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Solar dryers as a promising drying technology: a comprehensive review

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Abstract
Dryers are utilized in food industry and agriculture in order to extend the useful lifespan of corps. Thermal energy is required for water removal in the process of drying which can be provided by different sources. Solar thermal energy is one of the most applicable sources for drying processes with several benefits such as avoidance of greenhouse gas emission and availability. Regarding the involvement of various factors in the performance of solar dryers, this paper focuses on the works conducted on these systems. In this regard, various types of solar dryers including direct, indirect, mixed-mode and hybrid supplied by solar energy are discussed. According to the outcomes of this review paper, it can be determined that the performance of the solar dryers depends on various parameters such as the type of dryer, solar irradiation, drying time and operating condition. Moreover, it is found that there are several approaches applicable for improving the overall performance of the solar dryers such as utilizing thermal energy storage units, applying solar tracker and using modified materials. Furthermore, there is high potential for integrating the solar dryers with other systems to achieve higher efficiency and reliability. In addition to energy analysis and drying capacity, the solar dryers have been investigated more deeply by applying exergy analysis and the dependency of exergy efficiency on the operating factors are discussed. Environmental analysis conducted on solar dryers reveals high potential of these systems in carbon dioxide mitigation. In addition, the determined payback periods of these systems are acceptable in majority of the investigated cases which shows their advantage in term of economy.

Keywords Dryer · Solar energy · Hybrid systems · Renewable energy · Exergy analysis

Introduction

Drying is widely used in agriculture and food industry for several purposes including the extension of useful life of crops by removing their water content, further processing of crops or providing new products with different properties from the original form of fresh crops [1]. The majority of the currently used dryers use fossil fuels; however, owing to the issues associated with the utilization of fossil fuels including the emission of harmful gases such as carbon dioxide and NO_x in addition to their increasing price, renewable energy sources can be altered in these systems [2, 3]. Renewable energy sources can be used for providing the thermal energy required for drying process or can be applied as the power source for some of the components or accessories such as fans used in the dryers. For the cases of providing the required heat for the dryers, solar and geothermal sources are mainly used.

Among different alternatives, solar energy is one of the most attractive choices for dryers regarding its availability in high extent in different regions of the world and the possibility of generating power in small scale for driving the fans used in the drying systems. Solar dryers can be used in both rural and urban regions with different capacities. In general, the thermal energy of the solar irradiation is applied to supply the required heat for drying the crops and other materials. Moreover, by using solar facilities such as

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photovoltaic (PV) panels, electricity can be produced for the components of the dryers such as the fan. In addition, solar systems can be used with other energy systems in the dryers that are known as hybrid systems. The performance of the solar dryers is under the influence of different factors including the structure and architecture of the systems, solar irradiance and operating conditions. Since solar dryers are beneficial in terms of environment and availability, several studies have been performed to investigate the factors affecting the performance of these systems and improving their efficiency.

Solar dryers are conventionally categorized as direct, indirect, mixed-mode and hybrid types. There are several studies on each of the mentioned solar dryers that have investigated them from different points of view. According to the knowledge of the authors and their search findings, despite some review papers on solar dryers [2], there is not update review paper on solar dryers. In addition, the present review paper considers some aspects of solar dryers, such as exergy efficiency and exergy destruction rate, more deeply compared with the previous review works. Furthermore, hybrid systems based on solar energy for drying purpose are reflected here with details, and their findings are provided which would be useful for the scholars and scientists working on the reliability and performance enhancement of dryers. In the following sections, the studies on each type of solar dryers are reviewed separately and their important findings are provided. Subsequently, some suggestions are recommended for the upcoming works focusing on the solar dryers.

Method

In order to perform a comprehensive review, different scientific database including GoogleScholar and SCOPUS were used to find the relevant references to be reflected and discussed in this paper. The keywords applied for search were "Solar", "Dryer", "Renewable Energy" and "Drying Technology". Different combinations of these words were used to find all of the relevant references. Afterward, the documents were checked by two of authors in order to find the ones fit the scope of the paper. In cases there was disagreement, another author was asked to finalize the decision. Several inclusion criteria are considered for the selection of proper sources. First of all, just the documents in English are considered. In addition, no limitation was applied for the publication data. Furthermore, both numerical and experimental works are considered for the review. After selection of appropriate sources that fit the scope of the review paper, the main the documents were read and summarized and their key findings were listed. Finally, according to the knowledge of the authors in the relevant fields, and the outcomes and methods of the reviewed works, some suggestions were proposed by the authors.

Solar dryers

There are several criteria that can be applied for the classification of the dryers. In the current work, the solar dryers are categorized and discussed based on their working principles. In the following subsections, each type of the solar dryers is comprehensively reviewed to produce useful insight into these systems for the scientists and researchers working on them. In addition, some of the methods used for the performance enhancement of solar dryers such as using tracking system and Phase Change Materials (PCMs) [4], as the thermal storage unit, are discussed and represented.

Direct solar dryers

In the direct solar dryer, which is one of the main classes of dryers, the substance that is supposed to be dried is located in a transparent enclosure. Solar radiation, due to its thermal energy content, causes the drying of the material. In addition, thermal energy would be built up inside the enclosure owing to the greenhouse effect. In order to gain the maximum solar irradiance, the chamber is painted black in these types of dryers [1]. Gbaha et al. [5] investigated the performance of direct solar dryer with natural convection for which the schematic diagram is shown in Fig. 1. It was found that by increasing the temperature of drying air and its mass flow rate, the drying rate of the system was improved. It can be attributed to the higher thermal energy content of air that is applied as drying medium. The drying time is another factor that affects the drying rate in direct solar dryers. For instance, according to the results of a study done by Saleh et al. [6], it was observed that the moisture ratio reduced more significantly at the beginning of the drying time.

In some studies, models have been proposed based on the experimental data for the direct solar dryers. For instance, Dissa et al. [7] conducted experiments on direct solar dryer with four trays, as shown in Fig. 2, and utilized the experimental data for the modeling. It was observed that the drying curves were dependent on the variety and appropriately fitted by two-term and approximation of diffusion models. In this case, the R^2 value was higher than 0.9888, denoting the exactness of the proposed model.

Despite the simple structure of the direct solar dryers, due to some disadvantages such as the difficulty in controlling the temperature, these types of dryers have not been investigated as much as the other dryers; however, the mixed-mode and some of the hybrid types utilize the working principles of direct solar dryers. In Table 1, the main findings of the studies on the direct solar dryers are summarized.

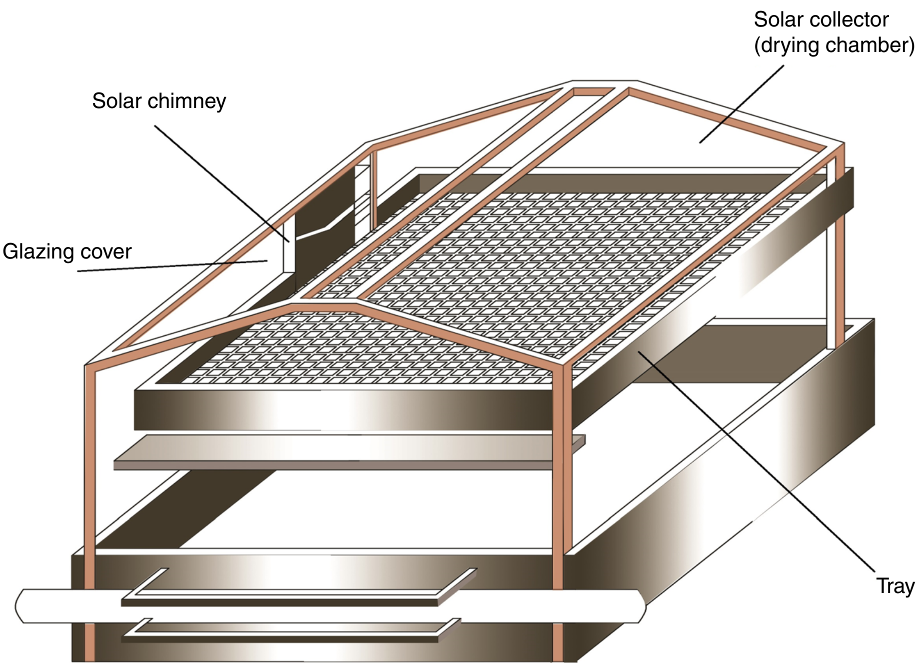


Fig. 1 Schematic of direct solar dryer with thermal circulator (adapted from Ref. [5])

