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Applications of solar energy based drying technologies in various industries – A review

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ABSTRACT

Drying of materials is an important and essential mechanism during the production process in industries. Drying fruits and vegetables is an ancient method used for food preservation. Apart from the agricultural sector, there are many industries such as automobile, rubber, paper and pulp, sugarcane, wastewater treatment, lignite/coal, etc. require heat energy for drying during production processes. Conventional energy sources such as coal, natural gas, and electricity are used for the heat energy required for drying. Due to the increase in cost and pollution involved in conventional sources, solar energy-based drying systems can be encouraged. This review work provides a detailed analysis of solar-based dryers used in various industries namely agricultural, marine, tea, sugarcane, automobile, rubber, pulp, and paper industries. In addition, the utilization of solar energy for sewage drying, industrial waste drying, and lignite coal drying for power generation are reviewed. Different types of dryers presently available in the market are also discussed in the review work. Various parameters used for the performance of the dryers such as drying rate, amount of energy required for drying, collector efficiency, drying efficiency, specific energy consumption have been discussed. Economic, environmental, and social aspects of solar dryers are also presented, and recommendations are given in the paper.

1. Introduction

In the present scenario, energy security is one of the important areas where the world is continuously looking for various methods and technologies. The main motive of energy researchers is, reducing the consumption of energy and finding alternate sources. Encouraging renewable energies as alternative options reduce hydrocarbon and other toxic emissions. Drying is one of the energy intensive processes which is used in many industries such as agriculture, sugarcane, tea, marine, automobile, paper, rubber, pulp and paper, sewage and industrial waste, lignite and coal, etc. Drying played an important role in the evaporation of moisture from industrial waste and sewage which can be used as fertilizer or for landfilling purposes (Mathioudakis et al., 2009).

The agricultural sector is a major sector where drying has been extensively used in preserving cereals, fruits and vegetables. Moisture is the main substance in the wet materials that causes the microbial and bacterial reaction which leads the material spoilage. The reduction of the moisture content (MC) up to a safe level, reduces the growth and reproduction of micro-organisms and it can be achievable only by drying. Thermal energy is a source mostly used for the drying process. Most of the time, conventional energy sources such as fossil fuel and electric energy were used for drying. Varieties of dryers available in the market with different heat supply modes and energy sources as listed in Table 1.

Consumption of fossil fuels greatly influences the environment as they emit toxic gases. The heat energy consumed during the drying process is about 12% to 40% of total industrial energy consumption in the developed countries, which employs 20–70% of the total cost of production depends on the type of industries. (Bennamoun and Belhamri, 2003; Pirasteh et al., 2014a). A natural source - solar energy could play a major role in drying processes and it minimizes the consumption of non-renewable sources by 27% to 80% (Prakash et al., 2018). Therefore, solar energy needs to be encouraged for drying applications. It is a clean, sustainable, economical, and environmentally friendly energy source.

Open sun drying (OSD) is a traditional method to dry crops, fruits, vegetables, and other products since ancient times. But it has some disadvantages such as large surface area, low quality on the dried product due to contamination of dirt and dust, unavailability of required

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Nomenclature

Abbreviations

A	Area of collector (m^2)
$C_{pa\backslash}$	Specific heat (J/ kg K)
db	Dry basis
DSD	Direct solar dryer
Ex	Exergy
HSD	Hybrid solar dryer
H_{fuel}	Heat value of fuel (kW/ kg)
h	Specific humidity (kg/ kg of dry air)
h_{fg}	Enthalpy of evaporation (kJ/kg)
h_{as}	Specific humidity as saturated condition (kg/ kg of dry air)
ISD	Indirect solar dryer
I	Incident solar radiation (W/m^2)
IP	Improvement potential
M, m	Mass (kg)
MC	Moisture content (kg per kg)
$\dot{m}$	Mass flow rate (kg/s)
m_m	Mass of material (kg)
OSD	Open sun drying
P_t	Total energy input (kW)
PCM	Phase change material
P_f	Fan power
Q_d	Energy for drying (kJ)
SAC	Solar air collector
SEC	Specific energy consumption (kJ/kg)
TES	Thermal energy storage
T	Temperature (K)
T_d	Drying temperature (K)
t_s	Save in time
wb	Wet basis

Greeks

η_o	Collector efficiency
η_d	Drying efficiency

Subscripts

a	air
atm	Atmospheric
c	collector
d	Dry, dryer
dci	Drying chamber inlet
dco	Drying chamber outlet
do	Dryer outlet
f	final
i	Initial, inlet
l	loss
in	inlet
m	Material
w	water

Table 1
Various methods involve in the drying operation.

Category	Method and range
Mode of heat supply	Conduction, convection, radiation, infrared, dielectric heat sources
Energy source	Electricity, coal, oil, natural gas, biomass, solar energy
Moisture content in the material	1 to 96 kg per kg of wet basis
Drying temperature	30 °C – 200 °C
Pressure	Vacuum to high-pressure level
Capacity	kilogram to tones of production
Shape, size, and structure	Powder, granules, film, solid material, crystalline, fabric, cardboard, fiber, etc.

drying temperature, larger drying time for high MC product, contamination by birds and animals, etc. Varieties of other solar-based drying systems are available which can overcome the negatives of the OSD method (and therefore, the OSD method is not discussed much in this review). These methods provide the drying process more efficiently with high-quality dried products.

In the area of solar drying, many experimental, theoretical, and numerical studies are available which shows the importance of solar-based drying processes in agricultural as well as non-agricultural sectors. Also, many reviews were reported by researchers on different methods of drying in the agricultural sector (Fudholi et al., 2015; Panwar et al., 2012). There were few review works on software tools used for drying problems (Malekjani and Jafari, 2018; Singh et al., 2015).

However, despite having the huge potential of solar thermal energy, there is a lack of review work focusing on the integration of solar thermal energy with industrial drying process applications. No review work was solely contributed to solar drying processes used in different industries. Solar dryers are commonly used in the agricultural sector which is mentioned in lots of studies but the available review works are very few in other industries such as marine, tea, sugarcane, automobile, rubber, pulp and paper, sewage, and industrial waste, lignite/coal.

The present review provides a thorough analysis of solar-based drying systems in agricultural and non-agricultural industries. Other industries can aware of the importance of solar drying so that they can also utilize this free energy. Therefore, the objective of this work is, (i) to review comprehensively the studies available on solar drying systems which are used in different industries, iii) to study different types of solar dryers, their design details and performance parameters involved, (iv) to get a collection of data in a single article by providing significant conclusions from the solar drying method used in different industries which may help the future researchers, (v) to review the economic, environmental, and social aspects of solar energy-based drying technologies and vi) to provide important information and points for future research in this specific area of solar drying.

Solar thermal energy for drying is an application of renewable energy that can be used by industries and also by farmers. Hence presented review paper helps the industries, farmers and researchers for the selection of appropriate dryers and it gives information on where solar thermal energy is used for drying, therefore, this topic is of potential interest to them. The article is structured as: Section 2 presents a brief report on the classification of solar drying systems based on their design, structure, type of material used for dryer, material to be dried, etc., Section 3 provides the different performance parameters of solar dryers. Section 4 gives information on different sectors where solar drying is employed. The economic, environmental, and social aspects of solar energy are discussed in Section 5. Section 6 provides few recommendations on drying systems and Section 7 furnishes the conclusions.

2. Classification of solar drying systems

A variety of dryers were noticed from different studies. Generally, these dryers are categorized based on their design, material used for the setup, type of assisted auxiliary heat source, the material used for the drying, material used for solar thermal energy storage (TES), etc. By considering these mentioned categories, a broad classification of dryers is drawn and shown in Fig. 1. All the solar dryer systems are explained very briefly in the following sections.

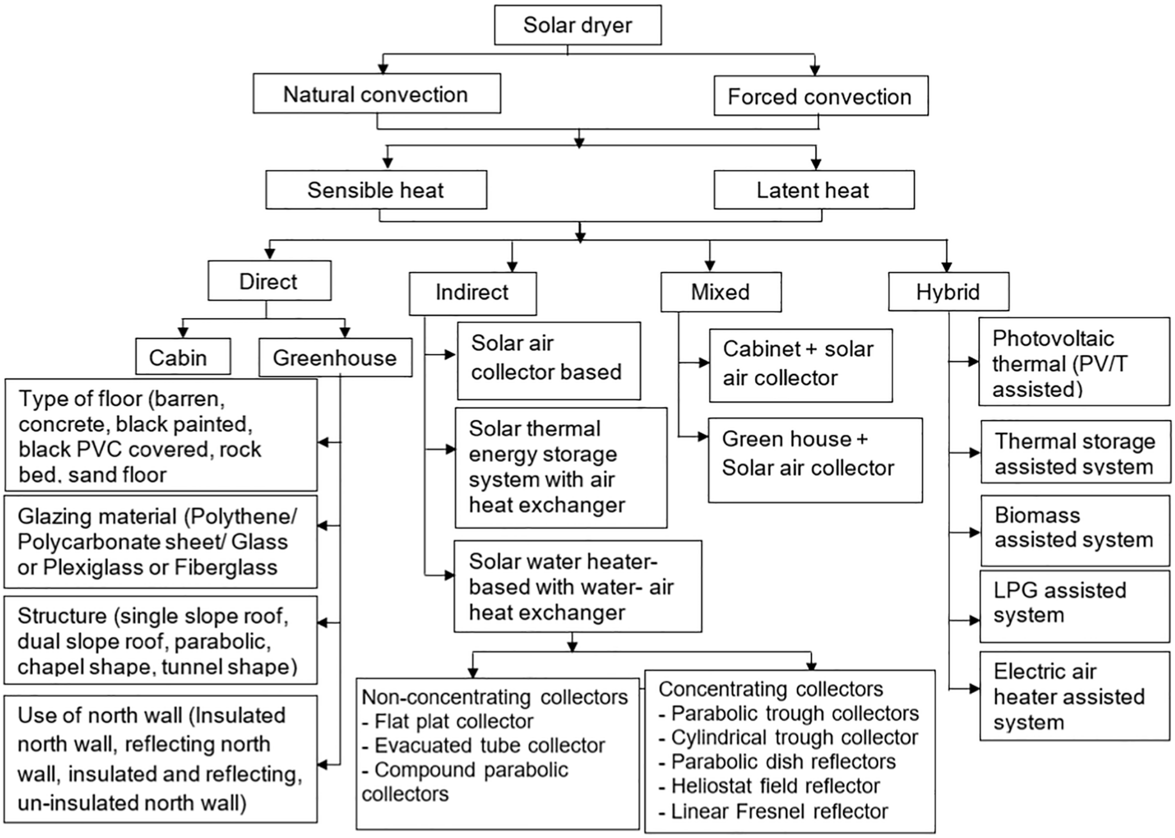

Fig. 1. Broad classification of various types of solar dryers.

