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Improvement of the Thermal Performance of Solar Drying Systems Using Different Techniques: A Review

Solar drying is one of the most important processes of preserving agricultural products. This review paper focused mainly on the enhancement of efficiency a solar drying system. The establishment of different techniques and factors, which may affect the performance of solar dryers, helps to improve solar dryers' effectiveness. Different types of solar dryers were described here; moreover, various performance analyses of solar drying systems (SDSs) were presented. Factors and techniques for improving efficiency of solar dryers were discussed as well. The effect of operating conditions, geometrical conditions, adding of reflectors, heat exchanger, heat pump, photovoltaic source, air circulation mode, and phase change material (PCM) on the efficiency of a solar drying system were studied and discussed. Results showed that climatic conditions such as ambient temperature and solar radiation have an important influence on the solar dryer performance. The chimney integrated in solar dryer increases the buoyant force applied on the air stream to maintain a greater air flow velocity, which removes one side of moisture. The concentrators found to be effective in reducing the drying time by increasing the air temperature inside the dryer. Photovoltaic panels provides electricity source to run electrical components such as the fan to provide a forced air circulation that removes more moisture from the product compared with the natural convection or the heat pump to ensure the drying process at night. PCMs store the thermal energy during sunshine hours and release it after sunset, which can reduce the heat losses and improve the thermal efficiency of the drying system. [DOI: 10.1115/1.4043613]

Keywords: solar dryer, thermal performance, drying time, solar energy, efficiency

1 Introduction

Nowadays, the needs for dried agricultural production, marine products, and medicinal plants have increased considerably in the world [1]. Renewable energy can play an important role to meet its world demand. Actually, solar energy is most reliable and eco-friendly. It can be used in different ways as solar PV or solar thermal for pumping and drying crops in agricultural sectors [2]. It is an effective alternative source of energy that is relatively preferred to other sources because it is free, abundant, and nonpollutant in nature compared with higher prices of fossil fuels [3,4]. It is a permanent and environmentally compatible source of energy in the world. Agricultural and marine products for storage must first be dried to preserve the quality of the final products [5]. In the method of production of crop, treatments of postharvest are highly requested by thermal means in several applications of food engineering. Actually, heat treatments are preferred because they can avoid the side effects of chemical treatments [6]. Among all sources of renewable energy, such as air, wind, and water, the one that has the least impact on the environment is the solar energy [7].

The application of solar energy was seen since the existence of human being on the earth. Nowadays, the way of life of people is dependent on the energy production and utilization, and hence, the demand and supply of energy are increasing in modern communities. At present, 77% of the world's energy is supplied by fossil fuels, which release polluting and greenhouse gases, degrades ozone layer, and excessively threatens environment [8]. Agricultural production is usually more than the consumption needs, resulting in wastage of food excesses during the short harvest periods and scarcity during postharvest period [9].

This paper presents a review of the previous works dealing with the improvement of solar dryers' efficiency. This study is aimed thus to determine the different techniques and factors that can highly improve the thermal performance of solar drying systems. The effect of some parameters such as operating conditions, geometrical conditions, adding of reflectors, heat exchanger heat pump, photovoltaic source, air circulation mode, and phase change material (PCM) on the efficiency of a solar drying system was reviewed and discussed.

2 Solar Drying Processes

Drying is one of the important posthandling processes of agricultural production [4–10]. It has been applied since immemorial times to preserve agricultural products [11,12]. It is known as the process of removing moisture from a product and can be implemented in two steps. In the first step, the moisture inside the product is brought to the surface and dried in air at a constant rate as water vapor. The second step involves a slow drying rate, and this process is related to the properties of the product to be dried [8,13]. Moreover, drying extends the shelf life of a product and provides a lightweight product for transportation and reduces storage capacity [14]. Open-air drying is the most commonly used procedure, especially in tropical and subtropical places. However, a lot

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Contributed by the Solar Energy Division of ASME for publication in the Journal of Solar Energy Engineering: Including Wind Energy and Building Energy Conservation. Manuscript received September 7, 2018; final manuscript received April 17, 2019; published online May 8, 2019. Assoc. Editor: Ming Qu.

of disadvantages are usually found: product damage caused by rodents, insects, and birds; product degradation due to direct exposure to rain, sun light, storms, and dew; contamination with particles and gases due to air pollution; and possible cracking of the product and loss of germination capacity [12,15].

Controlled drying is applied generally in industrial drying process. Warm air in such processes is usually provided by burning of fossil fuels, and large quantities of fuels are used around the world for this objective. The high cost of fossil fuels and the environmental impacts of their use have put severe constraints on their consumption. Most rural locations of developing countries suffer from nonaccess to grid electricity. In such places, crop-drying systems that make use of electrically operated heaters, fans, and other accessories are inconvenient [16].

3 Solar Drying Applications

The application of solar drying in industrial sectors can be investigated for different materials, such as brick, biomass, cement, polymers, textile, paper and allied products, and timber as well as for different processes such as drying of porous materials, pharmaceutical processes, and waste water treatment. In this time, the use of solar dryers in wastewater treatment reduces the duration and the expenses of the conventional drying process [13]. Solar dryers can be proved to be very useful devices from the energy preservation point of view. They circumvent some of the major disadvantages of classical drying [4]. Solar dryers have one of the most promising applications of solar energy technology. In solar dryers, solar energy was used as supplemental sources or as the sole sources of the needed heat, and the air flow can be generated by natural or forced convection. The technical directions in the development of solar dryers are integrated storage, compact collector design, high-efficiency and long-life drying system. Therefore, innovative applications of photovoltaic system for simultaneous production of electricity and heat are suitable as standalone applications and totally operated on solar energy [15].

4 Classifications of Solar Dryers

Solar dryers may be broadly classified into different types. Basically, four types of solar dryers have been successfully employed for the drying of horticultural produce. They are direct solar dryers, indirect solar dryers, mixed-mode solar dryers, and hybrid solar dryers [14]. In fact, the operation of these dryers is primarily based on the principle of natural or forced air circulation mode.

4.1 Direct Solar Dryer. In direct solar dryers, product is exposed directly to the sunlight, so that it can be simply dehydrated. In this type of solar dryers, a black-painted heat absorbing plate is provided that can collect and absorb the sunlight and convert it into heat. The product to be dried is placed directly on the absorber plate. This dryer may have glass lid covers and vents in order to increase the thermal efficiency [8] (Fig. 1).

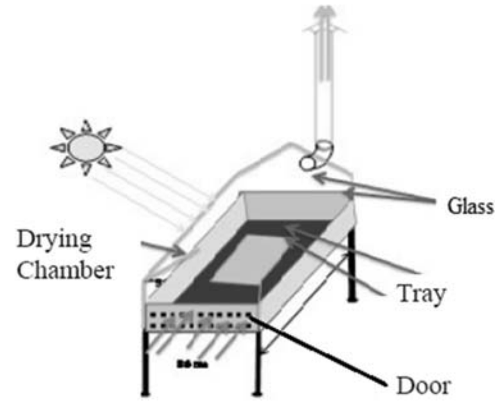

Fig. 1 Direct solar dryer [3]

4.2 Indirect Solar Dryer. Indirect solar dryers are consisted of a solar collector and a drying chamber. In the solar collector, the black-painted heat absorbing surface heats the ambient air, instead of direct exposure of a product to the sunlight. The heated air is subsequently passed through the product that is placed inside a drying room, takes the product moisture, and exits through the chimney [8]. A diagram of an indirect solar dryer is shown in Fig. 2.