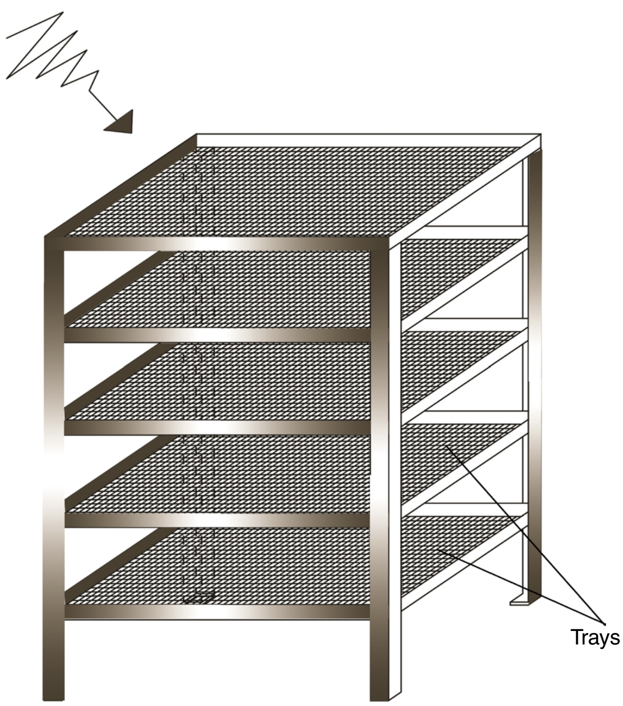


Fig. 2 Direct solar dryer with four trays (adapted from Ref. [7])

Indirect solar dryers

Another main type of the solar dryers is known as indirect type. In this type of dryers, solar irradiance is not directly applied on the material to be dried. To dry the materials, air as a medium is heated up elsewhere by using the solar irradiance and used for the drying process [8]. In this condition, the processes are more controllable compared with these of the direct types. Moreover, indirect dryers can be employed for cases that the direct irradiance is harmful for the material, i.e., the vitamin content can be destroyed [1]. The performance of these dryers is under the effects of several factors [9]. For instance, Lingayat et al. [10] used the same trays in an indirect solar dryers as shown in Fig. 3, and compared the moisture removal of the substances in the trays with the condition of open sun drying. They found that the highest removal of the moisture occurred in the first tray of the dryers and decreased by moving to the upper trays; however, the final moisture content in all trays of the dryers was lower than the case of open sun drying process. Higher moisture removal in the trays located in the lower positions could be attributed to the higher temperature of heated air at these positions compared with the upper locations. Operating condition is another factor influencing the performance of the indirect solar dryers. According to the results of a study on an indirect solar dryers [11], the increase in ambient temperature caused reduction in energy utilization ratio which is defined as the ratio of utilization of energy to the energy gained from sun.

By integrating the indirect solar dryers with some facilities such as solar tracking system, the performance of the system can be improved; however, it may not be justified in term of cost due to construction and labor requirement [12]. Another unit that can improve the performance of the indirect solar dryers is thermal storage [13–15]. Studies have shown that utilization of storage units in renewable systems could cause enhancement in the performance [16].

Table 1 Main findings of the works on the direct solar dryers

References	Application	Main findings
Gbaha et al. [5]	Drying banana	Increase in the drying air temperature and mass flow rate caused drying enhancement
Saleh et al. [6]	Drying local herbs	Increase in drying time caused lower reduction in the moisture ratio of the materials
Dissa et al. [7]	Drying Amelie and Brooks mangoes	A model was proposed for drying curves with R^2 of 0.9888

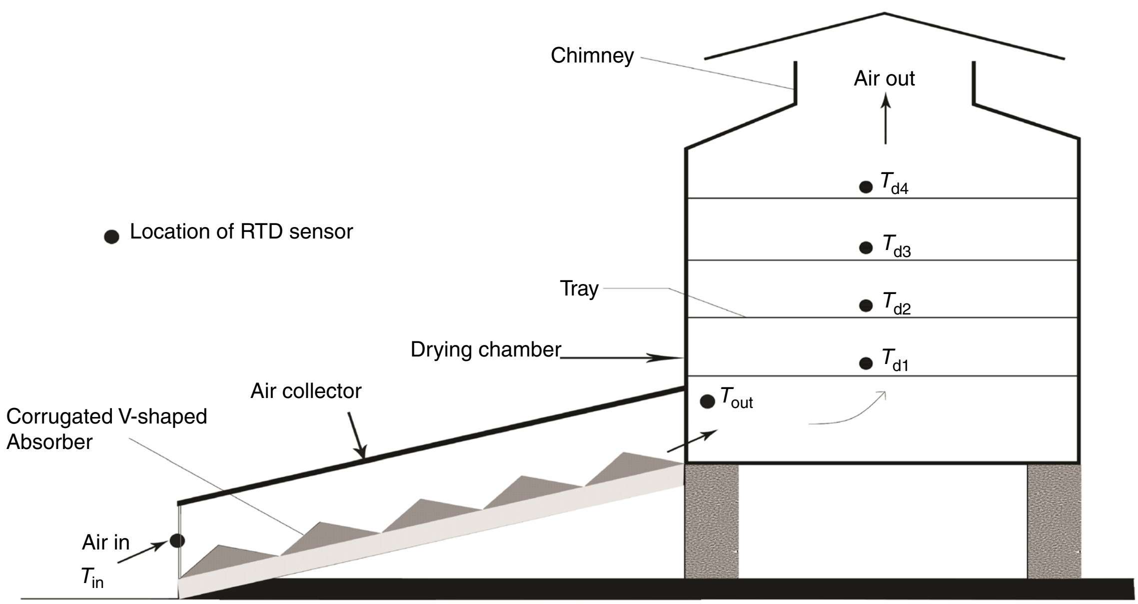


Fig. 3 Indirect solar dryers with four trays in different locations (adapted from Ref. [10])

By employing the thermal storage unit, the performance of the system could be enhanced due to the drying time elongation, since the required heat is supplied by the storage unit after sunset [17]. The performance enhancement of the dryers in case of using thermal storage unit is dependent on the storage material. Bhardwaj et al. [14] compared the effect of using sensible heat storage material and PCM on the performance of an indirect solar dryer. It was found that using both sensible heat storage and PCM caused the highest enhancement in the drying process and was followed by the sensible heat only and the PCM only storage units, respectively. Using the materials with improved heat transfer properties can enhance the performance of indirect solar dryers with PCMs. For instance, Alimohammadi et al. [18] used nanofluid in the solar collector of an indirect solar dryer, shown in Fig. 4. It was found that using the nanofluid could improve the overall efficiency by around 9.7% in comparison to water as the operating fluid. Besides the performance enhancement, utilizing thermal storage unit could be beneficial in term of economy. Lamrani et al. [19] investigated the effect of integrating thermal storage unit with an indirect solar dryer applied for wood drying. It was determined that for their case study, Tangier in Morocco, payback period of the system could be decreased by around 33% by integrating the storage unit. In addition to the abovementioned facilities, there are some others than can improve the performance of the solar dryers. For instance, Cakmak et al. [20] found that by installing swirl element inside the dryer and at the entrance of it, drying rate of the system could be enhanced. It can be attributed to the higher heat transfer rate in case of applying swirl in convective heat transfer mechanism.