2.1. Open sun drying (OSD)

The OSD is one of the commonly used methods of drying all over the world. In OSD, the material is spread over the ground or kept on the trays, floor and allowed to dry throughout the day by exposing it to open air and direct radiation of the sun (Muhlbauer, 1986). The risks involved in the OSD are; damage of material by birds, insects, and animals, quality degradation because of direct exposure of sun, dirt, dust, atmospheric pollution, quality degradation due to rain, air humidity dew, over-drying, insufficient drying, etc. (Arunsandeep et al., 2018). Due to these disadvantages involved in the OSD, people are searching for an alternate solar-based system that can partially control the input parameters so that a quality product can be improved.

2.2. Solar dryers

Some solar dryers maintain the controlled conditions required for drying such as temperature, velocity, humidity, etc. which are difficult in OSD. These controlled solar dryers are otherwise classified as indirect solar dryers (ISD) and direct solar dryers (DSD). It gives quality end products, low drying time, and dust-free products. These may be of natural convection type (passive method) (Lingayat et al., 2020a; Lingayat et al., 2017) or forced convection type (active method) (El-Sebaii and Shalaby, 2013). The overall efficiency of passive dryers varies from 20 to 40% which depends on the type of material, moisture content, temperature, velocity, and humidity of air (Udomkun et al., 2020). Most of the researchers are in favor of forced convection type dryers as they give better thermal efficiency and provide controlled drying conditions than natural convection dryers (Mustayen et al., 2014). Solar dryers can be provided with a TES system such as latent heat (Benli and Durmuş, 2009) or sensible heat storage (Ayyappan et al., 2016) unit to continue the drying during off sunshine hours.

2.2.1. Direct solar dryers (DSD)

The DSD is one of the commonly used alternate ways of OSD method. In this method, materials are kept in the chamber or in the space where they are exposed to the solar radiation transmitted through the transparent glazing. Transparent glazing can be any material, such as glass, plastic cover, polycarbonate material, etc. The DSD can be categorized as cabinet dryer and greenhouse dryer based on their design and construction and it can work in passive as well as active modes (Sontakke and Salve, 2015).

Cabinet dryer is a simple box type with transparent glazing for small-batch drying as shown in Fig. 2. For mass drying, greenhouse dryers have been widely used. Various types of greenhouse dryers are reported in the literature and can be categorized based on the type of floor, type of glazing material, northern wall condition, dryer construction. The floor used in greenhouse dryers can be made of concrete and sometimes with a black coat. Polycarbonate, polyethylene materials, or PVC film-coated fiberglass are used for glazing material (Elhage et al., 2018). A greenhouse dryer can be a single or double sloped roof, dome-shaped or

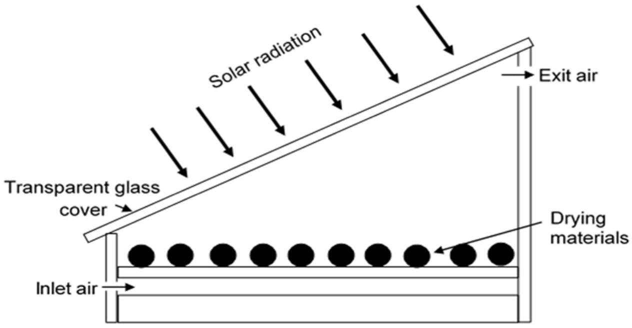

Fig. 2. Cabinet or box type solar dryer.

parabolic-shaped. The North wall provides in the greenhouse can be insulated or non-insulated. Singh et al., (2018) provided a detailed review of various types of greenhouse dryers and suggested few modifications. These dryers can provide a temperature in the range of 30 to 60 °C which is sufficient to dry fruits like apple, mango, papaya, strawberry, various types of vegetables, and other products like meat, marine products (Mezrhab et al., 2010; Rathore and Panwar, 2010; Singh et al., 2018).

2.2.2. Indirect solar dryers (ISD)

In this method, the product is not exposed directly to sun radiation but convective heat transfer between heated air and wet material is responsible for moisture removal (Lingayat et al., 2018; Lingayat et al., 2020c). Moisture removal rate and heat transfer can be controlled in a better way than DSD dryers. For improved airflow, natural convection systems can be replaced with forced convection systems (Mohanraj and Chandrasekar, 2009). Lingayat et al., (2020b) provided a detailed review of various types of ISDs and also suggested various possible locations for the TES system. A lot of researches have been reported to increase the thermal performance of ISD. Some of the advanced techniques can make the ISD more efficient and completely renewable by assisting with TES system with air heat exchanger, a solar water heater with water–air heat exchanger and all these will be discussed in Section 4.

2.2.3. Mixed-mode type solar dryer

Mixed-mode drying setups work on the joined principle of DSD and ISD methods. The dryer is provided with a transparent drying chamber and solar air heater for hot air generation. The drying time required to achieve the MC is less in mixed mode solar dryers compared with ISD because of the transparent drying chamber and solar air heater (Dhalsamant et al., 2018; ELkhadraoui et al., 2015).

2.2.4. Hybrid solar dryers (HSD)

In hybrid solar drying (HSD), auxiliary heating sources are used to dry the product during an off-sunshine hour and cloudy days or to maintain the constant temperature because of continuous fluctuation in solar radiation. Auxiliary heating sources such as an electric heater, biomass heater, liquid petroleum gas (LPG) heater, mechanical heat pump, etc. are used as a backup for thermal energy generation (Hossain et al., 2008; Mishra et al., 2020a; Yahya et al., 2017). This dryer is useful for drying high MC material as it protects the food from microbial attack because it is dried continuously (Mohanraj, 2014; Prasad et al., 2007; Thanaraj et al., 2007). The only disadvantage of the system is, it involves more manufacturing and maintenance costs and therefore it requires a specially designed structure.

Solar air collector (SAC) is the most important components in ISD, mixed-mode solar dryers and HSD. Some researchers reported various methods to increase the thermal performance of SAC and suggested different designs (Ozgen et al., 2009; Lingayat et al., 2020b). Esen et al. (2009a) suggested advanced modeling methods for its performance investigations such as artificial and wavelet neural network. The thermal storage system is also one of the important components in solar drying systems which stores the heat during peak sunshine hour which can be utilized after the sunset. Many researchers reported different methods to store the solar thermal energy in the form of sensible heat or latent heat (Esen, 2000; Esen and Ayhan, 1996; Esen and Durmus, 1998; Esen and Yuksel, 2013).

3. Various drying parameters involved in solar drying

Different types of solar dryers, as discussed in the previous section, have been used to generate the required air temperature for the drying. This section provides some basic theory involved during the drying process which is necessary to analyze the dryer performance and drying behavior of the material.

3.1. Amount of water removed from the product and energy requirement

The mass of water removed from the material (M_w) during the drying process can be estimated as

$$M_w = m_i(MC_i - MC_f)/(100{-}MC_f \tag{1}$$

Where m_i is the initial mass of material in kg, MC is the moisture content of the material on a wet basis. MC in the product can be estimated using, (Chandramohan, 2016a; Chandramohan and Talukdar, 2013).

$$\text{MC, wetbasis(wb)}, MC_i = (M_i - M_d)/M_i \tag{2}$$

$$\text{MC, drybasis(db)}, MC_i = (M_i - M_d)/M_d \tag{3}$$

Where M_i is the initial mass and M_d is the mass of the completely dried product in kg.

The initial MC of crops is generally estimated by an ASTM standard by heating them for 24 h at 105 °C in a hot air oven (Chandramohan and Talukdar, 2016).

The amount of heat required for the evaporation (E_{heat}) of moisture from the material can be calculated by the heat of evaporation by considering the humidity of drying air and can be mentioned as,

$$E_{heat} = \dot{m}_a(h_{do} - h_{atm}) \tag{4}$$

Where $\dot{m}_a$ is the mass flow rate of air in kg/s, h_{do} and h_{atm} are specific humidity at the dryer outlet and ambient in kg/kg of dry air, respectively.

Also, the total energy needed to evaporate the moisture (Q_d) can be estimated by adding the sensible and latent heats (Ayensu, 1997),

$$Q_d = m_m C_{pm}(T_d - T_a) + m_w h_{fg} \tag{5}$$

Where, m_w and C_{pm} are mass and specific heat of the material in kJ/(kg K), T_a is surrounding temperature, T_d is drying temperature, h_{fg} represents the enthalpy of evaporation (kJ/kg) at T_d.

3.2. Efficiencies, save in drying time and specific energy consumption

The main function of solar dryers is to harness solar thermal energy using solar air collectors (SAC) or transparent cover sheets. The overall efficiency (η_o) of the collector can be calculated (Esen et al., 2009b),

$$\eta_o = m_{fluid} C_{pa}(T_c - T_i)/A_c I \tag{6}$$

Where, m_{fluid} is the mass flow rate of fluid in kg/s, T_i and T_c are temperatures of air at inlet and outlet of the collector, A_c is the area of the collector in m^2 and I is incident solar radiation (W/m^2).

One of the performance parameters of the dryer is, save in drying time (t_s) which gives the drying time of ISD compared to OSD. It is calculated by,

$$t_s = \frac{t_{OSD} - t_{SD}}{t_{OSD}} \times 100\% \tag{7}$$

Where t_{osd} and t_{sd} are drying time in the open sun and solar dryer, respectively.

Drying efficiency (η_d) is the ratio of energy observed by the wet material for removing the moisture to the total energy incident on the collector. It can be estimated as,

$$\text{Fornaturalconvection}, \eta_d = \frac{Q_d}{A_c I} \tag{8}$$

$$\text{Forforcedconvection}, \eta_d = \frac{Q_d}{A_c I + P_f} \tag{9}$$

$$\text{Forthehybridsolardryer}, \eta_d = \frac{Q_d}{(A_c I + P_f) + (m_{fuel} H_{fuel})} \tag{10}$$

Where P_f is the fan power in kW, the product of m_{fuel} and H_{fuel} is the energy supplied by the auxiliary heating source.

Pick-up efficiency (η_p) indicates the moisture removal capacity of the drying air from the material and it is estimated as,

$$\eta_p = \frac{h_{do} - h_i}{h_{as} - h_i} \tag{11}$$

Where h_{do}, h_i and h_{as} are specific humidity of air at dryer outlet, inlet and saturated condition.