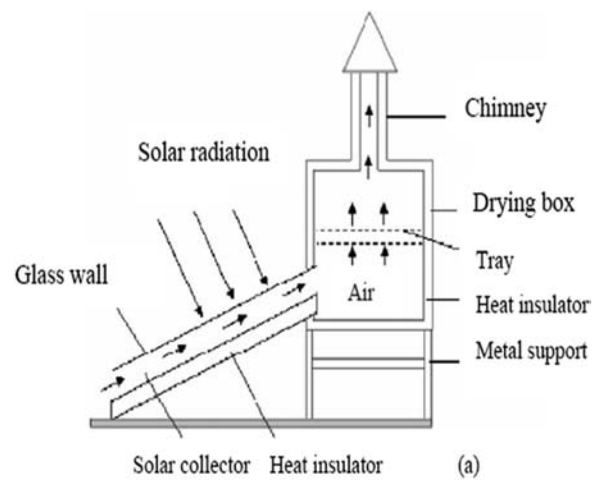

Fig. 2 Indirect solar dryer [6]

4.3 Mixed-Mode Solar Dryer. The mixed-mode solar dryer is a combination of the indirect and the direct solar dryer. This works under the combined action of the solar intensity incident on the product to be dried, and the air preheated in a solar collector provides the heat needed for the drying process [8]. A diagram of a mixed-mode solar dryer is shown in Fig. 3.

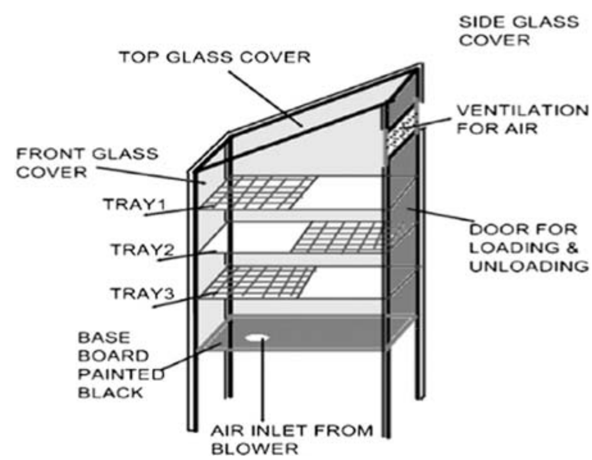

Fig. 3 Mixed-mode solar dryer [8]

4.4 Hybrid Solar Dryer. In the hybrid solar dryer, several sources of energy can be used along with solar energy to ensure suitable drying conditions (Fig. 4). Moreover, the drying process is not dependable only on the solar intensity. The blower can be used for proper air movement in hybrid solar dryer, which can be run on by a photovoltaic system. Hybrid solar drying system can control drying of any agricultural product efficiently and also helps to preserve the suitable quality of the product [8].

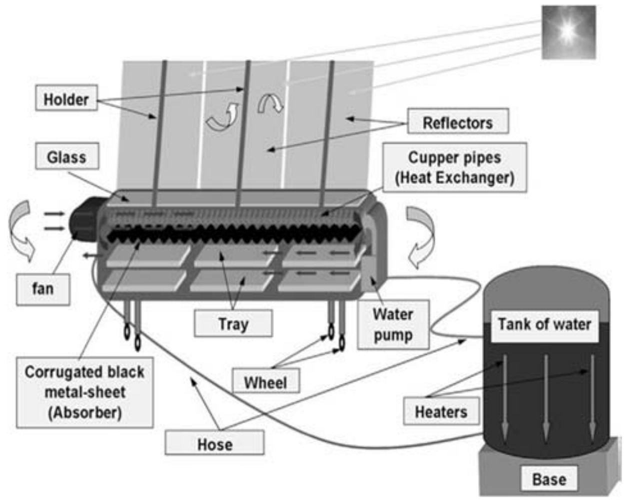

Fig. 4 Schematic diagram of a hybrid solar dryer [54]

5 Drying Technologies and Methods

Different solar dryers for food drying have been evaluated and constructed. They are available in different sizes and designs based on the drying capacity. To evaluate a solar dryer, it is essential to test its performance with the other solar dryers. The obtained results give the needed information to the manufacturers, users, and researchers.

VijayaVenkataRamana et al. [17] presented the status of drying technologies in developed countries. Development and performance evaluation of different types of solar dryers were presented. Various types of dryers like natural convection and forced convection dryers, direct and indirect dryers, integral dryers, greenhouse dryers, cabinet dryers, tunnel dryers, and mixed-mode dryers were reviewed. Pirasteh et al. [13] presented a review on the development of the solar drying application. They classified solar drying application into two main categories, that is, industrial and agricultural. It was concluded that solar energy enables the industries and agricultural sectors to improve their energy stability, modify their energy requirement, and increase energy sustainability, which leads to the improvement in the system efficiency. Mustayen et al. [2] presented a performance study of different solar dryers. They discussed the indirect, direct, and mixed-mode, active, and passive solar dryers that have shown potential in drying of agricultural products. The natural convection solar dryer is more advantageous and applicable than other types. The forced convection dryer is used in small firms with limited financial support from large industrial sectors. Singh and Kumar [18] tested thermally various solar dryer designs operated for natural and forced convection. The steady-state mathematical model based on the heat balance concept of solar dryer without load is applied to identify the dimensionless parameter called no-load performance index (NLPI). By comparison between the dryers, it was found that the mixed-mode dryer exhibits a maximum value of NLPI followed by indirect ones for both natural and forced convection. Boroze et al. [19] presented the inventory and comparative characteristics of solar dryers used in the Sub-Saharan zone. Thermo-economic analysis was carried out to determine which dryers were most successfully adopted. The criteria used to compare the dryers were the drying time, the dryer mass capacity, the treated product flow, and the dryer efficiency. The previous results showed that most of the dryers found in the field and also studied beforehand were indirect solar dryers, but they did not satisfy the users because of their low capacity and over-long drying time. Pangavhane and Sawhney [20] presented a review of research and development work on solar dryers for grape drying. It was found that to improve the acceptability of the solar dryer among the farmers, it is necessary to develop a large-scale solar dryer, which is economically favorable. Forced convection and thermal energy storage systems are necessary to continue drying process and for assuring reliability and better control, respectively. Mennouche et al. [3] proposed and investigated a new postharvest method using a laboratory scale direct solar dryer in order to valorize hard Deglet-Nour dates. Dates samples were soaked in distilled water and then dried by solar drying means. They proposed three drying enhancing methods to improve the quality of date samples are as follows: drying under shade, drying with solar ventilation (DSV), and combination drying method (DCM). It was found that the DSV and DCM modes were classified in favorable operating conditions needed for the studied case. Rahman et al. [21,22] studied the optimization of solar drying process by using mathematical modeling. The used models consider the physical changes of the dried product during drying. The genetic algorithmic process was used to estimate the process in different conditions. The obtained results taken from the models regarding the moister content and the thickness evaluation show the best fit with the experimental data. Chauhan et al. [8] reviewed the papers that studied the application of software in solar drying systems. They concluded that the application of software is very important in improving solar drying systems. Computational fluid dynamics through ANSYS and FLUENT can help to treat the thermal and the dynamic aspect of the phenomena. However, MATLAB and FORTRON are much recommended to develop mathematical models.