In addition to energy analysis, the performance of indirect solar dryers has been investigated from exergy and environmental points of view [21–25]. For instance, in a work [26], the performance of an indirect solar dryer with thermal storage and heat recovery units was investigated based on the exergy concept. It was found that the exergy efficiency of the system in sunshine hours was in ranges of 50.18–66.58% and 54.71–68.37% for the system without and with thermal energy storage, respectively. Vijayan et al. [27] investigated the performance of an indirect solar dryers integrated with PCM as thermal storage unit by applying exergy and environmental analyses. In addition, they assessed the effects of different factors such as mass flow rate of air and drying time

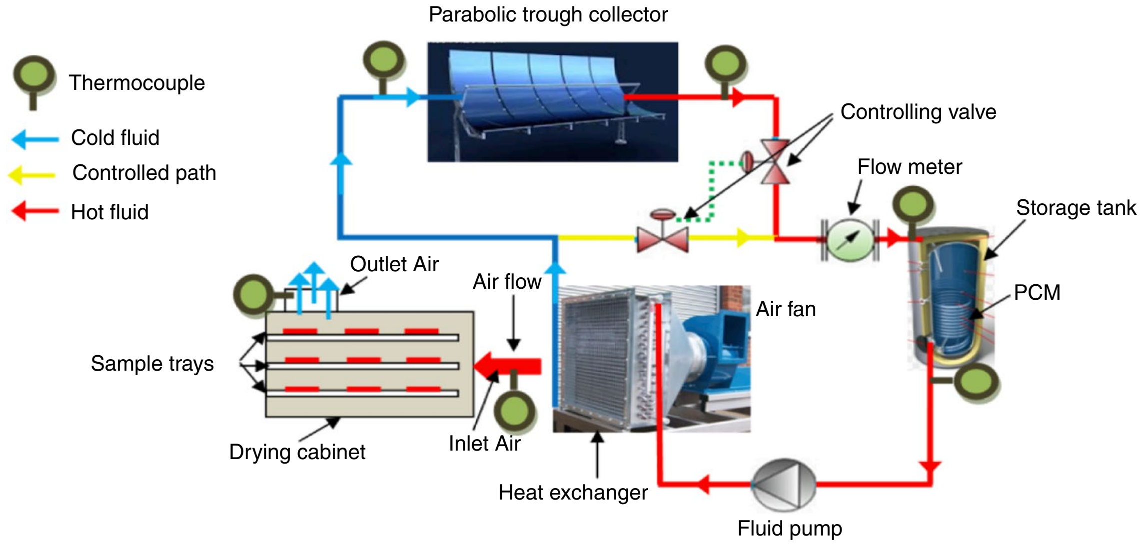


Fig. 4 Solar dryer with PCM and parabolic through collector [18]

on the exergy efficiency of the system. They observed that increase in air mass flow rate reduced the exergy loss which resulted in higher exergy efficiency of the system. Moreover, they found that the increase in the drying time resulted in higher exergy efficiency, attributed to the decrease in the exergy destruction of the drying process. The maximum exergy efficiency of the system, in case of 0.0872 kg/s air mass flow rate, was 40.68%. In addition, according to the environmental analysis, the increase in the life span of the considered system from 5 to 35 years led to a decrease in carbon dioxide emission from around 217.43 kg/year to about 31.06 kg/year.

Several models have been suggested for the performance prediction and simulation of the indirect solar dryers [28–32]. Based on these models, the potential of performance enhancement can be found [33]. For instance, Lingayat et al. [28] conducted a 2D simulation on an indirect solar dryer, with two types of tube shown in Fig. 5, and found that by roughening the surface of absorber, the heat gain of 106% could be added compared with the smooth surface dryer. In another work [34], an indirect solar dryer with two types of tube heater including hollow tube and the tube with iron mesh, as shown in Fig. 5, was examined by performing numerical simulation. It was found that utilizing the tube with meshes would result in better performance of the dryer due to its higher efficiency. The precision of the model was under the influence of different elements such as the used method and operating condition [35]. In a study done by Akpinar et al. [36], the data of drying was fitted to 13 different models. They found that employing logarithmic model in case of forced solar drying and Midilli and Kucuk model [37] in case of natural sun drying led to the highest accuracy. On the basis of the findings of this study, it can be concluded that for the selection of the most appropriate model for performance prediction of indirect solar drying system, the operating conditions must be considered. In another work [38], several drying tests were performed on the Granny Smith apples at various constant temperatures to use them in a model, proposed based on the Wang-Singh equation, in order to forecast the moisture ratio in the process of thin-layer drying. The proposed model was

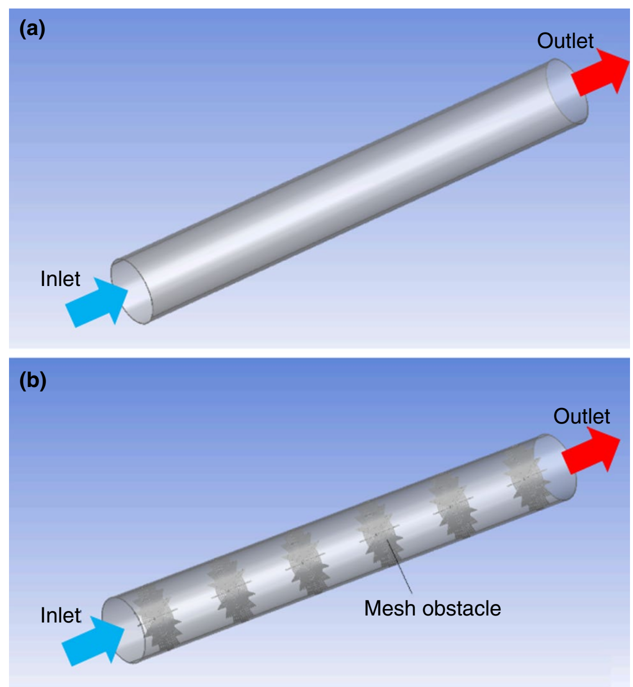


Fig. 5 **a** Hollow tube and **b** tube with mesh used in an indirect solar dryer [34]

accurate with the maximum deviation of 1.5%. Applying the same procedure for the indirect solar dryers led to the deviations lower than 10%, indicating good agreement between the model output and actual value. In another work [39], a dynamic model was proposed for an indirect solar dryer to investigate the system from exergy and energy points of view. They found that for the considered case there were critical moisture values. In one of the critical values of the moisture content (0.75), exergy destruction reached the maximum while in the second one (0.23) maximum exergy efficiency was obtained.

In Table 2, the main findings of the studies on the indirect solar dryers are summarized.

Mixed-mode solar dryers

The working principle of these types of solar dryers is a combination of the two former ones. In these dryers, the direct solar irradiance causes the drying of the substances and preheats the air in the solar collector to provide the thermal energy of drying process [1, 41]. In comparison with the direct and indirect solar dryers, applying the mixed-mode can lead to enhancement in the drying process [42, 43]. For instance, the performance of a mixed-mode dryer was compared with the same configuration in the indirect mode in an experimental work [44]. It was observed that the drying times of the tomato slices were 26 h and 17 h for the indirect and mixed-mode solar dryers, respectively. Due to the relatively efficient performance of mixed-mode solar dryers, this technology has been considered in both numerical and experimental works. In a study carried out by Abubakar et al. [45], a mixed-mode solar dryer was experimentally and numerically investigated. It should be noted that the study was conducted by considering the weather condition of Zaria in Nigeria, and the simulation was performed by using TRNSYS and MATLAB. They found that the average drying efficiency of the considered system was 25.35%. In addition, a comparison of the numerical and experimental data revealed good agreement. In another work [1], the performance of a mixed-mode solar dryer was compared with the open sun dryer. The schematic of the considered set-up of the mixed-mode solar dryer is shown in Fig. 6. It was found that drying the grapes in open sun condition took 7 to 8 days while it was decreased to 4–5 days in case of employing the mixed-mode dryer. In addition to drying the agriculture products, mixed-mode solar dryers show remarkable performance for other materials. For instance, Mehta et al. [46] compared the performance of a mixed-mode tent type solar dryer with open sun condition and observed that to reduce the moisture content of the fishes from 89 to 10%, it took 18 and 38 sunshine hours for the dryer and open sun mode, respectively.