Specific energy consumption (*SEC*) (kJ/kg) is the ratio of total energy input (P_t) to the quantity of water removed from the wet product.

$$SEC = \frac{P_t}{m_w} \tag{12}$$

3.3. Exergy parameters

The maximum amount of available energy from the system is called exergy. The amount of exergy which is destroyed when entering into the dryer is called irreversibility (Esen et al., 2007b). It is useful to find the available energy at various regions within the dryer. The exergy values were estimated with the help of a generalized energy balance equation (Celma and Cuadros, 2009) and the final expression of exergy (E_x) was reduced after imposing assumptions (Tambunan et al., 2010) and is mentioned as,

$$Ex = \dot{m}_a C_{pa}\left[(T - T_\infty) - T_\infty ln\left(\frac{T}{T_\infty}\right)\right] \tag{13}$$

The exergy inflow (Ex_{dci}) and exergy outflow (Ex_{dco}) of the system are mentioned as,

$$Ex_{dci} = \dot{m}_a C_{pdai}(T_{dci} - T_\infty) - T_\infty ln\left(\frac{T_{dci}}{T_\infty}\right) \tag{14}$$

$$Ex_{dco} = \dot{m}_a C_{cpdo}(T_{dco} - T_\infty) - T_\infty ln\left(\frac{T_{dco}}{T_\infty}\right) \tag{15}$$

Where T_{dci} and T_{dco} are the temperatures at the inlet and outlet of the dryer.

The exergy input to SAC (Zhu et al., 2018) was estimated using:

$$Ex_{in} = \left[1 + \frac{1}{3}\left(\frac{T_a}{T_{sun}}\right)^4 - \left(\frac{4T_a}{3T_{sun}}\right)\right] IA \tag{16}$$

Where, T_{sun} is the apparent black body temperature of the sun, which is about 5770 K (Kalogirou et al., 2016)

The exergy losses are determined using exergy inflow (Ex_i) and exergy outflow (Ex_o) as mentioned below,

$$Ex_l = \sum Ex_i - \sum Ex_o \tag{17}$$

The exergy efficiency (η_{Ex}) is estimated by,

$$\eta_{Ex} = (Ex_i - Ex_l)/Ex_i = 1 - (Ex_l/Ex_i) \tag{18}$$

The improvement potential, *IP* is estimated as,

$$IP = (1 - \eta_{Ex})Ex_l \tag{19}$$

4. Solar dryers in different industries

According to International Energy Outlook (IEO), U. S. Energy Information Administration, (2019), 50% of the heat generated is consumed by industries, 46% of heat is consumed by space and water heating and only 4% of heat is consumed for agricultural greenhouse heating. Energy consumption in the sectors namely industrial, transportation, residential, and commercial increases day by day due to an increase in demand. It is supplied by commercial energy sources including renewable energy but its contribution is very small compared to other sources (Monthly Energy Review January 2020, U. S. Energy Information Administration, 2020). Among the 35–38% of total energy industrial consumers, 11.5% of industries need temperature less than 150 °C, 8.5% industries require a temperature between 150 °C and 400 °C, and remaining industries need more than 400 °C (Knaack et al., 2018; The International Energy Agency (IEA) (2018)). This pattern of energy consumption is almost similar in all industries all over the world (Mujumdar, 2006). The various industries and their thermal energy requirement for solar drying are discussed in this section.

4.1. Agricultural and food industry applications

Water content in the food material causes its spoilage due to microorganisms and bacteria growth. Drying restricts the growth and reproduction of microorganisms to avoid spoilage, and also it is used to reduce the weight and volume of the material which saves the transportation cost (Chandramohan, 2016b). Dehydration in agricultural products needs a large amount of heat which can be supplied by harnessing solar thermal energy. The utilization of solar energy also helps to reduce conventional energy sources. Many researchers provided a review on different types of dryers and carried out mathematical, analytical, and experimental studies for thermal analysis, and proposed different techniques for enhancing the dryer efficiency (El-sebaii and Shalaby, 2012; Lamidi et al., 2019). Various conventional solar air heaters and their design and performance parameters are reported in the literature (Ekechukwu and Norton, 1999; Lingayat et al., 2020c; Mohana et al., 2020). A detailed review of the effect of various influencing parameters has been discussed by Mishra et al. (2020b).

Lakshmi et al., (2018) found the drying kinetics of black turmeric using a mixed-mode forced convection solar dryer integrated with a TES system. The moisture removal rate of turmeric has been examined by comparing the results with OSD. Two sets of thin layered black turmeric samples (each 200 g) were chosen for the investigation. The first set was placed in a solar dryer and another was placed for OSD. A shell and tube heat exchanger TES system was coupled with the solar dryer to dry the samples during night times. 35 kg of paraffin wax is used as an energy storage material. It was observed that the discharge air temperature at the outlet of the system was 6 – 10 °C more than the ambient temperature at night times. Turmeric was dried from an initial MC of 73.4% to 8.5% (wb) using a solar dryer and OSD which took 18.50 h and 46.50 h, respectively. The specific energy consumption of the product to dry was estimated and is 5.21 kWh/kg per kg of moisture. The average collector efficiency and overall drying efficiencies were found to be 25.6% and 12%, respectively. The quality of fresh and dried turmeric was tested and found better results for solar dried turmeric in terms of color, phenolic content, and flavonoid content. Similarly, there were other studies found with solar dryers, and the products dried are; red chili (Ndukwu et al., 2017; Rabha et al., 2017), bitter gourd (Zachariah et al., 2020), garlic (Shringi et al., 2014), apricot (Baniasadi et al., 2017), apple (Atalay et al., 2017) and orange (Atalay, 2019). Each studies' data such as drying capacity, final mass, initial and final MCs, average ambient and drying air temperatures, drying time, energy storage material, total and specific energy consumptions, the mass of water evaporation, dryer, collector, and exergy efficiencies are mentioned in Table 2.

It is observed from Table 2 that the highest drying air temperature (65 °C) was noticed at Lakshmi et al., (2018) among all other studies. The overall drying efficiency (η_d) is just 12% as mentioned in Table 2 because of plastic sheet is used as a collector cover instead of anti-refluxing glazed glass. The transmissivity of glazed glass is 0.9 therefore it can transmit 90% of the total incident solar radiation. Also, the glazed glass can transmit the solar heat flux in one way only. It cannot allow the reflected solar radiation from the absorber plate to the outside atmosphere. There is a possibility of improvement in collector design as the setup produced a low drying efficiency (12%) because of the huge

Table 2
Selected studies on solar drying of agricultural crop products and their drying and performance parameters.

Parameter	Lakshmi et al., (2018)	Ndukwu et al., (2017)	Ndukwu et al., (2017)	Zachariah et al., (2020)	Shringi et al., (2014)	Baniasadi et al., (2017)	Atalay, (2019)	Mohanraj and Chandrasekar, (2009)	Rabha et al., (2017)
Dryer Size/ Specifications	2.04 m length, 1 0.04 m width and 0.2 m depth	–	–	280 mm × 120 mm × 80 mm	1.2 m × 0.6 m × 0.5 m	0.7 m × 0.6 m × 0.15 m	2.3 m × 2.3 m × 2.3 m	1 m × 1 m × 1.5 m	2 m × 0.85 m × 0.37 m
Product dried	black turmeric	Red chili	Red chili	Bitter gourd	Garlic clove	apricot slices	Orange slices	Chili	Ghost chili pepper
Drying capacity (kg)	15	1	1	2.5	–	–	10	40	9
Final mass of the product (kg)	–	0.373 kg	0.398 kg	–	–	–	0.988 kg	–	1.02 kg
Initial moisture content of product (%)	73.4%	72.2%	72.2%	92%	55.5%	86%	93.5%	72.8%	85.5%
Final moisture content of product	8.5%	7.6%	10.1%	4%	6.5%	25%	10.76%	9.1%	9.7%
Average ambient temperature (°C)	–	28.25 °C	28.6 °C	32 °C	32 °C	–	27.3 °C	31 °C	32 °C
Drying air temperature (°C)	65 °C	40.35 °C	41.83 °C	48 °C	39–69	65 °C	55.4 °C	50.4 °C	50 °C
Drying time (h)	18.5 h (solar drying) and 46.5 h (open sun drying)	24.5 h	36.5 h	10 h	8 h	1.55 gr/h	7.2 h	24 h	42 h
Energy storage material	Paraffin wax	sodium sulfate decahydrate ($Na_2SO_4{\cdot}10H_2O$)	Sodium chloride (NaCl)	PVC caps, Al pipes and paraffin wax	PCM	Paraffin wax	Packed bed (Pebbles)	Gravel	Heat storage module
Total energy consumption (MJ)	–	7.37 MJ of solar energy and 0.204 MJ of thermo-chemical energy	11.49 MJ and 0.011 MJ of solar and thermo-chemical energy	–	–	–	88.1 MJ	–	21.3 MJ
Specific energy consumption (kWh/kg per kg of moisture)	5.21	3.34	5.28	6.1 (without PCM) and 3.6 (with PCM)	–	–	1.98	–	18.72
Mass of water evaporate (kg of water / kWh)	0.192	0.627	0.602	0.16 (without PCM) and 0.28 (with PCM)	0.54–1.05	0.933	0.505	0.87	0.053
Relative humidity (%)	22% (inside) and 65% (outside)	42.23% (inside) and 64.9% (outside)	59% (inside) and 64.9% (outside)	–	–	–	45.21%	60%	–
Drying efficiency (%)	12	18.79	11.89	18.6	–	10.7	34.4	21	4.05
Collector efficiency (%)	25.6	–	–	–	–	–	–	–	22.95
Exergy efficiency (%)	–	66.82	–	67 – 88	–	–	63.34	–	63

amount of heat losses such as convection and radiation.

A newly developed mixed-mode solar dryer is a better option for drying high-value medicinal agricultural products like black turmeric (Lakshmi et al., 2018). In DSD dryers, the food product directly absorbs the solar radiation through the collector cover, whereas, in ISD, the air is heated in a separate chamber and sent to the drying chamber. The mixed-mode dryers have the provision of both DSD and ISD dryers, therefore, it has the following advantages;

- A rapid drying rate is possible with the safe moisture level in the product.
- The time required to dry the products is less compared to DSD and ISD drying techniques.
- Uniform distribution of airflow rate is possible inside the dryer.