The inconvenience of those software applications is the inability to treat the chemical aspect of the dried product, which limits their uses.

6 Factors and Techniques Used for Improving Solar Dryer Efficiency

Thermal performance of solar drying systems depends on a lot of factors and techniques that can affect the drying process. Determination and definition of these factors help to improve the efficiency of solar dryers such as the insurance of the continuity of the drying process in the night with preserving the good quality of the dried products. Below, several studies list and mention the major factors and techniques that can improve the efficiency of solar drying systems.

Zarezade and Mostafaeipour [23] identified the effective factors and risks, which may impact on the use of solar dryers. Factor analysis methodology was performed using SPSS software. Results of the analysis reveal that there are three risk types and six major factors impacting the process of constructing, designing, and implementation of solar dryers. It can be concluded that those six factors regarding solar dryer implementing are geographical situation, performance, infrastructures, financial support, cultural and political, and social. The risks impact on the construction and implementation of solar dryers can be categorized into three major categories: external risks, construction risks, and financial risks.

Crops are dried for their long-term storage. Drying is an important process in preserving foods to make it available to consumers during the whole year; however, many factors affect the drying process [24]. The main factors affecting the efficiency of drying are presented in this paper.

6.1 Operating Conditions. Xiao et al. [25] studied the effect of drying temperature, air velocity, and sample thickness on thin-layer air impingement drying characteristics and quality of American ginseng slices. It was found that thin-layer air impingement drying enhances the drying rate dramatically compared with other drying methods. Drying temperature, air velocity, and sample thickness affected the rehydration rate and the drying time of dried slices. Sarsavadia [26] studied the effect of the air flow rate (2.43, 5.25, and 8.09 kg/min), air temperature (55, 65, and 75 °C), and fraction of recycled air (up to 90%) on the energy requirement of drying. It was found that the savings in total energy due to fraction of recycled air were determined at 65 and 75 °C air temperature for the above three air flow rates. The total energy required for drying of onion slices increased with an increase in the airflow rate and decreased with an increase in drying air temperature. Manaa et al. [27] studied the solar drying of tomato in the arid area. The experiments were performed with a forced convection indirect solar dryer. The obtained results showed that the water content and the speed of drying were affected by different parameters (the airspeed, the air temperature, the pretreatment, and the thickness of the product). The increase in the drying air temperature and the reduction of thickness of the slices increase the drying speed and decrease the drying time. The effect of the air velocity is less compared with the effect of the temperature. Shafiq and Eqwan [28] studied experimentally a direct and an indirect solar biomass dryer, in terms of its optimal configuration, drying capability, and suitability of usage for different conditions. The results show that the level of air flow, the manner in which sunlight is absorbed, and climatic conditions affect the drying rate. Chauhan et al. [29], Chauhan and Kumar [30], and Chauhan et al. [31] studied the thermal modeling for a greenhouse dryer. It was found that thermal modeling has an important role in development of the greenhouse dryer. It is found to be very useful in improving the drying parameters, which leads to the enhancement of the dryer performance.

6.2 Geometrical Factor. Several types of solar dryers with air-based solar collectors had been constructed, tested, and developed in various countries, yielding varying degrees of technical performance. These designs have been constructed in different geometries in order to enhance the drying time and the dried product quality.

A foldable solar grape dryer was developed and fabricated by Nair and Bongirwar [32]. The side walls of the dryer are fabricated using aluminum sheet and painted black from the outside. The dryer is able to dry about 100 kg of grapes at a time. Drying air temperature was found to be twice of the ambient temperature at noon. The main drawback of this dryer is that an increase in the outside wind velocity may decrease the inside temperature because heating takes place on the outer surface of the dryer (Fig. 5).

El-Sebaii et al. [33] studied an indirect natural circulation solar dryer with chimney, which is often known as an indirect passive solar dryer (Fig. 6). It consists of a solar collector, a drying chamber, and a chimney. The solar collector with an area of 1.0 m^2 uses a black-painted plate with the thickness of 0.002 m as an absorber. The drying room with the size of 1.0 m × 1.0 m × 1.5 m was made from wood and fixed with a matte black-painted galvanized iron cylindrical chimney with the height of 0.5 m and the diameter of 0.1 m. It was found that the chimney increases the buoyant force imposed on the air stream to provide a greater air flow velocity, which forms one side of moisture removal.

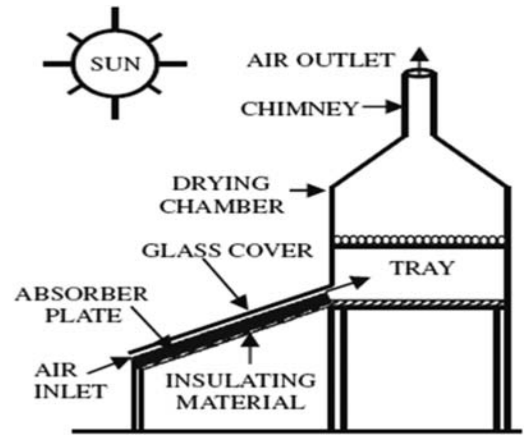

Fig. 6 Indirect natural convection solar dryer with chimney [33]

Pangavhane et al. [34] presented a new multipurpose natural convection solar dryer. This solar dryer consists of a solar flat-plate air heater, flexible connector, reducer with plenum chamber, drying chamber and chimney as shown in Fig. 7. The U-shaped corrugations are placed in the absorber plate parallel to the air flow direction. The space between the box and the bottom of the air duct is filled with glass wool insulation. For loading and unloading the trays, a door is provided at the rear end of the drying chamber. A chimney is provided at the top of the drying room to create the required draft through it. The drying air flow rate increases with an increase in ambient temperature by the thermal buoyancy in the collector. The efficiency of the collector of this solar dryer is found to be varied from 26% to 65%, while the drying period of chemically treated grapes is found to be within 4 days.

Abene et al. [35] studied a solar air flat-plate collector with obstacles (Fig. 8). This system is an indirect blow dryer that operates in the forced convection mode. The system consists of a solar collector acting as a hot air generator, a fan, and a drying unit. It was found that the presence of obstacles in the air stream helps to extract maximum quantity of heat from the absorber. Hence, the entering air temperature to the drying chamber through the collector increases.