Mixed-mode solar dryers can be simulated by using proper equations and methods. For instance, Tagne et al. [47] used fourth-order Runge–Kutta method to simultaneously solve heat and mass transfer equations of a mixed-mode solar dryer. The output of the proposed numerical simulation provided several data such as relative humidity and temperature of drying air in different locations. It should be mentioned that for accurate simulation of the dryer it is necessary to use some of the thermophysical properties of the materials which are supposed to be dried.

The performance of the mixed-mode solar dryers can be improved by some modifications for the components of the system. For instance, Stiling et al. [48] used concentrating solar panels in a mixed-mode solar dryer and found that using the concentrating panels in the system led to remarkable enhancement in the drying rate and 27% reduction in the drying time. Since exergy analysis provides better insight into the defects of the system and its potential for modification, exergy analysis can be more useful for this purpose. In this regard, some studies focused on the exergy analysis of mixed-mode solar dryers. Lakshmi et al. [49] investigated the performance of a mixed-mode solar dryer, shown in Fig. 7, by considering both energy and exergy analyses. They found that the overall efficiency of the dryer was 33.5% and the average exergy efficiency of the system was 59.1%. Moreover, according to the economic analysis, the determined payback period of the system was 0.65 year. The obtained value of the payback period reveals that there is no risk for commercializing the proposed system.

The main findings of the studies on the mixed-mode solar dryers are summarized in Table 3.

Hybrid solar dryers

In the hybrid solar dryers, the content of solar irradiance is applied for drying the materials while other technologies are employed for the circulation of the air inside the system or other purposes such as desalination, drying assistance and heating [50, 51]. For instance, the fans of the dryer systems can be driven by a power generation system such as wind turbine or PV panels [1, 52–54]. As an example, Etim et al. [55] coupled an indirect solar dryer with PV panels to produce the required power of the blowers used in the dryer. They found that by increasing the air inlet are of the dryer, enhancement in the performance of the system could be achieved. In a study performed by Fterich et al. [56], a mixed-mode solar integrated with PV/T system was experimentally investigated, where two trays were located in the system and the moisture content of the material, tomato, was measured after six days. It was observed that the moisture content of the materials decreased from 91.94 to 22.32%, 28.9% and 28.9% for the cases of the first and second trays and open sun dryer, respectively. In addition to the mentioned factors, configuration of the system and applied component affect the performance of the hybrid solar dryers. For

Table 2 Main findings of the works on the indirect solar dryers

References	Application	Main findings
Bennamoun et al. [9]	Drying agriculture products	The drying was affected by collector surface, properties of the material and temperature of air
Lingayat et al. [10]	Drying banana	The location of the substances in the drying chamber affected the final moisture
Wang et al. [8]	Drying mango slices	Average thermal efficiency of the system was in range of 30.9%–33.8%
Lamrani et al. [19]	Drying wood	Integrating thermal storage unit could reduce the payback time
Akpinar [11]	Drying mint leaves	Increase in ambient temperature caused reduction in energy utilization ratio
Mwithiga et al. [12]	Drying parchment coffee	Using solar tracking system led to enhancement in the performance of the system
Atalay [26]	Drying orange slices	Using thermal energy storage unit led to exergy efficiency enhancement of the system
Bhardwaj et al. [14]	Drying Valeriana Jatamansi	The material of thermal energy storage influenced the enhancement of the solar dryers
Vijayan et al. [27]	Drying bitter gourd slices	Exergy of the system was improved by increasing the air mass flow rate and drying time
Akbulut et al. [23]	Drying mulberry	Increase in the mass flow rate of the drying air caused reduction in the exergy loss
Bhardwaj et al. [17]	Drying valeriana jatamansi	Enhancement in the performance of the dryer by employing thermal storage unit
Tagne et al. [30]	Drying tropical wood	A model was proposed to predict the performance of the solar dryer
Sanghi et al. [32]	Drying corns	Computational fluid dynamics (CFD) was applied for the simulation of the dryer
Atalay et al. [25]	Drying strawberry slices	Fan had the lowest exergy efficiency among the components of the indirect solar dryer with PCM
Guler et al. [33]	Drying Pepino fruit	Applying mesh modification on the collector could improve the performance of the system
Alimohammadi et al. [18]	Drying apple slices	Using nanofluid in the dryer could increase the overall efficiency by 9.7% compared with water
Kesavan et al. [22]	Drying potato slices	Average pick-up efficiency of triple-pass dryer was 29.9%
Akpinar et al. [36]	Drying green pepper	Applying logarithmic model in case of forced solar drying led to the highest accuracy in the performance prediction
Sozen et al. [34]	–	Using mesh on the surface of the tube would lead to higher efficiency of the system
Vijayan et al. [35]	Drying bitter gourd	The most appropriate model for solar dryers depended on the type of system
Shalaby et al. [40]	Drying O. basilicum and T. neriifolia	Drying air temperature reached higher values in case of utilizing PCM
Cakmak et al. [20]	Drying seeded grape	Using swirl element could enhance the drying rate
Babar et al. [13]	Drying mushroom	Utilizing passive flat plate collector solar dryer led to 35–40% reduction in the drying time compared with open sun drying
Cano et al. [38]	Drying Granny Smith apples	Using the model based on the Wang-Singh equation led to accurate prediction of moisture ratio in the process of drying
Lingayat et al. [28]	Drying agriculture food product	Heat gain was increased in the dryer with roughened surface compared with the smoot surface one
Hatami et al. [39]	–	There were critical moisture ratio values in which the maximum exergy destruction and efficiency were obtained
Shringi et al. [31]	Drying garlic cloves	Drying rate was reduced by increasing the drying time
Nabnean et al. [24]	Drying cherry tomatoes	The payback period of the system was estimated to 1.37 years

instance, the effect of number of PV/T collectors on the performance of a mixed-mode solar dryer integrated with partially covered number of photovoltaic thermal (N-PV/T) collectors, shown in Fig. 8, was investigated [57]. It was found that despite the increase in the equivalent thermal energy by increasing the number of collectors, the equivalent thermal and exergy efficiencies decreased. In another study [58], vertical kind PVT dryer was investigated in case of integrating fins over the absorber plates and the PV cells. They utilized a parameter known as waste exergy ratio, indicating the ratio of exergy loss to constituent exergy input, to compare the systems in different conditions. It was noticed that waste

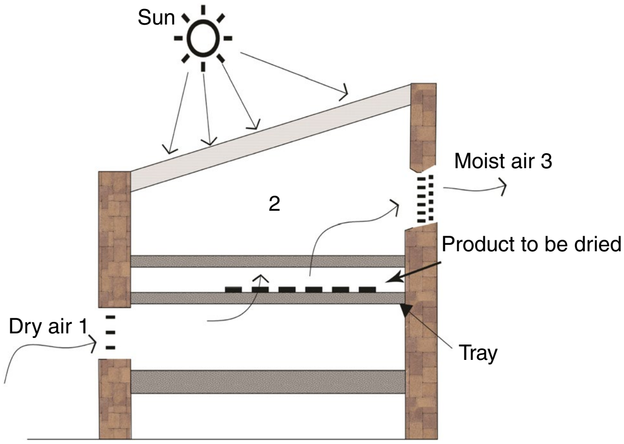


Fig. 6 Mixed-mode solar dryer used for drying grapes (adapted from Ref. [1])

exergy ratio for the finned and finless configurations were in the range of 0.43–0.56 and 0.47–0.58, respectively. In addition to energy and exergy analysis, the hybrid solar dryers with PV/T system can be investigated from environmental point of view. For instance, Tiwari et al. [59] performed an exergoeconomic analysis on a hybrid solar dryer with PV/T system and found that by elongating the lifespan of the system from 5 to 25 years, carbon dioxide mitigation increased from 12.95 ton to 81.75 ton.