A natural convection solar dryer (NCSD) was integrated with TES materials such as sodium chloride (NaCl) and sodium sulfate decahydrate ($Na_2SO_4{\cdot}10H_2O$) for continuous drying of red chili at Nigerian climate conditions (Ndukwu et al., 2017). Three cases of experiments were conducted namely; dryer with $Na_2SO_4{\cdot}10H_2O$ (Case-I) and NaCl (Case-II) TES systems and dryer without TES system (Case-III) was used to dry red chili to reduce the MC from 72.27% (wb) to 7.6% (wb), 10.1% and 10.3%, respectively. It took a drying time of 24.5 h, 36.5 h, and 40.5 h for case-I, II, and III, respectively. There is not much considerable difference in drying time of Case-II and Case-III experiments. But the considerable difference is there in Case-I and Case-III and almost 16 h drying time is saved in Case-I. Therefore, $Na_2SO_4{\cdot}10H_2O$ can be used as an efficient TES material (Ndukwu et al., 2017).

The overall drying efficiency and energy utilization of the three cases differed from 10.61 to 18.79% and 7.54–12.98 MJ, respectively. The exergy efficiency of the dryer at night times (with NaCl and $Na_2SO_4{\cdot}10H_2O$) was 81.19% and the same for the overall drying process (round-a-clock) was 66.82%. It was concluded that approximately 602 tonnes/year of CO_2 could be limited from entering the air using $Na_2SO_4{\cdot}10H_2O$ as a TES medium compared to a diesel-powered dryer. The most important finding is effective energy utilization. Case-I, II, and III have consumed energy of 3.34, 5.28, and 5.92 kWh/kg of moisture removal. It proves that these types of NCSD integrated with TES effectively minimized various heat losses which lead to efficient energy usage.

A novel photovoltaic (PV) assisted greenhouse cabinet mixed-mode solar dryer integrated with a TES system was used for drying bitter guard slices (Zachariah et al., 2020). The paraffin wax was used as TES material which was packed into the dryer cabinet. 2.5 kg of the bitter guard were dried from 92% to 4% MC (wb) which took 10 h with the TES system and the same took 1 day without the TES system as mentioned in Table 2. The required specific energy per kg of moisture removal from the product was 3.6 kWh per kg of water (with TES system) and 6.1 kWh per kg of water (without TES system), respectively. The specific moisture removal rates from the product (bitter gourd) with and without the TES system were 0.28 and 0.16 kg of water per kWh, respectively. The overall η_d of the solar dryer with and without the TES system was 18.6% and 10.8%, respectively. The primary findings are; an increase in overall η_d and a reduction in drying time. It just took 10 h to completely dry the product which is a good sign in the development of mixed-mode type solar dryers. A similar kind of study was carried out by Shringi et al., (2014) for drying of garlic clove. The cloves were dried from 55.5% to 6.5% MC (wb) at the drying time of 8 h. The energy and exergy efficiencies were between 67.06% and 88.24 % and 3.98% to 14.95%, respectively.

An experimental investigation of a mixed-mode forced convection solar dryer (FCSD) integrated with a TES system was carried out by Baniasadi et al., (2017). A blower was used to maintain a continuous supply of air for drying apricot slices. Paraffin wax was used as a TES material and it was placed at the bottom of the cabinet tray. The basic difference between this system and other mixed-mode dryers was the structure and construction of the solar collector. The collector plate was tilted to 30° and the total collector area was partitioned into three zones in the form of trapezoidal shapes. Experiments were carried out with and without the TES system to remove MC from initial MC of 86% to final MC of 25% as shown in Table 2. The dryer with a TES system provides a 50% higher drying rate than without a TES system. The η_d and moisture removal pickup efficiencies were 10.7% and 9.8%, respectively.

The impact of packed bed TES system and waste heat recovery system (recuperator) was examined on the performance of a solar dryer which was used to dry apple slices (Atalay et al., (2017). The novelty of the dryer was the drying air was again and again recirculated with the help of a recuperator. So that 50 to 60% of the waste heat was utilized effectively in the dryer. The average temperature of the air was between 55 and 60 °C as presented in Table 2. The stored thermal energy in the packed bed system was 210 MJ. The drying process was continued till the final moisture of the apple slices was reached 10%. The average drying time was 6 h. The drying process took 8 kW of energy to complete the drying process. The specific moisture removal rate of the product was 0.819 kg per kWh.

The practical feasibility of a low-cost solar drying system integrated with a packed bed TES system was investigated using an experimental study (Atalay, 2019). The drying kinetics of orange slices were studied to investigate various performance parameters such as exergy, energy, sustainability index, improvement potential, and waste exergy ratio. Orange slices were dried from 93.5% to 10.28% MC (refer to Table 2). The average energy required and specific energy consumed to dry the orange slices was 89.89 MJ and 1.89 kWh per kg, respectively. The specific water evaporation rate (SMER) was 0.53 kg per kWh. The exergy efficiency was in the range of 50.18–66.58 % and 54.71–68.37% for dryers without and with the TES system. The sustainability index and improvement potential were in the range of 2.15 to 3.17 and 0.016 to 0.07 kW, respectively. This system has improved drying efficiency (34%) and SMER because of minimum heat losses from the system.

An experimental analysis was performed in an indirect FCSD with TES material (gravel) to dry red chili (Mohanraj and Chandrasekar, 2009). The MC of the red chili was reduced from 72.8% to 9.2%. The average drying air temperature inside the cabin was 50.4 °C (refer to Table 2). A high drying rate of 6.2 kg/kg of dry matter per hour was achieved in the initial stages of drying. The thermal efficiency of the solar dryer was 21% with a specific moisture removal rate of 0.87 kg/kW h. A similar analysis with energy and exergy analysis in an FCSD was carried out by Rabha et al., (2017). A paraffin wax-based shell and tube latent heat storage unit was used in the setup. It was examined with 20 kg of red chili with an initial MC of 73.5% (wb). The product was dried up to the MC of 9.7% (wb) in four consecutive days (the effective drying period is 35 h). In comparison with the OSD method, the newly developed FCSD method saved 122.8% of the drying time of chili. The exergy and energy efficiencies of the TES unit were between 18.3 and 20.5% and 43.6–49.8%, respectively. The exergy efficiency of the drying cabinet was in the range of 24.6% to 98.1% with an average of 52.2%. The specific energy requirement and the gross efficiency of the solar drying system were 6.8 kWh per kg of moisture and 10.8%, respectively. The power consumption of the dryer was 0.7 kWh per kg of moisture which was only 10.3% of the specific energy consumption of the chili.

A similar study of FCSD with paraffin wax was performed by El Khadraoui et al., (2017). The performance was evaluated at two different cases under no-load conditions: with PCM and without PCM. The daily energy and exergy efficiencies of FCSD with PCM were 33.9% and 8.5%, respectively. At night time, the drying air temperature inside the drying cabinet was 4 to 16 °C higher than outside ambient temperature. A similar kind of research was already attempted by El-Sebaii and Shalaby, (2013) for drying thymus and mint under Tanta, Egypt weather conditions.

An HSD dryer for osmotically pre-dehydrated cherry tomatoes was designed by Nabnean et al., (2016). 100 kg cherry tomatoes were dried at a temperature between 30 and 65 °C for 4 days. The osmotic pretreatment of tomatoes before solar drying helps to improve final quality. Sekyere et al. (2016b) developed a solar dryer with six infrared heat lamps to simulate solar radiation in laboratory conditions. Concrete absorber and rock pebble bed were used to store solar energy and assisted with an electric heater. Performance of dryer was investigated with 2.3 kg pineapple slices and the MC in the solar dryer was reduced from 912 to 155% (db) in 7 h. Yahya et al., (2018) carried out the performance and economic analyses on solar-assisted heat pump fluidized bed dryer integrated with biomass furnace for rice drying. MC of rice was reduced from 32.85% (db) to 16.29% (db) in 22.95 min, with a mass flow rate of 0.1037 kg/s at an average temperature of 80.9 °C. The payback period of the system was1.6 years.

In recent days, new parameters such as waste exergy ratio, sustainability index, and improvement potential are introduced to assess the performance of dryers with storage systems (Atalay, 2019). From the recent studies related to the TES device, the drying efficiency was 21% (Mohanraj and Chandrasekar, 2009) which was less than 20% a decade before. It was proved that FCSD with a TES storage system can enhance the performance and overall efficiency of the drying system. One more new term (pick-up efficiency) is introduced by Baniasadi et al., (2017) to evaluate the actual performance of the solar dryer based on the removed moisture from the food product. The structure of a dryer suggested by Baniasadi et al., (2017) is relatively less complicated and never utilized the auxiliary energy during daytime. The drying rate was reduced by 50% with the use of energy storage material. The dryer integrated with the TES system could recover an energy payback period of 1.91 years and also a discounted payback time of 0.8 years which is lower than the life span of the dryer making it environmentally and economically safe (Zachariah et al., 2020).

4.2. Marine industries

Marine industries also one of the major sectors where solar energy plays an important for the drying of married products. A solar dryer with a TES system was developed for shrimps drying (Murali et al., 2020). The water-based TES system stored the energy during peak sunshine hours. Also, the dryer was assisted with liquefied petroleum gas (LPG) as an auxiliary heating source. 50 kg shrimp were dried from 76.71% (wb) to 15.38% (wb) within 6 h of drying as mentioned in Table 3. Solar collector supplied 73.93% of heat and the rest of the energy (26.07%) was assisted by the LPG water heater system (Murali et al., 2020). Table 3 provides the various studies on the solar drying of marine applications.

An indirect type hybrid FCSD dryer with an artificial heat source of diesel burner was designed and developed by Fudholi and Sopian, (2019) to dry salted silver jewfish. V-groove collector was used to enhancing the heat flux absorbing capacity of the collector. The diesel burner was assisted with the dryer so that the drying could be effectively performed with a continuous supply of heat. The dryer took a minimum of 8 h to remove the MC from 64% to 10% (wb). The specific energy consumption rate of the dryer was 2.92 kWh/kg (as shown in Table 3). The drying and exergy efficiencies of the hybrid system were 23% and 31%, respectively.

The same marine food (silver jewfish) was dried in another study (Bala and Mondol, 2001). They investigated the performance of a solar tunnel dryer at Bangladesh atmospheric conditions. A 20 m length and 2 m width of tunnel dryer were used for the drying process. MC was reduced from 67% (wb) to 16.78% (wb) in 36 h. This chemical composition of dried fish indicated that the fish dried in the solar tunnel dryer was a quality product for consumption. A hybrid solar dryer assisted with biomass-based air heating system had been tested by Hamdani et al., (2018) for fish drying. Solar energy was used from 9.00 am to 4.00 pm followed by a biomass burner from 4.00 pm to the next day at 6.00 am. Overall, the drying air temperature was maintained at 40–67 °C and the mass of fish reduced to 12.5 kg from 25 kg (as mentioned in Table 3). The maximum drying air temperature maintained inside the cabin was 50 °C (in the daytime) and 67 °C (at the night with the help of a biomass dryer). The total moisture removal rate from the product (on a wb) is 50.5% to 12% within a drying period of 23 h. The total incurred cost of the hybrid solar dryer was $ 1870 with the break-even point of 2.6 years.

