validation.

Data availability Not applicable.

Declarations

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Consent for publication Not applicable.

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