Similar to the other types of solar dryers, the hybrid ones can be integrated with thermal storage unit to improve their performance and make them applicable in the hours when there is not solar irradiance [60, 61]. Baniasadi et al. [62] experimentally investigated a mixed-mode solar dryers integrated with PV panel, battery and PCM, as the thermal energy storage unit. They found that in case of using the PCM, drying time of the considered substance decreased by around 50%, indicating significant enhancement in the performance of the system. Besides utilization of thermal storage unit, some novel ideas have been proposed to extend the drying time of solar dryers. For instance, in a configuration proposed by Ceylan et al. [63], a halogen lamp was added to a hybrid solar dryer composed of PV panel, heat pipe collector, battery and fan. In this configuration, the drying time would be extended due to increase in the temperature of the air used for drying the material by switching on the lamp. For the PV-assisted solar dryers, applying other technologies such as tracking system can lead to further enhancement in the performance. Akhijahani et al. [64] used tracking system in a PV-assisted solar dryer and found that using tracking system remarkably reduced the drying time. This reduction could be attributed to the increase in the collector and inside air temperatures due to the utilization of tracking system. In addition to PV panels, other renewable-based energy technologies can be used for running the fans used in hybrid solar dryers. For instance, Ndukwu et al. [65] applied wind turbine generator for driving a fan used in a mixed-mode solar dryer and found that it would be possible to improve the drying rate of the system by using the wind turbine for driving the fan. Other renewable energy technologies can be employed for the performance enhancement of hybrid solar dryers in different ways. Sandali et al. [66] used geothermal water heat exchanger in a

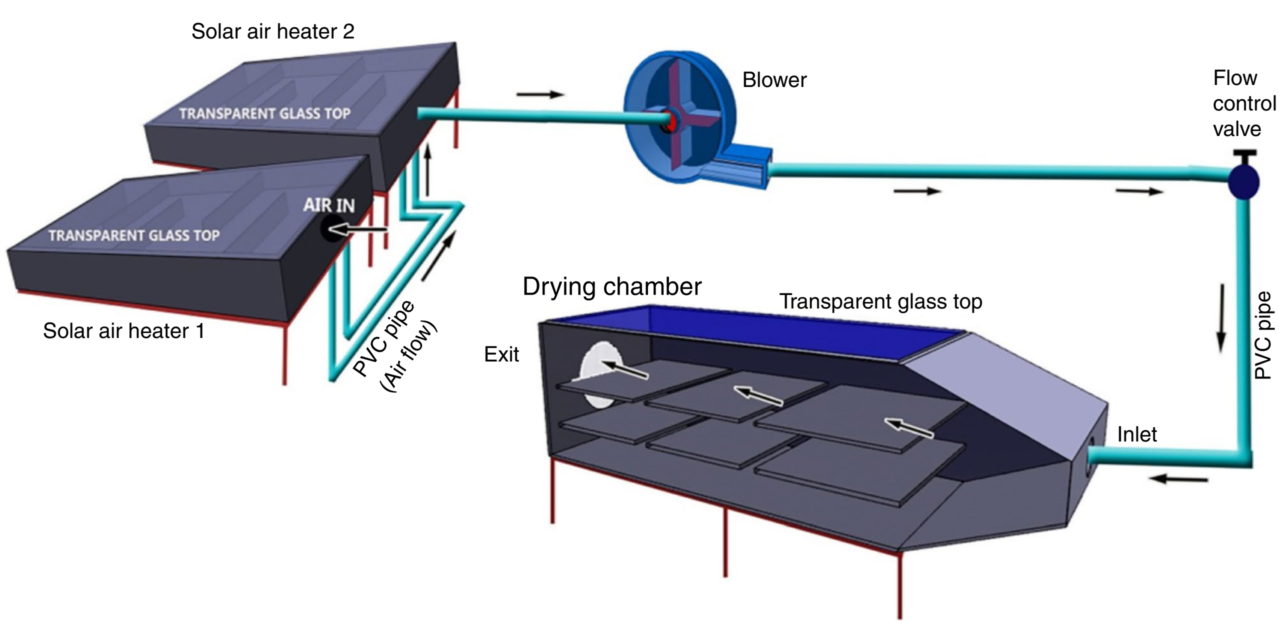


Fig. 7 Schematic of a mixed-mode solar dryer [49]

Table 3 Main findings of the works on the mixed-mode solar dryers

References	Application	Main findings
Abubakar et al. [45]	Drying yam slices	By applying TRNSYS and MATLAB for simulation, the performance of the dryer could be accurately predicted
Montero et al. [42]	Drying olive pomace	Using the mixed-mode dryers could result in enhancement of the drying process compared with indirect one
Cesar et al. [44]	Drying tomato slices	Using mixed-mode solar dryer led to significant lower drying time compared with the same configuration in indirect mode
Gatea [41]	Drying beans	Solar radiation, temperature of inlet air and design factors affected the performance of solar dryer
Mehta et al. [46]	Drying fish	Compared with open sun mode, using mixed-mode solar dryer led to significant acceleration in drying of the fishes
Ayua et al. [43]	Drying vegetable and chili	Using mixed-mode dryer led to faster drying compared with direct type
Lakshmi et al. [49]	Drying stevia leaves	The payback period of the system was 0.65 year
Stiling et al. [48]	Drying fruit	Using concentrating solar panel led to remarkable enhancement in the drying rate
Tagne et al. [47]	Drying red chili	Mixed-mode solar dryers could be accurately simulated by using appropriate approach
Pardhi et al. [1]	Drying grapes	Using the mixed-mode and open solar dryer took 4 and 8 days, respectively, for drying the grapes