The technical feasibility of industrial solar dryer integrated with linear Fresnel collector and concrete TES for production of pasta was conducted by Liu et al., (2015). A dryer capacity of 2.4 MW was used. Thermic oil was heated with a linear Fresnel collector. Hot thermic oil was used to heat the water with the temperature range of 120 to 140 °C which was then supplied to heat the air for pasta drying. The proposed solar dryer could save 40% annual thermal energy in a pasta factory.

Marine foods are highly sensitive tissues that need to be dried with much care. The partial moisture within the food destroys the tissues and it may be unusable then. The safer MC within the fish is reported as 15–20% (wb) (Rahman, 2006). The studies with 15–20% of final MC were not found for fish drying in literature. Such an intensive drying process, the dryer needs a lot of energy and it cannot be feasible by solar energy alone or need more researches to achieve the same. In such a situation, hybrid dryers can be designed (Hamdani et al., 2018) to run the dryer round-a-clock so that the micro-organisms reaction can be avoided. The possible options are solar energy with bio-mass energy (Hamdani et al., 2018) or industrial waste heat energy, or diesel burner (Fudholi and Sopian, 2019).

Most of the time, the marine foods were dried with dry salts. The dry salts always take further MC from the tissues. When the muscles were with more MC and dried with a higher temperature, the salt is diffused uniformly all its geometry because the diffusion coefficient is a function of temperature and MC. A good salting process was explained for Tilapia fish in (Rahman, 2006). The fish-salt ratio is 3:1, salting time was up to 24 h, the effective drying time of 6–20 h with the drying air temperature range of 40 to 60 °C are the other drying data provided in (Rahman, 2006). From the experimental works of marine food drying, it was found that the average collector exit temperature was 75 °C with an average drying efficiency of 25.42%. The average temperature attained inside the chamber lies between 60 and 65 °C.

4.3. Tea industries

Tea is one of the most consumed drinks. China and India have a major contribution to tea production which is near about 29.56% and 25.35% of the total world tea production (Chang, 2015). Withering, drying, grading, and packing are processes involved in tea production that are energy-intensive and these processes consume 85% of thermal energy and 15% of electrical energy (Sharma et al., 2019). The thermal energy required for the drying process during tea production can be fulfilled by solar energy. Vacuum-assisted solar dryers were designed and experimented for drying black tea by Pou and Tripathy (2020). The relationship between input parameters such as vacuum level, loading rate, and output parameters such as color, aroma, index, drying time and energy consumption were presented. The system was optimized based on the maximum liquor color and aroma index with minimum energy consumption and drying time. Liquor color, aroma index, drying time and energy consumption were estimated to be 20.08, 11.65, 4.44, 140.66 min and 21450.7 kJ, respectively, at an optimum vacuum level of 570.71 mmHg and loading rate of 0.96 kg m^{-2}. Ozturk and Dincer

Table 3
Selected studies on solar drying of marine applications.

Paper	Size / Specifications	Product dried	Drying capacity (kg)	Initial moisture content	Final moisture content	Air Temperature (°C)	Drying time (h)	Heat source	Energy consumption (kJ)	Drying efficiency (%)	Exergy efficiency (%)
Murali et al., (2020)	4.23 m × 1.00 m × 1.80 m	shrimp	50	76.71% (wb)	5.38% (wb)	55	6	Solar system (2,06,641 kJ) and LPG water heater (72,890 kJ)	2,79,531	37.09	–
Bala and Mondol, (2001)	40 m^2 area	Salted silver jewfish	150	67% (wb)	16.78% (wb)	52.2	36	Solar energy	–	–	–
Fudholi and Sopian, (2019)	13.8 m^2 area	Salted silver jewfish	51	64% (wb)	10% (wb)	50	8	Solar system and Diesel burner	2.92 kWh/kg	23	31% (Avg.)
Hamdani et al., (2018)	2.6 m × 0.8 m	Queen fish	25	50.5% (wb)	12% (wb)	50 (day time), 67 (night)	23	Solar system and biomass fueled air heater	–	–	–

(2019) conducted the exergo-economic analysis of solar dryer integrated with PV unit for drying of tea leaves. MC in 100 kg wet tea leaves was reduced from 80% (wb) to 3% (wb) in four days. The capital cost and the capital productivity of the dryer were estimated to be $5953 and 1.54, respectively. The energetic loss ratios, exergetic loss ratios, exergy efficiency and exergy destruction were estimated as 76.45 MJ/$, 72.63 MJ/$, 74% and 201.6 GJ, respectively.

Chamomile leaves (herbal tea) were dried in a solar dryer and the drying kinetics were estimated by Amer et al. (2018). The dryer was assisted with a solar collector, reflector, water air heat exchanger, and solar heated water storage tank with an electric heater as a supplementary heat source. Water was used as a sensible heat storage medium which stored heat energy during day time. Two drying chambers were used with a capacity of 32–35 kg. One drying chamber was placed just below the absorber surface and the second one was placed in a series with the first chamber. Temperature controllers were used to controlling the required drying temperature. The system was useful to dry chamomile from 75% to 6% (wb MC) which helped to reduce the drying time by 27–30 h compared with OSD. Midilli model was suggested for fitting the drying kinetics of chamomile.

An FCSD dryer with an auxiliary heating system was used to dry Mexican tea leaves (Kane et al., 2008). During the experiments, the following parameters such as solar insolation, ambient temperature, drying air temperature, relative humidity, and airflow rate were varied. It was concluded that the temperature was the most influential parameter during drying. The diffusion coefficient of tea leaves was in the range of 1.0209 to 1.0440 × 10^{-9} $m^2.s^{-1}$ and the activation energy was 89.15 $kJ.mol^{-1}$. They reported that Wang and Singh model is the best model for the characterization of Mexican tea leaves drying.

The economic viability of roof-integrated solar dryer for tea drying was investigated by Palaniappan and Subramanian (1998). The dryer was provided with other sources of heat energy such as coal and firewood. The built collector area was 212 m^2. The solar energy usage on the dryer saved the annual fuel consumption by 25%. Sopian et al. (2000) carried out the experimental analysis on a solar-assisted drying system for herbal tea drying. The solar collector was provided with V-grooves so that it could create enough turbulence and hence enhanced the heat transfer rate. The collector area of 20 m^2 could provide a hot air temperature of more than 50 °C at a flow rate of 15.1 m^3/min. An auxiliary heating system was employed if the air temperature was less than 50 °C. The dryer effectively drying the herbal leaves from 87% MC (wb) to 54% MC (wb) in 12 h.

From the above studies on tea leaves drying, the following highlights were observed. Vacuum-assisted solar dryers help to produce quality black tea after providing the optimum vacuum level and loading rate (Pou and Tripathy, 2020). Exergo-economic analysis needs to be performed to find the energy and exergy losses from the dryer. Also, expenses incurred for the drying system and the payback period can be identified as these are important terminologies for tea industries. A hybrid solar dryer with a reflector, thermal storage, and two drying chamber could effectively help to save the drying time up to 20 h compared to OSD. These types of dryers can be commercialized in rural areas so that small-scale farmers get benefitted (Amer et al., 2018). The annual fuel consumption is reduced up to 26% by pre-heating of tea-processing air using a solar air heating system (Palaniappan and Subramanian, 1998).

4.4. *Automobile industry*

The automobile industry has a long and complex manufacturing process. Paint curing is an important process in automobile industries which is carried out by thermal energy mainly in the form of hot air at a temperature in the range of 80–150 °C. Also, during the manufacturing process of automobile components, hot air is used to dry the components at a temperature below 90 °C. This heat energy can be retrieved from solar energy instead of using a commercial energy source. The automobile sector is one of the developing sectors as well as expensive, the usage of solar energy is highly advantageous. Also, it has a lot of potential for the involvement of a solar air heating system for various operations. SAC or water-based collector with a water–air heat exchanger can be used for air heating up to 80 °C to 150 °C which can save a lot of fossil fuel consumption (Giampieri et al., 2020; Orsato and Wells, 2007).

The polymeric coating is another important application in the automobile sector. It is used to avoid corrosion in steel plates. It is also advantageous such as less toxic and environmentally friendly compared to other chemical coatings (Singhal et al., 2014). It is made up of layer by layer and each layer needs to be properly dried to make the subsequent layer. A high temperature drying air up to 90 °C is necessary to dry each layer. Solar drying can be preferred by providing proper arrangements so that the excess cost involved in commercial energy can be avoided. More understanding is required between chemists and drying researchers to take forward this specific research area with solar drying to the next arena.

4.5. *Rubber industry*

Rubber is an elastic substance used in a wide range of goods production. Rubber is produced by natural latex from the plant or by artificial synthetic method. Drying plays an important role in maintaining the quality of the final rubber sheet from raw material. Breymayer et al. (1993) reported that the improper drying of raw rubber material results in low-grade rubber sheets which are about 80% of the total production which have to be sold at relatively low prices. Drying is generally done by a simple hot air-drying method or by smoke drying method. In the air-drying method, wet rubber sheets are dried with the OSD or by producing the hot air by conventional energy sources. In the case of the smoke-drying method, smoke was generated by burning firewood and biomass in the smokehouse to remove the moisture from rubber sheets. Rubber is generally dried in the temperature range of 45–60 °C and it can be easily achievable using solar energy (Tanwanichkul et al., 2013). Breymayer et al. (1993) developed the dryer integrated with SAC and traditional firewood/biomass smokehouse as an auxiliary heating source. SAC with recirculation of exit air from the dryer helped to generate a drying air temperature range of 45–60 °C. A total of 320 kg of rubber sheets were dried using a solar dryer and the sheets lost their MC from 60% to 0.5% which reduced the firewood consumption. It took five days to achieve 0.5% MC in the solar dryer with biomass whereas, it took seven days with the solar dryer alone. But the developed system is very advantageous because if commercial energy is used for seven continuous days (instead of solar drying), the expenses will increase further. An ISD dryer assisted with an electric air heater was used for natural rubber drying which provided the quality rubber as a final product (Pratoto et al., 1998). The moisture content of rubber sheets was dried from 60% to 0.5% (wb) in 8.8 h at 100 °C.