Finck-Pastrana [36] constructed an indirect solar dryer where they have the ability of directing the flow of hot air from the solar collector inside the drying room determining the adequate zone to which they want to direct the drying agent (Fig. 9). The

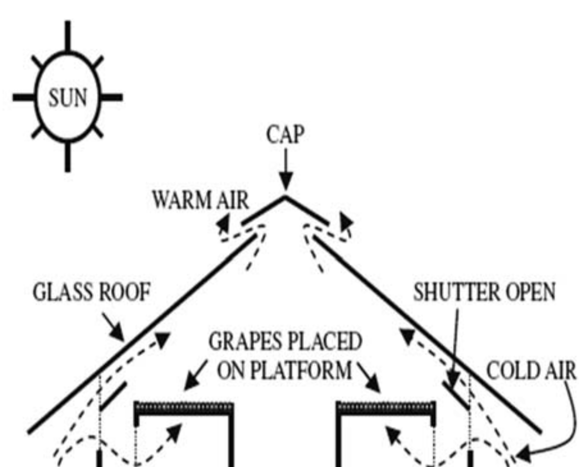

Fig. 5 Glass roof solar dryer [32]

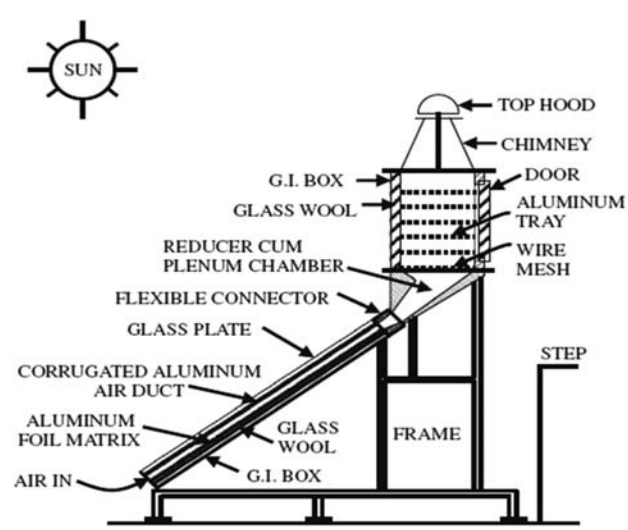

Fig. 7 Multipurpose natural convection solar dryer [34]

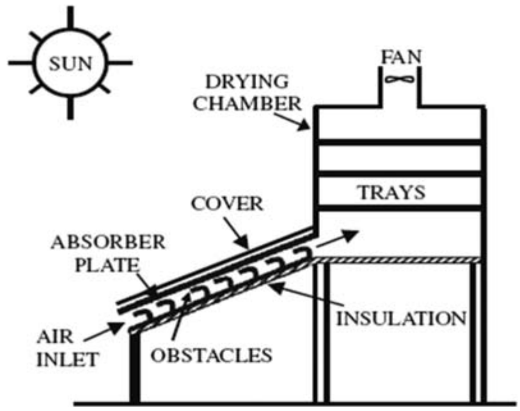

Fig. 8 Solar air collector with obstacles [35]

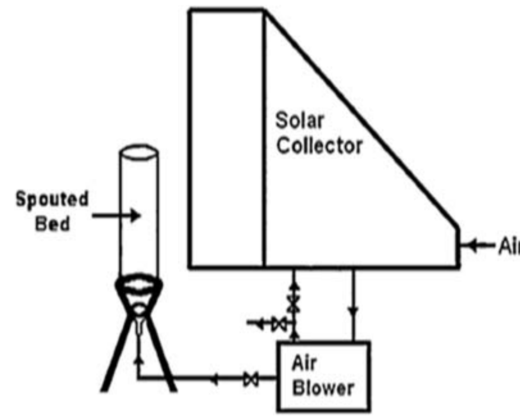

Fig. 10 Schematic diagram of a solar-spouted bed dryer [37]

connection between the solar collector and the drying room is via a neoprene hose. The hot air that enters the drying chamber is directed using the entrance preferentially as the type of a product that is wanted to dry and the speed that is required in the process.

Sahin et al. [37] studied the effect of a solar-assisted spouted bed and open sun drying on the drying rate and quality parameters of pea. The solar-assisted spouted bed dryer, used in the experiments, consisted of a solar air heater to provide hot air and an air blower to provide spouting column for drying of the sample (Fig. 10). It was found also that the air temperature changed between 20 °C and 27.4 °C during open sun drying, while the temperature of the inlet air of a solar-assisted spouted bed dryer varied between 35.3 °C and 65.5 °C. The drying rate was much higher, and therefore, the drying time was lower in solar-assisted drying compared to that in open sun drying.

Lamnatou et al. [38] developed a new solar dryer by using an evacuated tube collector. The results showed that the warm outlet air of the collector reaches a suitable temperature levels for drying of agricultural products without the need of preheating. Thus, the solar collector was used as the heat source for a drying room in the frame of the development of a new indirect solar dryer. The proposed dryer has a capacity for drying a larger quantity of products due to the high efficiency given by the solar collector. Duran et al. [39] studied a passive solar dryer that includes a chimney and a wind turbine to improve the air flow rate. The obtained results showed that the drying time was reduced to less than two sunny days with improving of the final quality in relation to the traditional charqui. The provided air flow rate by both devices was complimented, allowing the drying process to be continued during the night when the ambient relative humidity was low by using the wind extractor.

Chauhan and Kumar [40–42] studied the performance analysis of a greenhouse dryer by using insulated north wall under natural convection mode. The performance of the green house dryer has been tested in two cases: with and without using a solar collector. The obtained results show that the north wall insulated greenhouse dryer when using a solar collector was found to be most effective for drying compared with earlier developed greenhouse dryers. The north wall reduced the radiation losses with the help of a reflector, and consequently, the maximum utilization of solar radiation was achieved.

6.3 Adding of Concentrators and Reflectors. Ringeisen et al. [43] studied the effect of adding a concave solar concentrator built from low-cost, locally available materials to a typical Tanzanian solar dryer (Fig. 11). The concentrator was built from a wooden L-shaped frame. It was found that the concentrator proved to be effective, reducing the drying time by 21% by increasing the drying air temperature, which can reduce the relative humidity. An additional study on the quality of the fresh and dried tomatoes found that the acidity, pH, lycopene, color, and vitamin C determined that there was no difference in quality between tomatoes dried without and with the concentrator.

Stiling et al. [44] used concentrating solar panels (CSPs) in a mixed-mode solar dryer to improve the process of solar drying Roma tomatoes. Solar panels were used to maximize incident solar radiation on the solar dryer, and one of the dryers used a

Fig. 9 Indirect solar dryer with variable steering flow [36]

Fig. 11 Dryer 2 (left) is exposed to the concave solar concentrator, and dryer 1 (right) is the control [43]

mobile and an easily adjustable flat (CSP). The results showed that the temperature inside the dryer with CSP was approximately 10 °C higher than the one in the dryer without CSP. With using concentrating solar panels (CSP), the faster achieved drying rate, under both sunny and simulated cloudy conditions, shows the ability to dry products to acceptable moisture content in a reasonable time, with the objective of decreasing postharvest loss.