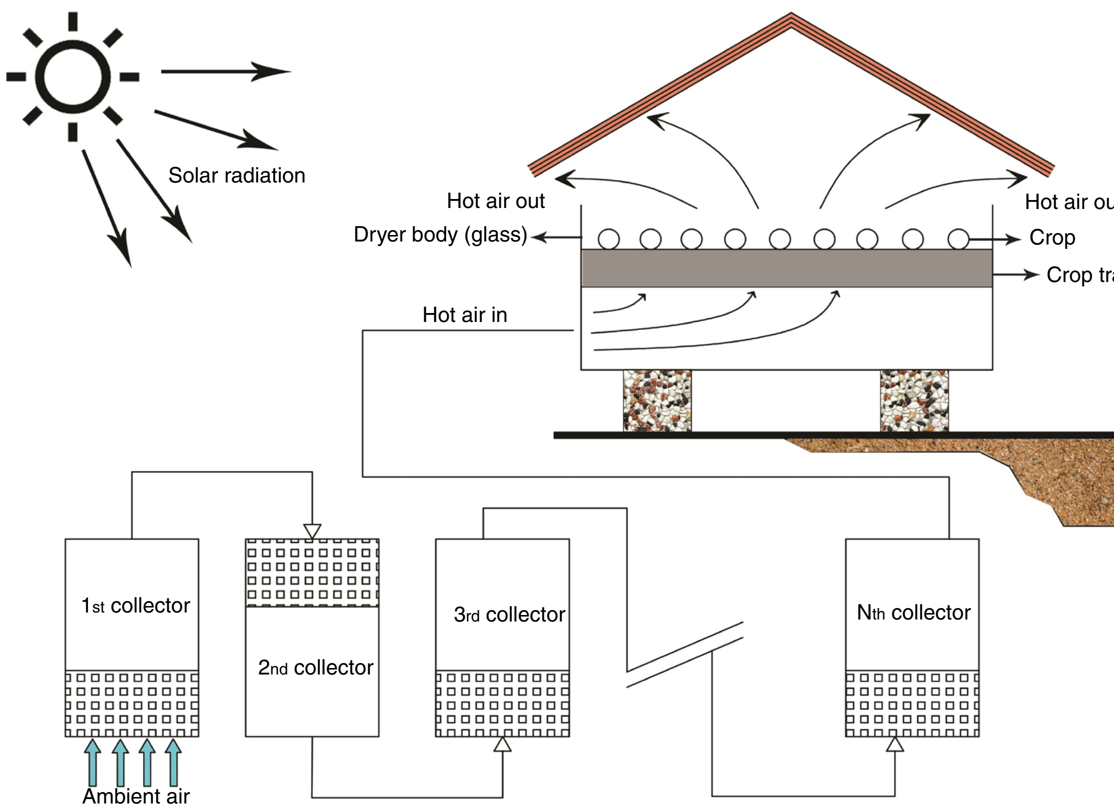


Fig. 8 Mixed-mode solar dryer with different numbers of PV/T collectors (adapted from Ref. [57])

direct solar dryer and found that by employing this idea it was possible to ensure the performance continuity of the dryer even in night hours.

Other technologies such as desalination units can be integrated with the solar dryers. For instance, Kabeel et al. [67] coupled humidification–dehumidification (DHD) desalination unit with a two-stage indirect solar dryer. The schematic diagram of the considered system is shown in Fig. 9. They considered the effects of several parameters on the overall performance of the system. In this study, it was observed

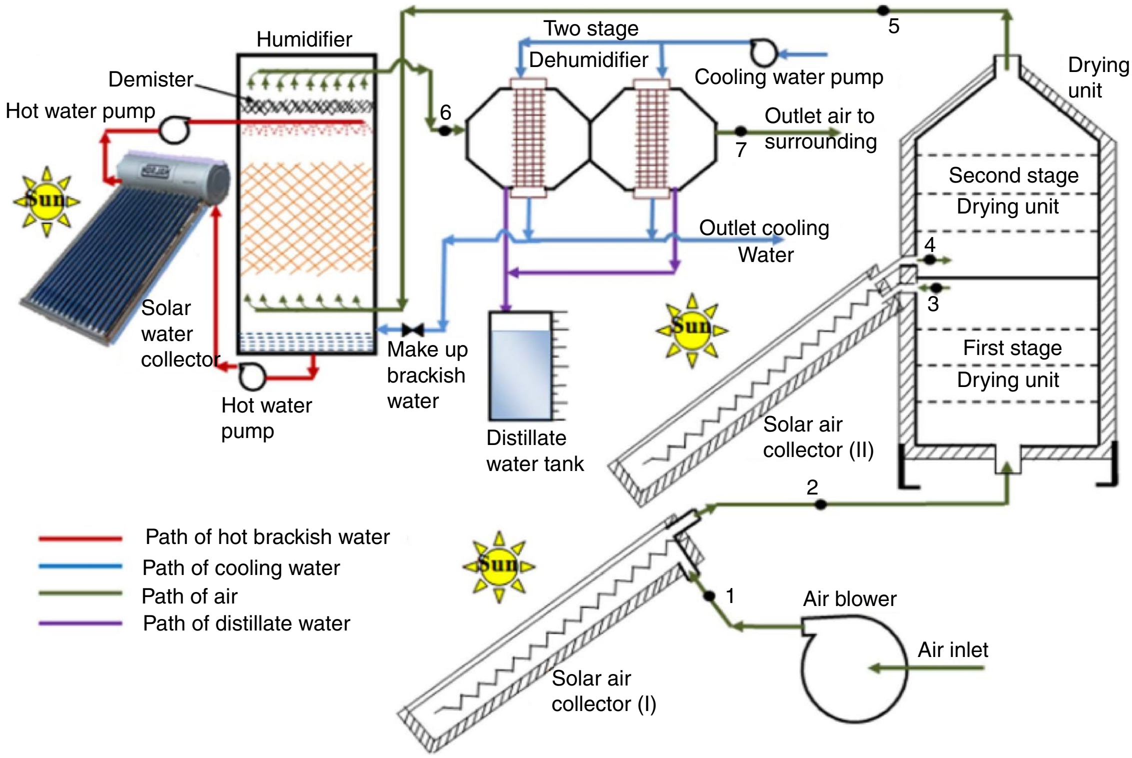


Fig. 9 Indirect solar dryer coupled with DHD desalination [67]

that increasing the mass flow rate of the air, productivity of distillate water increased. Moreover, comparison of the two-stage and single-stage configurations revealed significant enhancement of moisture removal in case of employing two-stage architecture. In another work [68], an indirect solar dryer was integrated with the condenser section of an air conditioning system reach higher efficiency. The schematic of the designed system is shown in Fig. 10. By using this configuration, the requirement for the fan or blower for moving the air was eliminated. Moreover, it was observed that by integrating the indirect solar dryer with the air conditioning system, dryer efficiency could increase by 13%.

Another system that can be integrated with solar dryer for the performance enhancement is heat pump [69]. In a study performed by Mortezapour et al. [70], a hybrid system composed of PV/T solar dryer and heat pump was designed

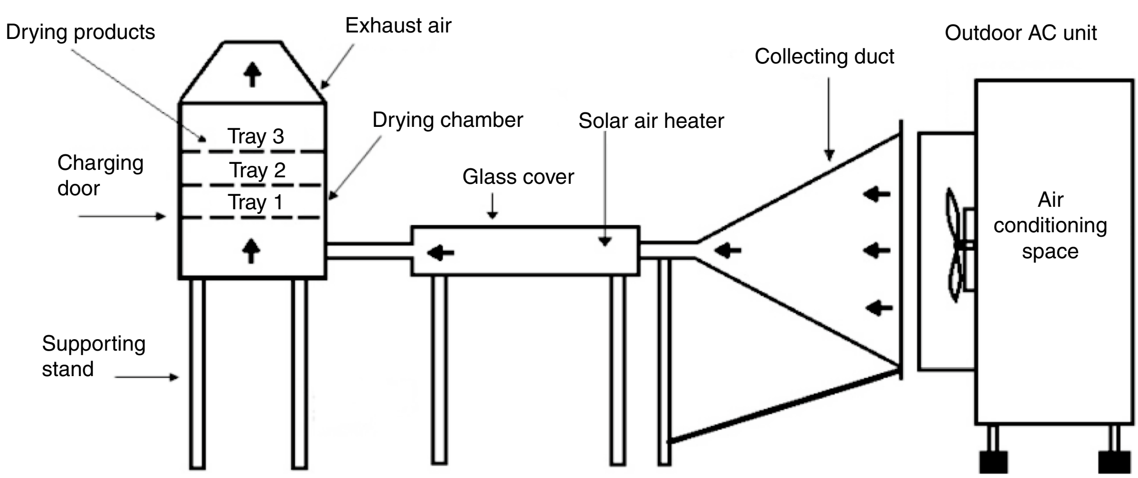


Fig. 10 Indirect solar dryer integrated with air conditioning system [68]