Dejchanchaiwong et al., (2016) compared the drying performance of mixed-mode and ISD dryers while drying with 30 natural rubber sheets. Better quality and drying rate was noticed for the mixed-mode dryer compared to the ISD. Both dryers helped to reduce the drying time by 2–3 days compared to OSD. Dryer efficiencies of the mixed-mode and ISD dryers were 15.4% and 13.3%, respectively. MCs in rubber sheets were reduced from 32.3 to 2% (wb) and 29.4 to 8% (wb) in four days using mixed-mode and ISD dryers, respectively.

The performance of the greenhouse solar dryer for rubber sheet drying was analyzed by Janjai et al. (2015). The dryer was able to provide the temperature from 32 to 55 ℃ which was useful for effective drying of 750 kg rubber sheets without affecting its quality compared with OSD. The dryer was useful to reduce the MC of rubber sheets from 24 − 30% (wb) to 0.4–3.9% (wb) in five days where OSD could reduce only 13% in five days. They also developed an ANN model to predict the drying characteristics of rubber sheets.

Artificial neural network modeling was carried out to develop the dryer for mass production. Jitjack et al. (2016) suggested a parabolic greenhouse dryer with area-enhanced panels for effective drying of rubber sheets as shown in Fig. 3. There were two setups made to compare the results. One was made with a parabolic greenhouse collector and in another, additional collector plates were provided for enhancing the collecting area. Better quality of rubber sheets was noticed in the enhanced area model compared with simple parabolic greenhouse dryer. The dryer was able to provide a maximum temperature of 55 ℃, which helped to reduce the drying time by 3.5 days compared to the dryer without area-enhanced panels.

When the rubber sheets are dried with natural and OSD drying methods, the final dried product took a lot of drying times, and sometimes it took 10–20 days. Such a long drying time creates huge color changes on the final product. Sometimes, more MC and long drying time produce fungus growth on the product and thereby deteriorating the natural color further. These are all not encouraged by the purchaser or the product price is reduced from the standard price which creates a lot of inconvenience to the rubber farmers. Therefore, the rubber sheets need to be dried within few days so that the freshness is maintained which attracts the buyer. Such issues can be solved using solar drying techniques. A perfectly designed solar dryer produces up to 70 °C (Lingayat et al., 2020a) air temperature inside the drying chamber, therefore, rubber sheets can be dried enough in these setups. More experimental and numerical studies are required to run the setup with different volumes of rubber sheets so that industries come forward to make their setup and finally it can reach farmers.

4.6. Pulp, paper, and allied industries

The pulp and paper industry is one more sector where solar-based technologies can play an important role to reduce energy costs. Different processes involved in these industries are pulp making, bleaching, paper making, drying, etc. Drying is the process that happened at the final stage at a temperature between 60 °C and 150 °C. It is a very important and critical process that consumes a large amount of heat (Gemechu et al., 2012). The commonly used method of OSD for handmade paper can be replaced by solar drying (Madhavan and Ramachandran, 2015). An ISD dryer was developed for drying twelve A4 size paper sheets (each 22 g) at a time. The collector outlet temperature was in the range of 45 to 70 °C. The dryer was useful to reduce the MC of sheets from 50% to 7% (wb) during 65 to 75 min of drying time. An economic analysis was carried out and found that a payback period for the dryer was 95 days.

Hjort and Thomas, (2014) developed a small prototype of a solar dryer assisted with a water heater and air–water heat exchanger for the application of paper drying. The prototype was tested for different handmade paper types at different input conditions. The specific energy consumption was 3.5 MJ / kg of water evaporated and the dryer efficiency was 80%. The developed prototype is useful for developing a large-scale setup.

Fig. 3. The pictorial view of greenhouse solar dryer with natural rubber sheets inside (Jitjack et al., 2016).

The potential of solar energy for process heat and its advantages on the reduction of CO_2 emissions in the paper and pulp industry was presented by Sharma et al. (2016). Annual process heat requirements were estimated based on location and raw material used and estimated the performance of commercial systems. Tagnamas et al. (2021) used a convective solar dryer to find the drying kinetics and characteristics of the carob pulp at various drying temperatures from 50 to 80 °C and velocity of 0.18 and 0.09 m/s. It was observed that the diffusion coefficient varies with temperature. It was in the range of 1.56 to 6.98 $\times$ 10^{-9} m^2/s. The energy and exergy efficiencies were estimated and these are in the range of 4.23% to 7.25% and 30.12% to 80.5%, respectively.

Among the above studies, it is identified that the pulp and paper industry sector also reliably used solar energy. There were many setups developed for the paper and pulp drying process. This sector needs to be addressed well for future development. It needs more studies so that these industries can develop their system to dry the materials with solar energy. The thermal energy and the quality of energy needed for pulp and paper industries need to be estimated. The other major thermal energy requirement factors such as land availability, location, fuel cost, quality of steam required, compatibility of existing method, other emergency heating systems, etc. need to be investigated for the benefit of this sector.

4.7. Sugarcane industry

Bagasse is crushed fibers left over after the juice from the sugarcane industry which is an excellent raw material that can be used as fuel for electricity generation, bio-methane production, animal feed, and fertilizers (Rabelo et al., 2011). Generally, the dry bagasse is used as fuel to heat the cane juice in the heating pan. For effective combustion, it is necessary to remove the moisture from the bagasse (Venkata Sai and Reddy, 2020). Few studies reported that the solar drying method can be chosen for drying the wet bagasse before feeding into the furnace for combustion (Phadkari et al., 2017; Subahana and Natarajan, 2016). Phadkari et al. (2017) developed an FCSD setup for solar drying of bagasse pulp where 1000 g of bagasse fibers were dried. The proposed dryer was useful to dry the bagasse from the initial MC of 48% to 16.77% (wb).

Theoretical and experimental analysis of solar tunnel dryer was carried out by Subahana and Natarajan, (2016) for drying of switchgrass, rice straw, and sugarcane trash. The setup was made with four compartments and the bottom of the compartment was made with wood for avoiding heat losses. Aluminium chambers with stainless steel meshes were provided for keeping the materials. Four different soils such as red (absorptivity of 0.65), yellow (0.73), grey (0.84), and black (0.95) were used in four compartments to check the effect of absorptivity of soils. The rice straw was dried for 8 h and its MC reached 0.906, 0.872, 0.849, and 0.837 kg/kg of db for red, yellow, grey, and black soils, respectively. It shows that when the absorptivity of soil is increased, the moisture removal rate is decreased. When absorptivity increases, more portion of heat energy is absorbed by the soil results in lower temperature inside the compartments. It creates a low drying rate of rice straw. The setup was given with a provision to conduct the experiments for parallel and cross-flow passage. The crossed flow gave much better results because of more turbulence inside the compartments and hence the grasses get high exposure to hot air. Maximum temperatures of 78 and 63 °C were observed during theoretical and experimental analysis of rice straw drying with yellow-colored soil.

Vijayaraj and Saravanan (2008) carried out a numerical study on the drying behavior of rectangular bagasse to predict the temperature and moisture distribution within it. Variation in mass transfer coefficient and heat transfer coefficients were estimated which varied in the range about 0.0001 to 0.0125 m/s and 0.01 to 0.5 W/m^{2}K, respectively. Embong et al. (2016) proposed a method to extract the SiO_2 from sugarcane bagasse ash. The authors suggested a pre-treatment method using low-concentration acid followed by a solar drying process. The proposed method was efficient for the production of sugarcane bagasse ash with high pozzolanic reactivity to extract SiO_2 that can be used as an alternative to cement. The solar dryer was used for drying sugarcane bagasse after washing in a constantly rotating cylinder for 20 min.

Sugarcane bagasse is an effective feedstock in combustion chambers and is also used for bioethanol production. This waste consists of a huge of MC and it needs to be removed properly. This moisture removal process can be done with solar drying. OSD drying creates high contamination on the final dried product which may affect the combustion process and also more studies need to be made with ISD dryers. The energy, exergy, and economic parameters need to be estimated and analyzed thoroughly so that more industries can utilize this concept which may directly benefit the farmers.

4.8. Sewage and industrial waste

Sludge and wastewater are a mixture of liquid and solid-like municipal waste or industrial waste that is discharged into the river or sea without pretreatment. A significant quantity of waste, in the form of sludge, is produced after wastewater treatment which carries 95% of water content. Presently, mechanical systems are used for dewatering but these systems are not useful for pathogen reduction where thermal heat can play an important role. Thermal heat has a high operational cost. So, solar energy for thermal heat generation can be an economical and efficient solution. Dried sludge reduces the storage, handling, and transportation cost for sludge.

A case study on wastewater sludge drying was conducted by Belloulid et al., (2019) in Morocco. The greenhouse dryer was designed for sludge drying to reduce the water from sludge and results were compared with OSD. Fresh sludge samples with 80% initial MC were considered for the experiment. To reach the final MC of 20%, OSD took 45 h and 65 h whereas, the greenhouse dryer took 32 h and 57 h in summer and winter, respectively. Ameri et al., (2020) conducted a study in Algeria on the drying behavior of wastewater sludge in indirect and direct solar drying (ISD and DSD). Drying rate, moisture diffusion coefficient, and drying efficiency were analyzed and found that better performance on the ISD method than the DSD method. The average drying temperature was observed to be 43 and 41 °C in ISD and DSD, respectively. The diffusion coefficient was in the range of 1.91 to 9.12 × 10^{-8} m^2.s^{-1}. The activation energy for ISD and DSD dryers was 32.16 and 32.01 kJ mol^{-1}, respectively.

Mechanical dewatering is a method to separate sludge into a liquid and a solid part. This dewatered sludge need to be dried again to remove its MC. A study was performed by Salihoglu et al. (2007) to remove MC from the dewatered sludge with a plastic glazed solar tunnel greenhouse dryer. Solar drying after mechanical dewatering helped to reduce the sludge weight by 60% and the addition of 15% lime before drying helped to reduce the pathogen in the sludge. Solar dryer with rock bed as a TES material was used for sludge drying (Poblete and Painemal, 2020). Rock bed material helped to improve the drying process and reduced the drying time by providing the required temperature after sunshine hours. The energy efficiency of the dryer with the TES system was 21.68% higher than the dryer without TES.