Maiti et al. [45] studied the influence of adding reflectors on the performance of a solar dryer. The drying system was an indirect, natural convection batch-type solar dryer fitted with North–South reflectors. It was found that with using reflectors, the collector efficiency without load was improved from 40% to 58.5% under peak solar irradiation conditions during a typical day.

6.4 Photovoltaic Source. Sevik [46] investigated experimentally a system for drying of various agricultural products under different climatic conditions. To determine the effects of potential induced degradation (PID) control on the system and to evaluate the drying behavior of various products at 50 °C with different mass flow rates for a drying analysis, he studied how to keep a constant drying air temperature with PID to obtain a homogeneous air temperature inside the drying room. The given results showed that the solar collector, photovoltaic (PV) unit, and heat pump (HP) unit can work in coordination with each other and give a dried product having good physical and chemical properties.

Li et al. [47] investigated experimentally a solar-assisted heat pump in-store drying system (Fig. 12). The system consisting of heat pump, fans, flat-plate air collectors, grain stirrer, and air ducts is proposed to make full use of incident solar energy and to reduce the electricity consumption. It was found that the solar-assisted heat pump drying system improved the performance of the in-store drying process. The uniformity of the grain moisture content was improved, and the drying rate was increased.

Sevik [48] studied experimentally a new design solar dryer using a double-pass solar air collector, photovoltaic unit, and heat pump. The solar dryer performance has been tested for drying of carrot. It was found that the system (solar heat pump dryer) can be easily operated without the need of the heat pump under normal ambient air conditions (average temperature of 30 °C and average relative humidity of 30%). The solar collector can be used efficiently in several thermal applications such as greenhouse heating, space heating, and air preheating. Čiplienė et al. [49] studied experimentally the use of hybrid solar collector (Fig. 13) for drying process. The solar dryer containing two different solar collectors was developed: the

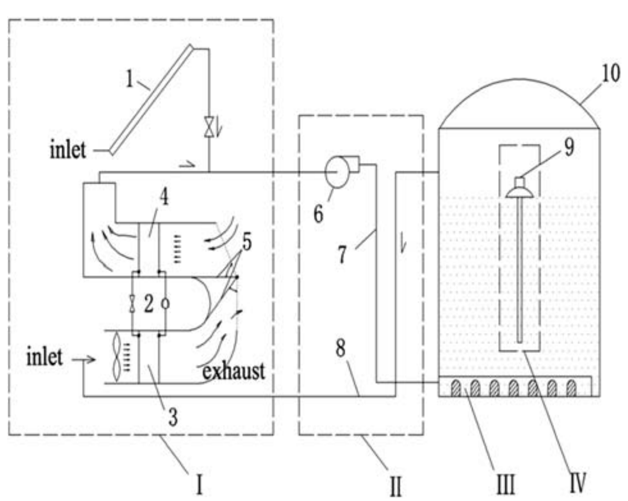

Fig. 12 Schematic diagram of the solar-assisted heat pump in-store drying system: (1) solar air collector, (2) air source heat pump, (3) evaporator, (4) condenser, (5) movable diaphragm, (6) supply fan, (7) ventilation supply tube, (8) air recycle tube, (9) grain stirrer, and (10) granary [47]

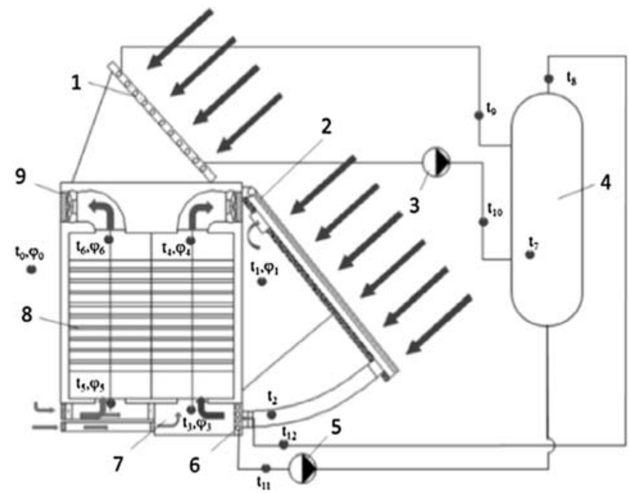

Fig. 13 Basic scheme of the dryer for medicinal plants: (1) flat-plate type solar collector (8 m^2 area), (2) air-type solar collector (12 m^2 area), (3) and (5) a pump, (4) a tank with water for heat storage, (6) heat exchanger, (7) air mixing chamber, (8) drying chambers, and (9) fan [49]

air-type solar collector for heating the product and the flat-plate solar collector for accumulation of the converted heat energy. The results showed that by combining two different solar collectors, the solar energy for drying could be used continuously and permanently by employing the accumulation energy, in order to ensure the stability of the drying process by compensation of the solar radiation.

Chouicha et al. [6] studied a solar hybrid drying of sliced potatoes by forced convection in an indirect solar dryer using extra energy via a heater by joule effect generated by photovoltaic modules. The obtained results showed that with the use of one solar panel, the obtained drying time was 3 h. While in the case of using two panels, the drying time was 2 h and 45 mn. Tsamparlis [50] studied a hybrid solar dryer that consists of a solar heating unit and a drying room as shown in Fig. 14. Heating unit is organized into two units with two flat-plate collectors and ten evacuated tube collectors in each one. The obtained results showed that the dried grapes obtained from this dryer have a good quality and that the drying time of grapes is significantly reduced to around 30–40 h.

Amer et al. [51] examined an integrated solar system used for drying of chamomile (Fig. 15). This system consists of a heat exchanger, a reflector, a collector, main drying chamber below collector, an additional drying chamber, and an electric heater

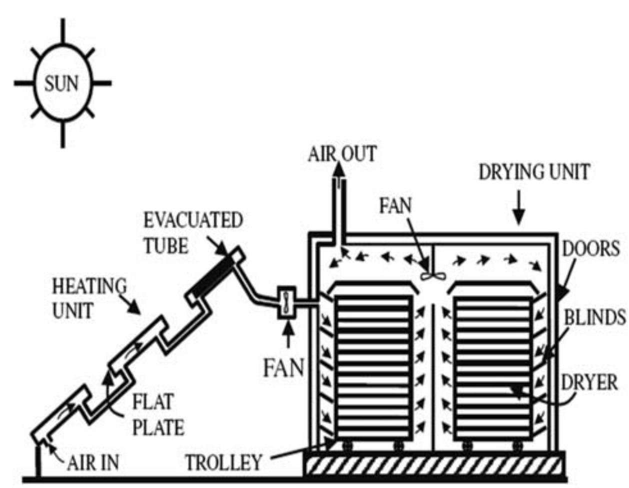

Fig. 14 Hybrid solar dryer [50]