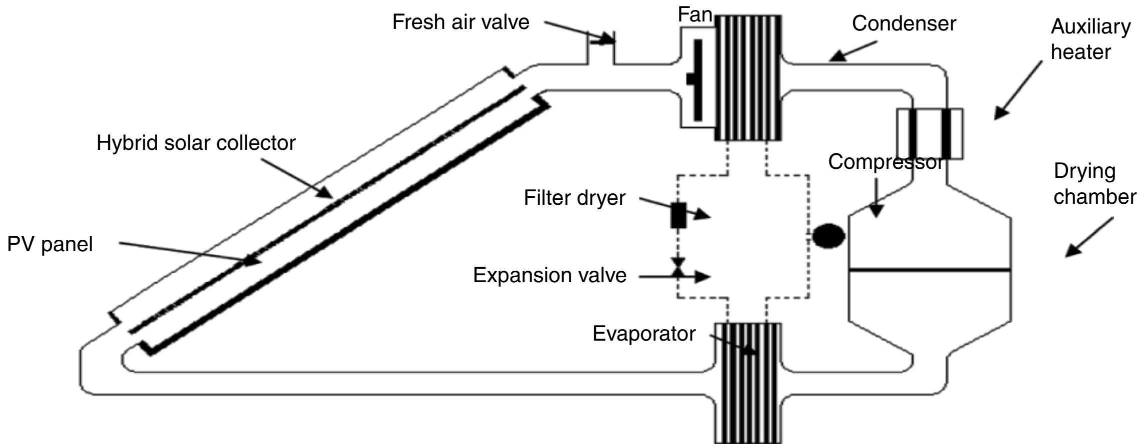


Fig. 11 Schematic diagram of PV/T dryer with heat pump [70]

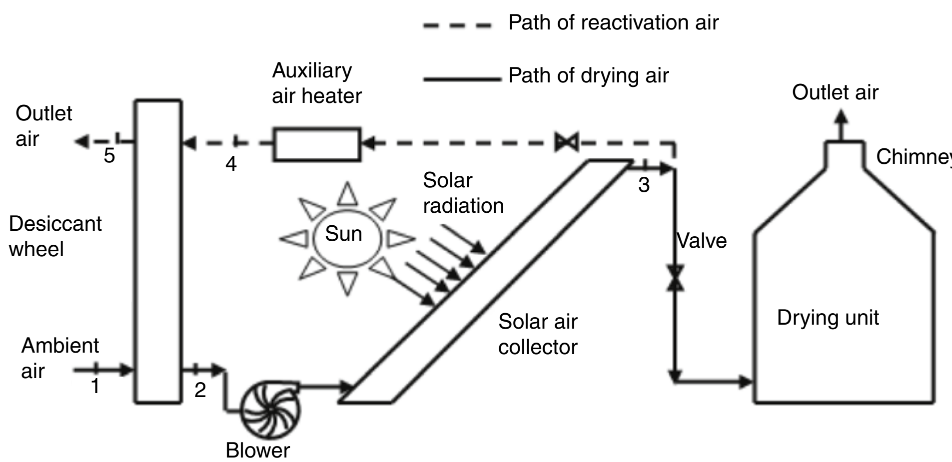


Fig. 12 Solar dryer with desiccant wheel [71]

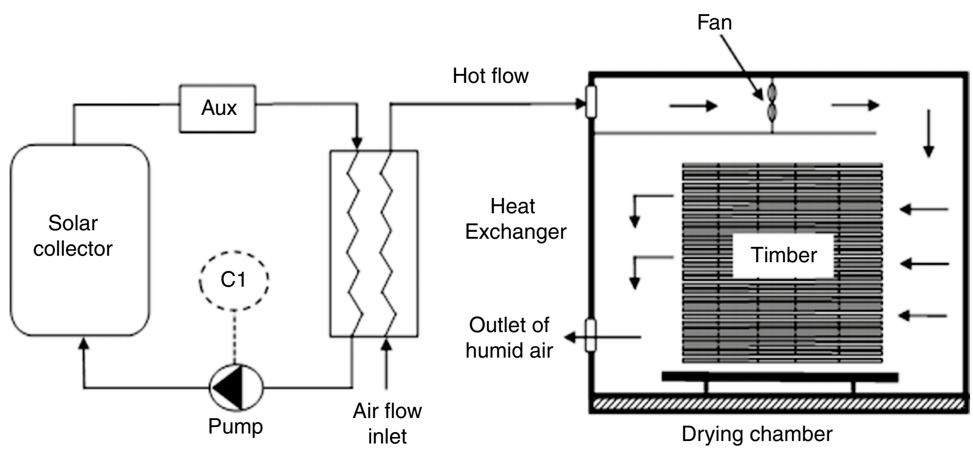
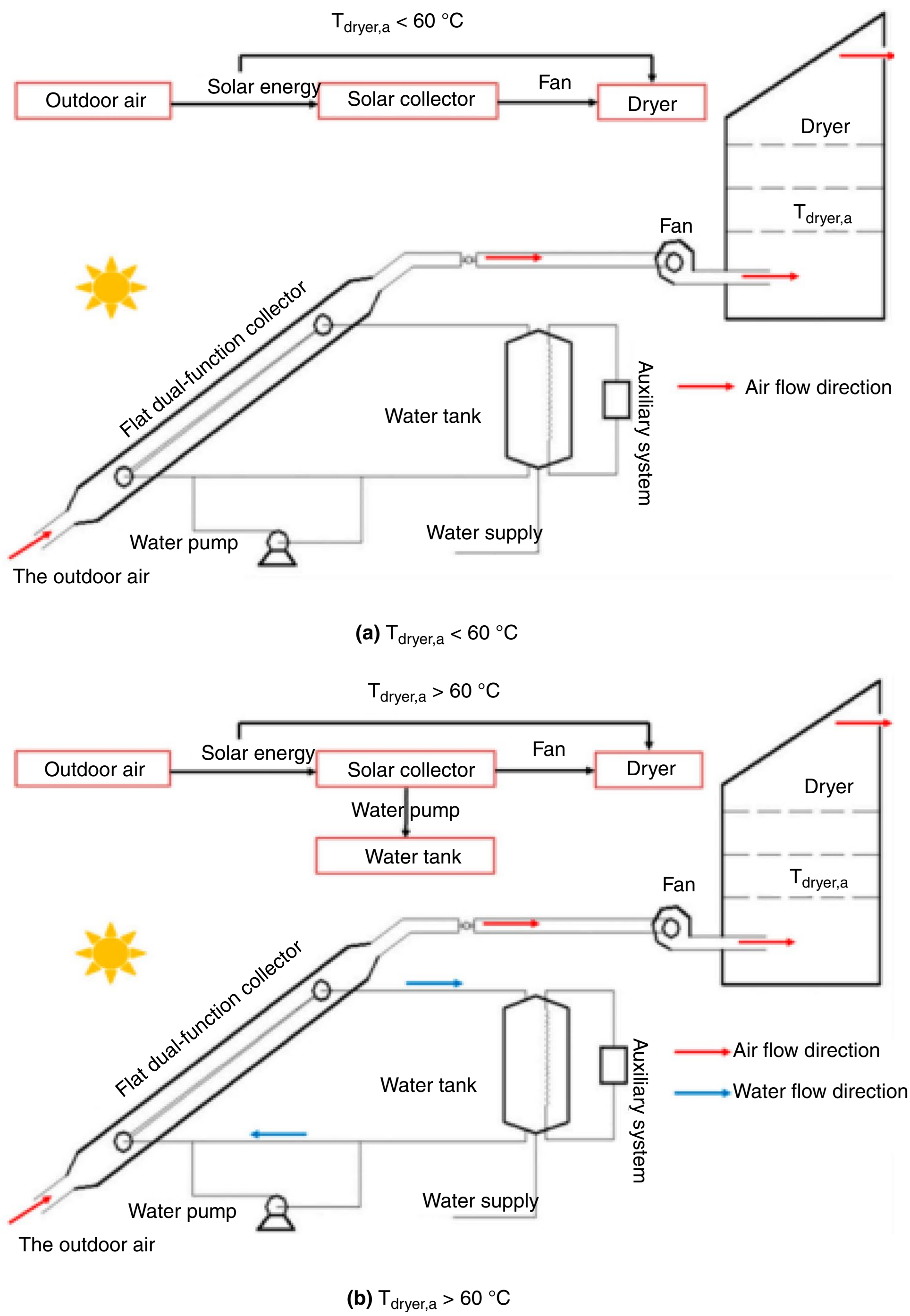