Biogas plant waste slurry is a good natural fertilizer for agricultural land. Also, the dried slurry can be used for landfilling as it consists of a lot of natural nutrients. Drying of slurry is the major task in the biogas plant. If the plant was provided with necessary arrangements for solar drying, then the exhaust slurry can be properly treated with 15–20% of lime and can be dried. The drying time of the slurry was reduced to 65% compared to the OSD method (Kumar and Prakash, 2019). As the temperature requirement in wastewater drying is not more than 80 °C which is achievable with the help of greenhouse dryers, ISD, and mixed-mode dryers.

Once again proved that the ISD process is always better than the DSD process under the same working conditions (same solar radiation). Based on the evaluation of thermodynamic characteristics of drying of sludge, it is known that OSD creates an uneven drying, whereas, ISD produces better performance. This sector needs a further analysis on bacterial reaction before, during, and after the drying process and more studies are needed to concentrate on dewatering, stabilization, incineration, thickening, etc. so that the solar drying of sludge can be projected in a better way to industries and society.

4.9. Lignite coal industry

Lignite is the foremost fossil fuel used in thermal power plants for electricity generation which carries about 30–70% of MC. The MC creates further difficulty during the combustion process. It is necessary to remove the MC before feeding into the combustion chamber (Nikolopoulos et al., 2015). Liu et al., (2017) analyzed the performance of solar drying of lignite coal in a thermal power plant as shown in Fig. 4. A parabolic dish collector was used for the pre-drying of lignite coal and the dried lignite was fed into the boiler for combustion which helped to increase the boiler efficiency. It was observed that the overall combustion efficiency of lignite coal was influenced by the preheating of coal before feeding into the boiler. Also observed that both dryer efficiency and boiler efficiency influenced the solar-to-electric conversion efficiency. The solar-to-electric conversion efficiency of 34% was achieved for the proposed plant.

A solar dryer with flat plate air solar collectors was used for the pre-drying of lignite in a solar-lignite hybrid power generation plant (Xu et al., 2018). The dried lignite, using solar energy, has a high calorific value which helped to increase the plant efficiency. Thermal energy, exergy efficiency, and economic analysis were carried out to find the effect of dried lignite on system performance and lignite expenditure. The solar-dried lignite helped to increase the boiler efficiency by 1.2% which saved the lignite expenditure cost and increased the overall energy efficiency by 0.5%. Solar electrical efficiency was estimated to be 21.2%. A similar type of solar lignite hybrid power generation system was proposed by Xu et al. (2017). The effect of integration of solar energy for pre-drying of low-rank coal and low-temperature pyrolysis on system performance was investigated. It was observed that the solar drying of low-rank coal helped to achieve the required quality of coal for boiler feeding. The proposed system was integrated with a typical 600 MW supercritical power plant for further analysis. Overall energy and exergy efficiencies of the system were estimated to be 90% and 89.8%, respectively.

Han et al. (2020) proposed a solar lignite hybrid power generation system where solar-driven heat pumps were integrated with waste heat recovery. The system gave a two-stage drying for the lignite. Waste heat was absorbed by the solar-driven heat pump and utilized for pre-drying of lignite, which helped to increase the heating value of the fuel. Both thermodynamics and economic analysis were carried out for the 660 MW power plant. The authors claimed that the proposed method helped to generate the additional 50.3 MW power with 3.47% higher efficiency.

From the above studies, it is proved that solar energy is successfully used to dry lignite/coal. The coal/lignite is a huge quantity, sometimes in tonnes, compared to few kgs of food materials or other industrial applications. Drying of huge quantum (of lignite/coal) is a tough task and need expensive solar plants with huge collector area. Once it is made, the system works fine without further expenses. Also, the dryer gives enhanced performance parameters such as energy, exergy, solar-to-electric conversion, boiler efficiencies (Xu et al., 2017; Xu et al., 2018) when normal dryers were updated with solar dryers. Also, MC presents in lignite/coal gives more problems in coal generating unit and fuel handling equipment and hence this natural energy can be used to remove the MC.

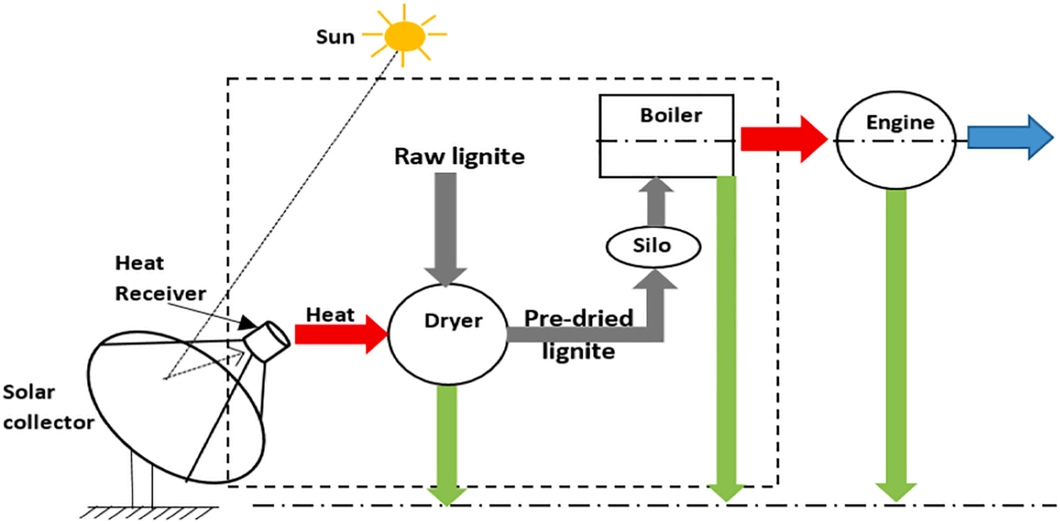

Fig. 4. Schematic of lignite solar drying for preheating of lignite before firing (Liu et al., 2017).

From the above studies on various industries, it is observed that solar energy has huge potential in the area of renewable energy sources and it can be implemented effectively. Table 4 gives the temperature required and types of dryers used in various industries for drying operation.

5. Economic, environmental and social aspects

The investment cost of the solar dryer is more compared to the conventional method of drying (Bennamoun, 2011) but compared to traditional OSD drying, it offers several economic advantages such as reducing the fuel cost and emission from fuel. Also, a quality dried product increases its market value. Annualized costs, the life cycle of dryers, and payback period have been used to examine the economic feasibility of dryers but it depends on many factors such as drying material, geographical location, size, capacity, design factor, system efficiency, etc. (Kumar et al., 2016; Lingayat et al., 2020b). Also improved nutritional value, less space occupied by dryers, and higher yield also should be considered while doing the economic analysis. Emission from the fuel after combustion is responsible for global warming and pollution problem. Various policies and norms are implemented in different countries to reduce emissions.

The governments suggest running different industries with the help of solar energy and also give subsidies on solar-based systems (Pirasteh et al., 2014b). The power consumed by the fan in the forced greenhouse dryer is only 5% of the total energy required. If the fan is also run by solar energy or PV panels, then the total artificial energy required is zero (Mugi and Chandramohan, 2021). If conventional energy sources assisted with solar energy, then the dryers could save 20–40% of conventional fuel energy (Liu et al., 2015). Many researchers reported that the use of solar dryers could reduce CO_2 emissions compared to other drying techniques (Ekechukwu and Norton, 1999; Hii et al., 2012). As per the report of (REN21, 2019), about 20% of the global energy is generated from renewable energy sources which included wind, solar, biomass, geothermal. Also, renewable policies create employment opportunities in the solar energy sector. The use of solar energy would significantly reduce the environmental pollution problem and improve public health.

There are some industries which already employed solar energy for different drying operations and are listed in Table 5.

6. Important findings

All the solar drying methods used in different industrial applications were explained in the previous sections. The important findings of each industrial application on solar drying are listed in Table 6. There were many agricultural materials such as turmeric, red chili, bitter gourd, garlic, apricot, apple, orange, black turmeric, cassava, ghost chili pepper, cherry tomato, pineapple, rice, etc. were dried in a solar dryer as discussed in this article (section 4.1). Solar dried turmeric gave good results in the form of its color, phenolic content, and flavonoid content. The heat losses such as convection and radiation must be reduced to increase the system performance. Paraffin wax was used as a TES material in most of the studies in food drying applications.

The marine foods such as shrimps, salted silver jewfish, queenfish, and Tilapia fish were dried in solar dryers as discussed in section 4.2. Fish flesh is a very sensitive tissue so that it needs to dry continuously to avoid wastage. Therefore, along with solar energy, other auxiliary sources of energy such as biomass, industrial waste heat, diesel burner, etc. must be used to dry the tissues round-a-clock so that a better final product could be achieved. The studies available for solar drying of the tea industry are chamomile tea leaves (Amer et al., 2018) and Mexican tea leaves (Kane et al., 2008) and they showed that the solar-dried tea leaves gave good results in terms of color and flavor. Also, the hybrid solar dryers reduced the drying time up to 20 h (section 4.3).

Paint curing and polymer coating are the applications of solar drying in the automobile industry. The paint curing needs an air temperature range of 80 to 150 °C which is possible using solar energy (Giampieri et al., 2020). The polymer coating is used on the steel surfaces which is used to avoid corrosion. This polymer coating needs to be effectively dried and the solar drying concept can be preferred for this application (section 4.4). 80% low-quality rubber is produced worldwide because of improper drying and therefore, these sheets are sold for low market price (Breymayer et al., 1993). Smoke drying is the preferred drying method that needs to be used for rubber sheet drying. The temperature range maintained in the solar dryer is 45 to 60 °C. Solar dryer reduced the drying time of rubber sheets up to 3 days compared to the OSD method (section 4.5).

The developed setup for paper drying (Madhavan and Ramachandran, 2015) gives a pay-back period of 95 days only and it's an alarming fact that all possible options of solar paper drying trials need to be encouraged (section 4.6). The sugarcane industry is another sector using solar energy to dry the crushed leaves (bagasse) and waste stem. They are used for biomass and landfilling purposes as they have good nutrients and importantly used for bio-ethanol production as mentioned in section 4.7.

Solar energy is used in sewage and wastewater treatment as dewatering cannot eliminate the bacteria in the sludge. As the contents are huge, it is better to use solar energy to dry the sludge. The dried solid

Table 4

The temperature required and various types of dryers used in various industries during the drying processes.