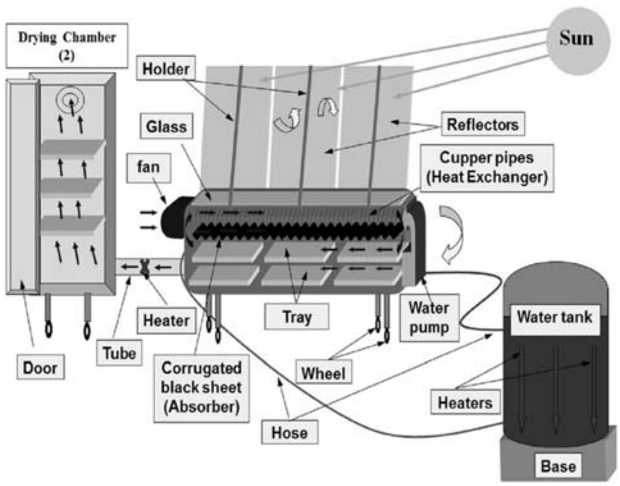

Fig. 15 Schematic diagram of the components of the integrated solar dryer system [51]

immersed in the water tank. It was found that this system operated for about 30–33 h to reduce the moisture contents of a product from 72–75% (wb) compared to 60 h to reduce it to 9–10% (wb) using open sun drying. This system can store the solar energy in water during sun shine hours and use this energy at cloudy days or after sunset to raise the temperature of drying air.

6.5 Forced Air Circulation Mode. Several designs of forced convection solar drying systems had been constructed, tested, and developed. Direct-mode forced convection solar drying systems essentially consist of a fan/blower to force the drying air circulated through the product and a drying room covered with a transparent sheet. While indirect-mode forced solar drying systems essentially consist of a drying chamber, an air heater, and a blower/fan to duct the heated air to the drying room.

Ben Salma and Combarnous [52] studied the development of a solar dryer by using forced convection. The drying unit is composed mainly of a drying chamber and a solar collector. The heat transfer in the drying room with the product is generated by forced convection, which is created by an electric fan. It was found that a combination between forced and natural convection is of much interest, through the use of a fan, to control precisely the quality of the drying process. The importance of using baffles in the solar collector is to increase its efficiency even with low air flow rate. Fudholi et al. [53] tested an indirect forced convection solar drying system for drying of palm oil fronds. It was found that drying of 100 kg of palm oil fronds reduced the moisture content from 60% to 10% in 22 h. The thermal efficiencies of the solar collector, drying system, and pick-up were about 31%, 19% and 67%, respectively. The improvement potential of solar drying system for palm oil fronds ranged from 8 W to 455 W, while the efficiency of the collector ranged from 9% to 48%. Sinul et al. [54] evaluated the dryer performance under natural and forced convection modes. In forced convection, it reached an average drying temperature of 40 °C, while in natural convection, the hot air reached an average drying temperature of 45 °C. It was found that in natural convection, the mass of tomatoes was reduced from 1800 g to 180 g, while in forced convection, it reduced from 1800 g to 140 g. The comparison between the two modes show that forced convection removed more moisture from tomatoes compared with natural convection, and the heat transfer rate is more in forced convection than that in natural convection. Mumba [55] studied a solar grain dryer with photovoltaic-powered air circulation. The use of photovoltaic solar cells is to supply the fan by electrical power. This solar dryer can dry 90 kg of maize grain per batch from an initial moisture content of 33.3% dry basis to fewer than 20% dry basis in one dry. The drying air temperature has been controlled to be ranged in 60 ± 3 °C. The solar dryer was found to be very effective with many benefits, such as improving of the dried product quality and protection of drying environment. It was found that this kind of dryer is suitable for rural zones where fossil fuel and electricity are either extremely expensive or nonexistent. Chauhan et al. [56–58] studied the heat transfer analysis of a greenhouse dryer. The greenhouse has been fabricated and tested in no-load condition under the forced convection mode. Several thermal performance indicators have been analyzed. The obtained results show that the crop drying under the forced mode is found significantly faster than that under other modes of drying.

6.6 Additional Components

6.6.1 Heat Exchanger. Misha et al. [59] studied drying of kenaf core fiber at low solar radiation using a solar solid desiccant dryer and heat exchangers. The system was equipped with electrical heater to maintain the temperature of hot air high if the solar radiation becomes low. The desiccant wheel system is used as a heat source to supply dry and hot air for the drying room. It was found that this system reduced the drying time by 24% from 20.75 h to 15.75 h compared to open sun drying because it was used even in the absence of solar radiation to continue the drying process. The obtained results showed that the solar-assisted solid desiccant dryer can operate even at low solar radiation for drying of kenaf core fiber. Reyes et al. [60] doubled the thermal conductivity of cans filled with paraffin wax by adding 5% w/w of aluminum wool. They used a heat exchanger for accumulating the solar energy, and this exchanger is composed of 48 cans filled with 9.5 kg of paraffin wax mixed with aluminum wool. The conductivity of this mixture could be augmented by increasing the percentage of aluminum strips. The time needed to melt the wax completely in sunny day is 3 h. During a period of 2 h, the temperature with 3.5 m^3/h air flow rate increased from 20 to 40 °C. This application can be used in drying process. Amer et al. [61] studied a hybrid solar dryer that consists of a solar collector, a reflector, a drying chamber, and a heat exchanger with a heat storage unit (Fig. 16). The heat energy was stored in water inside the heat storage unit by the effect of solar radiations and electric heaters. The results showed that the drying process can be continued at night by using the heat energy stored in the water tank. It was also found that the efficiency of the solar dryer was raised by recycling about 65% of the drying air.

6.6.2 Heat Pump. Sevik et al. [62] proposed a simple and cost-effective solar heat pump system (SAHP) with flat-plate collectors and a water source heat pump for drying mushroom. The use of solar energy and heat pump systems can be done separately or

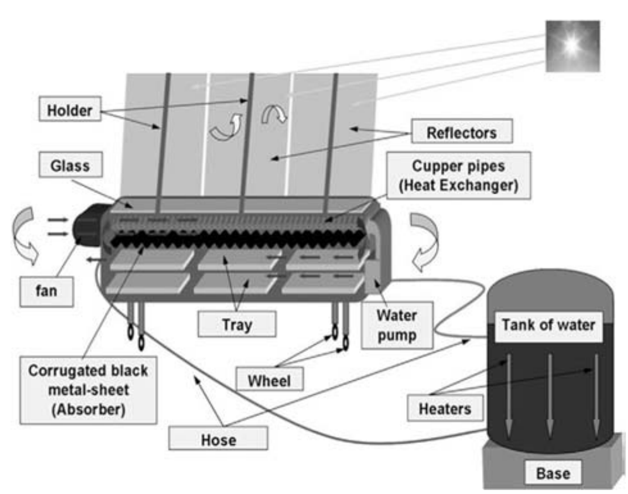

Fig. 16 Schematic diagram of a solar hybrid dryer [61]

together. The results showed that the drying process can be continued with solar energy in day time, while the heat pump system can be used in other times (at night). The drying process that used SAHP is found to be much more quick process than the open sun drying. Fadhel et al. [63] presented a review on advanced solar-assisted chemical heat pump dryer. A solar-assisted chemical heat pump dryer is a new solar drying system, which has contributed to better quality dried products and better cost-effectiveness as well as saving energy. The integration of solar thermal system to the chemical heat pump would assist in expanding the use of chemical heat pump also for several applications in the tropical region. Mohanraj [64] studied the energy performance of a solar-ambient hybrid source heat pump drier (SAHSHPD) for drying under hot humidity weather conditions. The results showed that the quality of the product that was dried under SAHSHPD was found to be higher in comparison with other drying methods.