Fig. 13 Hybrid solar dryer with auxiliary heater [72]

as shown in Fig. 11. It was observed that integrating the heat pump with the dryer, the average consumption of total energy reduced by 33%. In addition, it was found that the proposed system could reach high efficiency, up to 72%. Moreover, it was concluded that increasing the air temperature and its mass flow rate, the efficiency of the system in both modes, with and without heat pump, increased. Desiccant wheel, a rotary dehumidifier, is another unit that can

Fig. 14 Schematic diagram of a hybrid solar dryer in different modes [75]



improve the performance of solar dryers. In a study conducted by Kabeel et al. [71], a new configuration of solar dryer, as shown in Fig. 12, with desiccant wheel was introduced and tested. They found that employing the wheel in the solar dryers led to 153% in average useful heat gain in comparison with the system without the wheel. In another work [72], an indirect solar dryer was integrated with an auxiliary heater to provide the required thermal energy of the dryer in case of low solar radiation. The schematic diagram of the system is shown in Fig. 13. According to the output of the simulation obtained by applying TRNSYS, employing the solar collector, energy consumption of the auxiliary heater decreased which led to lower emission of carbon dioxide. It should be mentioned that renewable

Table 4 Main findings of the works on the hybrid solar dryers

References	Application	Main findings
Tiwari et al. [57]	Drying different crops	Increase in number of PV/T collectors caused increase in equivalent thermal energy while the equivalent exergy efficiency reduced
Kaewkiew et al. [51]	Drying chili	The required times for appropriate drying of the chili were 3 and 5 days for cases of hybrid drying system (with PV) and natural sun, respectively
Tiwari et al. [59]	Drying different crops	Elongation in the lifespan of the system caused higher carbon dioxide mitigation
Etim et al. [55]	Drying cooking banana	Increase in the air inlet caused performance enhancement
Vasquez et al. [60]	Drying agro-product	A model was proposed for the performance prediction of the system
Goud et al. [54]	Drying green chili and okra	The drying efficiency of the system was dependent on the materials used for drying
Baniasadi et al. [62]	Drying apricot slices	Using thermal energy storage led to around 50% reduction in the drying duration of the substances
Reyes et al. [61]	Mushroom dehydration	Significant improvement in the thermal efficiency was achievable by integrating PCM with the hybrid solar dryer
Fterich et al. [56]	Drying tomatoes	Using the mixed-mode dryer with PV/T system led to significant reduction in the moisture contents of the materials
Ceylan et al. [63]	Drying tomato	Using halogen lamp led to drying time extension
Kabeel et al. [67]	Drying mango slices and desalinate water	Using two-stage unit led to enhancement in the drying compared with the single-stage one
Chandrasekar et al. [68]	Drying grapes	Integration of the dryer with air conditioning system could lead to 13% increment in efficiency
Mortezapour et al. [70]	Drying saffron	Average total energy consumption reduced by 33% in case of integrating heat pump
Akhijahani et al. [64]	Drying tomato slice	Using tracking system could significantly accelerate the drying of PV-assisted solar dryer
Sandali et al. [66]	–	Using geothermal water heat exchanger improved the performance continuity of the system
Kuan et al. [69]	Drying banana slices	Average coefficient of the performance (COP) of the heat pump assisted solar dryer was 2.72
Ndukwu et al. [65]	Drying potato slices	Applying wind turbine for running a fan of mixed-mode solar dryer in addition to integrating thermal storage unit could significantly improve drying process
Kabeel et al. [71]	Drying different materials	Using the desiccant wheel in the solar dryer significantly increased useful heat gain
Lamrani et al. [72]	Drying wood	Using the solar collector in the hybrid system led to reduction in the energy consumption of auxiliary heater and carbon dioxide emission
Hao et al. [75]	Drying lemon slices	Payback period of the system was 3.63 years

energy-based heater, such as the ones using biomass [73, 74], could be integrated with the solar dryers to make them more appropriate in term of environment.

In addition to the abovementioned analyses, other kinds of analysis have been carried out on the hybrid solar dryers. For instance, Hao et al. [75] performed 4E analysis including energy, exergy, economic and environment on different modes of hybrid solar dryers that is schematically shown in Fig. 14 Schematic diagram of a hybrid solar dryer in different modes. In the economic analysis, construction and material costs were considered as the capital costs while for the operation cost of the system only the electricity consumption, applied for fan and pump, was considered. Moreover, they considered 1% capital cost as the maintenance cost of the system. According to their analysis, the payback period of the system was estimated to be 3.63 years and carbon dioxide reduction of the system was 21.79 kg/batch. Moreover, the exergy efficiency of the drying cabinet was estimated in the range of 39.38–71.7%. They observed the highest value of exergy efficiency on the end of drying day that was similar to some previous works.

In Table 4, the main findings of the studies on the hybrid solar dryers are summarized.

Recommendations for the future works

Despite carrying out several modifications on the various types of solar dryers, there are some novel ideas that can lead to further enhancement in the performance of these systems. One of these ideas is employing nanotechnology. Studies have shown that using nano-incorporated composites in the thermal energy storage system could enhance thermal energy absorption [76], which would lead to performance enhancement of the solar dryers integrated with storage units. Moreover, using nanotechnology in some other components of the solar dryers can enhance the overall performance of the system by improving the photo-thermal characteristics of the material. Studies have shown that utilization of nanofluids for heat transfer could improve the performance of the systems [77–79]. In this regard, nanofluids with enhanced thermophysical properties could be attractive alternatives for the operating fluid of the dryers' components such as collectors and heat exchangers [80]. Furthermore, nanofluids could be applied for improving the generated power of PV cells by cooling them, which would cause higher efficiency and electrical output [81]. Besides the mentioned hybrid systems for supplying the power of dryers, other types of renewables with applicability for electricity generation, i.e., geothermal [82], can be integrated with solar systems to provide the required energy of dryers.

In addition, different configurations of fans/blower can be tested in the solar dryers to find the most appropriate arrangement. For this purpose, numerical simulations of different cases would be an applicable and feasible approach. Furthermore, performing optimization on the design variables of the solar dryers may cause obtaining dryers with improved performance and efficiency. These suggestions are provided for the practical and experimental works; however, some suggestions can be recommended for the works focusing on the modeling of solar dryers. For instance, due to the applicability of intelligent techniques in modeling complex systems [83, 84], it would be useful to employ these approaches for the modeling of solar dryers and predicting their performance. Regarding the ability of these methods, it is expected to forecast the outputs of the solar dryer systems with high precision by considering all of the influential factors as the inputs of the models.

Conclusions

Dryers can utilize different sources of energy to supply the required thermal energy for drying processes. Solar dryers are attractive options due to their relatively high efficiency and low greenhouse gas emission. Different types of solar dryers have been reviewed in this work, and the main findings are as follows:

- Configuration and type of dryer in addition to operating conditions are among the most influential factors on the performance of solar dryers.
- By applying storage unit it would be possible to extend operating hours and consequently improve the performance of solar dryers.
- In addition to storage unit, utilization of other technologies such as tracking system could improve the performance of solar dryers.
- Modification on the dryer components and applied mediums causes performance improvement.
- Solar dryers can be integrated with different systems such as heat pumps, PV modules and desalination unit. In case of integration with other technologies, the overall performance would be improved.
- Exergy analysis has been applied for deeper analysis of solar dryers. It is found that operating condition and drying duration affect the exergy efficiency of these systems.
- Various models have been introduced for the solar dryers. Exactness of these models is dependent on the utilized approach.
- Comparing the dryers with assistance of solar energy and the ones utilizing just fossil fuels or electricity reveals high potential for mitigation of carbon dioxide.
- Payback period of the solar dryers is dependent on some factors such as the type of system; however, it is reasonable in the investigated cases.

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