The disadvantage of the use of the heat pump is that it needs the electricity to run, which limits its uses when there is no availability of the photovoltaic source [63].

6.7 Using of Thermal Energy Storage Materials. Having a solar energy storage system is very important in energy conversion and is responsible for performing the drying process of many agricultural products even when direct sunlight is very low or not available. Although many agricultural food products, such as grains, fruits, and vegetables, are often dried under the open sun, this method can lead to reduce the quality and quantity of the final product. There are several technologies for storing energy in several forms including thermal, electrical, and mechanical energy [65].

6.7.1 Inside the Solar Collector. Akmak and Yıldız [66] studied the drying kinetics of seeded grape in solar dryer with PCM-based solar-integrated collector (Fig. 17). The system consists of an expanded surface solar air collector, a solar air collector with phase change material, and a drying room. The phase change material has been used to perform the drying process even after sunset. It has been found that drying time decreases when drying air velocity increases and the drying process has occurred in decreasing drying period.

Sopian et al. [67] evaluated the performance of a solar drying system equipped with a double-pass collector with an integrated storage system. This system consists of a blower, an auxiliary heater, a solar collector, and a drying room. The lower channel of the solar collector is filled with porous media that act as heat storage systems. Drying time is found to be 7 h. The system efficiency is around 25–30%, and evaporative capacity is 1.26 kg/h. Furthermore, the auxiliary heater is used under low solar radiation conditions, particularly in the evening and in the morning. El-Sebaii et al. [33] investigated an indirect natural convection solar dryer with storage material and chimney used for drying grapes. The obtained results showed a significant improvement of the dryer thermal performance. The sensible heat storage material (sand) that is placed in the solar collector provided a drying air temperature at the inlet of the drying chamber with a range of 45.5–55.5 °C.

The major disadvantage of PCMs, as reported by many researchers, has been the low thermal conductivities possessed by many PCMs, leading to low charging and discharging rates (especially for the organic-based materials). The phase change material is useable and effective only during sunny days. However, it is useless and not effective during cloudy days [68].

6.7.2 Inside the Drying Chamber. In other works, the storage material was used inside the drying chamber with different types, positions, and quantities in order to improve the thermal performance of solar dryer.

Shalaby and Bek [69] investigated a novel indirect solar dryer implementing the PCM as the energy storage medium (Fig. 18). The system consists of PCM storage units in order to store the solar energy, which can be used after sunset. It was found that while using PCM, the temperature of the drying air is higher than the ambient temperature by 2.5–7.5 °C after sunset for 5 h. This novel drying system can successfully maintain the desired drying temperature for seven consecutive hours every day.

Jain and Tewari [70] studied the performance of an indirect solar crop dryer with the phase change material. The system consists of a solar collector, a packed bed energy storage material (paraffin wax), drying plenum with crop trays, and a natural ventilation system. The packed bed solar energy storage with a capacity of 50 kg of PCM was combined with the solar dryer. After sunshine period, it was found that the temperature of the drying room was observed with 6 °C higher than the ambient temperature. Shalaby et al. [71] reviewed the previous works on solar drying systems that used PCM as an energy storage medium. The results showed that PCM reduces the heat losses and improves the thermal efficiency of drying systems. It was concluded that such materials as

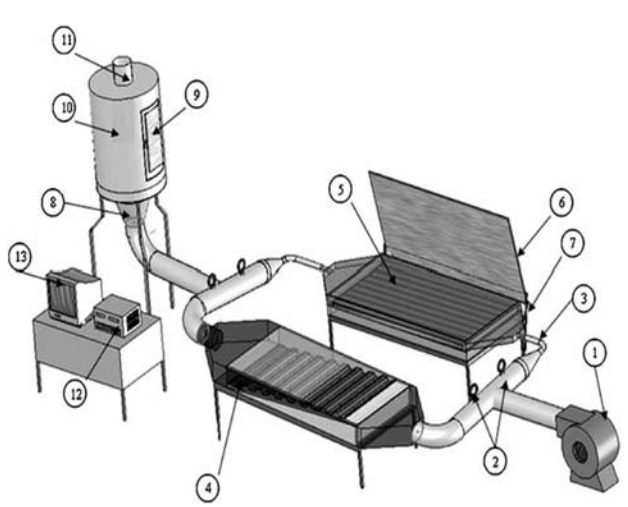

Fig. 17 Schematic view of the manufactured experimental setup: (1) fan, (2) valves, (3) connection pipe, (4) expanded surface solar air collector, (5) collector with PCM, (6) adjustable mirror, (7) adjustable collector tripod, (8) diffuser, (9) observation glass, (10) drying room, (11) air exit chimney, (12) data logger, and (13) PC [66]

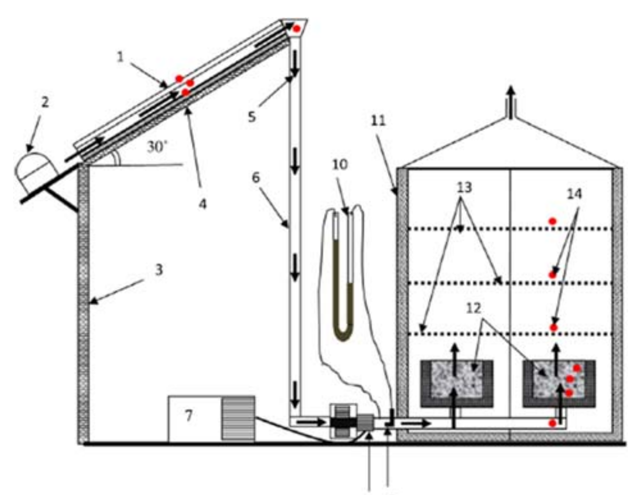

Fig. 18 Schematic diagram of the experimental setup: (1) solar air heater, (2) pyranometer, (3) the room wall, (4) the room roof, (5) flowing air, (6) PVC tube, (7) inverter, (8) three-phase induction motor coupled with fan, (9) pilot tube, (10) U tube manometer, (11) drying compartment, (12) PCM, (13) trays, and (14) thermocouple positions [69]

expanded graphite, graphite, carbon fibers, and high thermal conductivity particles can improve the efficiency of solar energy devices using paraffin wax as thermal energy storage medium. Srivastava et al. [72] investigated the using of lauric acid as the phase change material to store solar energy. They studied the effect of inlet air velocity and inlet air temperature on the charge and discharge time, and during the charge period, only the effect of inlet air velocity was taken into consideration. They concluded that thermal energy storage is the most effective use of solar energy to resolve the discrepancy between the energy supply and demand in solar heating applications. Dina et al. [73] evaluated the efficiency of a solar dryer integrated with desiccants thermal energy storage for drying cocoa beans. They tested two types of desiccants, molecular sieve $13 \times (Na86[(AlO_2)86.(SiO_2)106].26H_2O)$ and $CaCl_2$. It was found that during sunshine hours, the air temperature in drying chamber varied from 40 °C to 54 °C and higher than ambient temperature by 9–12 °C. Reyes et al. [74] studied mushroom dehydration in a hybrid solar dryer using the phase change material. The system consists of a solar panel, paraffin wax, and electric resistances. It was found that the use of solar energy reduces the electric energy consumption. Incorporating phase change material contributed significantly to improve the global thermal efficiency of the drying system. Agarwal and Sarviya [75] studied the shell and tube type latent heat storage as a solar dryer. The heat transfer characteristics of the latent heat storage system have been evaluated during charging and discharging process using air as heat transfer fluid (HTF). It was found that HTF is suitable to supply the hot air for drying of food product during nonsunshine hours or when the solar radiation is very low. Ayadi et al. [76] investigated the performance of a solar collector and a storage system for a drying unit (Fig. 19). Experimental results show that the efficiency of the solar collector at the flow rate of 0.024 kg/s is 30.52%, and the temperature difference created by the storage system is about 10 °C with efficiency more than 60% and 90% during charging and discharging processes, respectively.

Bal et al. [77,78] presented a review of a solar dryer with thermal energy storage systems for drying agricultural products. The results showed that with the use of a storage unit, agricultural materials can be dried at night, while night drying was not possible with a normal solar dryer without using energy storage system. The solar energy storage system can reduce the time between energy supply and energy demand; furthermore, it plays an important role in energy conservation.

PCM plays an important role in the improvement of drying systems performance. However, it is still not applied in a wide range in the world due to its high cost, which makes it unavailable everywhere [79].

By comparison between different techniques of improving solar drying systems performance, it appears that the technique of storage of solar energy is the most efficient one. It ensures the drying process even after sunset. Storage of solar energy can be done in two forms: sensible (through porous medium) or latent heat (through PCM). However, it was found that the storage of latent heat is better than the storage of sensible heat in quantity of stored heat point of view. By using a porous media that acts as heat storage systems, the system efficiency is found to be around 25–30%. However, while using packed bed solar energy storage of PCM, it was found after sunshine period that the temperature of the drying room is 12 °C higher than the ambient temperature [67,73,77]. The second preferable technique is the use of photovoltaic panels to provide an electricity source. That source can be used to run such apparatus, which can help to improve the solar drying systems' performance such as heat pump or fan. The obtained results showed that the dried product obtained after using heat pump has a good quality and that the drying time of the product is significantly reduced to around 30–40 h. Running fan provides a forced air circulation, which removes more moisture from the product compared with natural convection [46–48]. Adding of concentrators proved to be an important technique of improving the solar dryers' performance but with less efficiency than that of the other previous techniques. It can reduce the drying time by 21% by increasing the drying air temperature compared with the dryer without CSP [43–45]. Geometrical forms of the solar dryers affects too the thermal performance. In the indirect solar dryer, the obstacles installed above the absorber plate help to extract maximum quantity of heat from the absorber plate, which increases the drying air temperature. The warm outlet air of the collector reaches a suitable temperature levels for drying of agricultural products by using an evacuated tube collector [33,35,38]. Operating and climatic conditions such as wind velocity, ambient temperature, airflow rate, and solar radiation have a high effect on the drying process. In spite of that, those conditions need to be controlled to ensure the best functioning of the drying system [25–28].

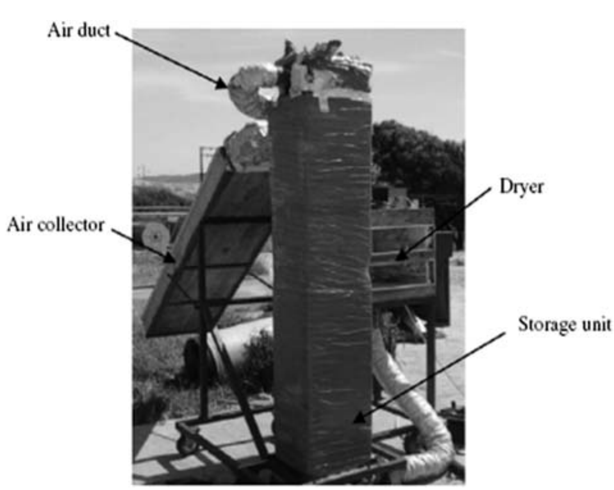

Fig. 19 Photograph of the drying solar unit [76]

7 Conclusions

The solar drying of agricultural products is one of the most important applications of solar energy. This review presents different techniques that help to improve the thermal performance of solar dryers.

This review paper shows that the total energy required for drying of an agricultural product increases with the increase of the air mass flow rate and decreases with the increase of the temperature of drying air. The increase of drying air temperature leads to increase in the speed of drying and therefore reduce the drying time. The drying air flow rate increases with an increase in ambient temperature by the effect of the thermal buoyancy in the solar collector.

The chimney integrated in solar dryer increases the buoyant force applied on the air stream to maintain a greater air flow velocity, which can form one side of moisture removal.

The concentrators found to be effective in reducing the drying time, increasing the air temperature inside the dryer, and reducing the relative humidity.

The solar air heater is the most important component in the indirect solar drying system; then, the improvement of the solar air heater leads to better thermal performance of the solar drying system. Photovoltaic panels provides electricity source to run electrical components such as the fan or the heat pump. The solar-assisted heat pump drying system improves the drying process because this last one can be continued and operated even at night with using heat pump system. Running fan provides a forced air circulation, which removes more moisture from the product compared with natural convection.

The storage of solar thermal energy using PCM in solar drying reduces the time between energy supply and energy demand, thereby playing an important role in energy conservation and improves the solar drying energy systems. PCM stores the thermal energy during sunshine hours and releases it after sunset, which can reduce the heat losses and improve the thermal efficiency of the drying system. Thermal energy storage system and forced convection are necessary to continue the drying process at night and to ensure reliability and better control, respectively.

To improve the solar drying process, we propose:

— A system of stabilization of the operating conditions
— A rearrangement of the auxiliary electric source
— Providing other sources of heat such as geothermal water heat exchanger

Acknowledgment

The authors would like to thank the laboratory of LENREZA for the provided material to perform this work.

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