Sector	Process	Temperature Range (°C)	Type of solar dryers used
Agricultural and food industries	Drying	40–200	• Almost all types of natural and force convection solar dryers with and without TES
Marine industries	Drying	40–80 °C	• Solar water heating system with air–water heat exchanger. • Indirect type hybrid FCSD dryer Fudholi and Sopian, (2019) • Solar tunnel dryer (Bala and Mondol, 2001). • Hybrid solar dryer (Hamdani et al., 2018)
Tea industries	Drying of tea leaf	40–70 °C	• Vacuum-assisted solar dryers (Pou and Tripathy 2020) • Indirect type FCSD with PV-T collector (Ozturk and Dincer, 2019) • Indirect type natural convection solar dryer (Amer et al., 2018) • Roof-integrated solar dryer (Palaniappan and Subramanian, 1998) • FCSD dryer (Kane et al., 2008).
Automobile industry	Surface treatment Drying of finished components	20–120 60–150	• Solar water heating system with air–water heat exchanger. (Giampieri et al., 2020; Orsato and Wells, 2007).
Rubber industry	Drying of rubber sheets Preheating	45–150 50–70	• ISD with SAC (Pratoto et al., 1998). • Mixed-mode solar dryer (Dejchanchaiwong et al., 2016) • Greenhouse solar dryer (Janjai et al. 2015; Jitjack et al., 2016)
Pulp, paper and allied industries	Drying	45–80	• Indirect type natural convection solar dryer (Madhavan and Ramachandran, 2015) • Solar water heating system with air–water heat exchanger (Hjort and Thomas, 2014).
Sugarcane industry	Drying of bagasse	40–65	• FCSD (Phadkari et al. 2017) • Solar tunnel dryer (Subahana and Natarajan, 2016)
Sewage and industrial waste	–	40–65	• Greenhouse dryer (Belloulid et al., 2019: Salihoglu et al. 2007) • Mixed-mode dryers. ISD and DSD (Ameri et al., 2020)
Lignite coal industry	~70	Pre-drying of lignite coal	Parabolic dish collector (Liu et al., 2017; Xu et al., 2018)

waste can be used for the landfill. Also, the storage, transportation, and handling costs of dried sludges were low (section 4.8) compared to raw wastes. MC in lignite/coal reduces the combustion characteristics and also create problem in lignite/coal units. The solar-dried lignite/coal produced high fuel value and the boiler efficiency was improved as explained in section 4.9.

Table 5

Industries using solar energy for drying applications (Solar Termal Heat for Industrial Processes (SHIP), 2019).

Industry	Industry name	Process	Type of collector	Temperature (°C)
Agriculture and Food	Coopeldos, Costa rica	Coffee drying	Solar air heater	40–45
	Duren Coffe, Panama Duren	Coffee drying	Solar air collector	40–45
	Keyaqa Orchards, USA	Walnuts drying	Solar air collector	~43
	Gengli Fruit Drying, China	Fruit drying	Solar air collector	50–70
	Malabar Tea Drying, Indonesia	Tea drying	Solar air collector	~35
	Carriers and Sons, United state	Food drying	Solar air collector	~43
	AMR dal Mill, India	Drying of pulse	Solar air collector	65–75
	Aroma Plant Romania, Romania Aroma	Drying of medicinal plants	Solar air collector	
	Sonoma Country Herb Exchange, USA	Drying of herbs	Solar air collector	
	Grammer Solar Argentina, Argentina	Drying of tobacco	Solar air collector	
	India Tobacco Division, India	Conditioning of tobacco	Solar air collector	~95
Rubber and Plastic Products	Inter Rubber Latex Co. Ltd., Thailand	Drying of natural rubber	Solar air collector	
Concrete	Leitt Beton Gmbh, Austria	Drying of pre-fabricated concrete components	Solar air collector	
Furniture	Carpenting Hamminger, Austria	Wood Drying	Flat plate collector	25–115
Mining	Korner Kvk, Austria	Preheating, drying of raw material	Flat plate collector	50–80

7. Recommendations proposed for better performance

After predicting the potential of solar energy for different industrial drying applications, it is important to propose the solar dryer system, which should be simple in design, cost-effective, and suitable for drying various food and other products. Different techniques and methods have been suggested and implemented for a reduction in drying time and better product quality. The assistance of a solar water heater with dryers is one of the possible solutions to make the hybrid drying systems using renewable energy. Various types of solar water heaters of concentrating type and non-concentrating types are available in the market. They are; flat plate collectors, evacuated tube collectors, compound parabolic collectors, parabolic trough collectors, cylindrical trough collectors, parabolic dish reflectors, heliostat field reflectors, linear Fresnel reflectors, etc. These collectors can provide a temperature range of 30 to 500 °C (Mekhilef et al., 2020; Pranesh et al., 2019). The assistance of solar drying systems with a water storage system and water–air heat exchanger can make the dryer more efficient for a wide range of applications in the area of solar drying Fig. 5 shows a generalized technic for thermal energy conservation that can be implemented for various drying applications. Solar collectors are used to absorbing solar radiation. Fluid flowing through the collectors absorbs the heat from the collector and is stored in the tank. The heat energy retrieved from the

Table 6
Important findings from the literature.

S. No	Authors (year)	Research outcomes and findings
Agricultural and food industries		
1	Lakshmi et al. (2018)	Drying air temperature is the highest (65 °C) among all other research works. The collector efficiency is low (12%).
2	Ndukwu et al. (2017)	Dryer with TES material of $Na_2SO_4 \cdot 10H_2O$ consumed energy of 3.34 kWh per kg removal of MC from the products. NCSD integrated with TES effectively minimized various heat losses which lead to efficient energy utilization.
3	Zachariah et al. (2020)	A mixed-mode solar dryer integrated with PCM produced an increase in η_d and reduction in drying time. It took 10 h time to completely dry the product.
4	Baniasadi et al. (2017)	At the end of the drying process, 25% of MC is available inside the product (apricot slices) Add 2 more important results.
5	Atalay et al. (2017)	Effective utilization of waste heat (about 50 to 60%) is possible with this system. The drying process took 6 h to completely dry the apple slices.
6	Atalay (2019)	Improved drying efficiency (34%) and SMER of 0.505 kg of water/kWh New parameters such as waste exergy ratio, sustainability index, and improvement potential were introduced. Energy and exergy efficiencies decreased up to 68.37%.
Marine industries		
1	Murali et al. (2020)	Drying shrimps is a very fast process compared to all other drying products. It took only 6 h time to dry 50 kg of shrimps. Drying and collector efficiencies were also improved up to 37.09% and 42.37%, respectively.
2	Bala and Mondol (2001)	A new drying method (solar tunnel dryer) was introduced to dry the salted silver Jew fish. The setup saved the product from rain, dirt, dust, and insects and also maintained the quality.
3	Fudholi and Sopian (2019)	The drying efficiency of the system is improved up to 29% using a hybrid drying system (solar + auxiliary diesel burner) to dry salted silver Jew fish. The specific energy consumption (SEC) is reduced to 2.92 kWh / kg of moisture removal.
4	Hamdani et al. (2018)	The cost incurred to fabricate a hybrid solar dryer to dry 100 kg of fish is $ 1870. Dry fish production capacity was 12,000 kg per year, selling price $ 3.3 / kg, obtained IRR = 18.61%, NPV = $ 21.091 and break-even point = 2.6 years.
Tea industries		
1	Amer et al. (2018)	Solar dryer with reflector, thermal storage system and two-chamber dryer can be used to increase the drying rate and capacity of dryer.
2	Palaniappan and Subramanian (1998)	The roof-integrated solar dryer can be used along with conventional energy sources to reduce the annual fuel consumption by about 25%.
Automobile industry		
1	Giampieri et al. (2020)	The paint drying in automobile surface is performed with a temperature limit of 50 to 80 °C. Water-based paints took 3 to 8 h of drying time compared to solvent-based paints (2 to 5 h).
Rubber industry		
1	Breymayer et al. (1993)	Smoke-assisted solar drying can be used for the better quality of natural rubber.
2	Dejchanchaiwong et al. (2016)	A mixed-mode solar dryer produced better results for rubber sheet drying than the ISD dryer.
3	Janjai et al. (2015).	A greenhouse dryer can be used for the mass production of dried rubber sheets.
Pulp, paper and allied industries		
1	Madhavan and Ramachandran (2015)	Handmade paper is dried in a solar dryer. It helped to reduce the drying time and gave better quality paper compared to OSD. Solar dryers were functional during day time even there is no sunlight and more humidity.
2	Hjort and Thomas (2014)	A solar-heated hot water flat tank could be a better and efficient option for paper drying. Experiments were performed for different operating conditions and paper types. It can be made functional in larger-scale dryers.
Sugarcane industry		
1	Subahana and Natarajan (2016)	A tunnel dryer with TES material of soil and preheated air gave a better moisture removal rate than a simple tunnel dryer.
2	Vijayaraj and Saravanan (2008)	The solution was used to approximate and quantify the different heat and mass transfer phenomena in bagasse for different conditions of drying.
Sewage and industrial waste		
1	Ameri et al. (2020)	ISD process is always better than DSD process under the same working conditions. Thermodynamic characteristics of the drying of sludge process were introduced to find out the nature and disorderness of drying process.
2	Belloulid et al. (2019)	The developed solar dryer for sludge and waste is fit for arid regions. The drying time saved in the solar dryer is 13 h in summer and 8 h in winter compared to OSD
Lignite coal industry		
1	Liu et al. (2017)	Drying of lignite/coal with solar energy increased the fuel value and the overall combustion efficiency of lignite coal. The solar-to-electric conversion efficiency was more than 34%.
2	Xu et al. (2018)	Solar-lignite hybrid power generation system helped to increase the boiler efficiency by 1.2% and saved lignite expenditure cost. Overall energy efficiency increased by 0.5%.

hot water (from the tank) transferred to the drying chamber and the materials can be dried.

This approach can be explored in all drying applications in industries. Integration of efficient utilization of solar energy with other renewable energy systems such as photovoltaic-thermal, dryer with TES system, solar and biofuel can improve the efficiency of the dryers. To make the solar drying system 100% renewable, it can be assisted with a ground source heat pump system. (Esen, 2006; Esen et al., 2007a) This needs detailed research in depth which can provide a positive impact on drying efficiency. Already a lot of mathematical (analytical and numerical) studies are available but most of the experimental studies are limited up to laboratory scale. So, it’s another research area where solar dryers can be explored on large scale for enhancement of production capacities.

A cost-effective approach by considering the capital and operational costs along with solar-based technologies is necessary for the effective implementation of dryers. The PCM is found to be a better option in the TES system of solar dryers. The efficiency of solar dryers can be improved by adding nano-materials in PCM which is used to increase the thermal conductivity of PCM. Even though the solar energy approach looks simple, a deep understanding of complex drying operations is necessary for large-scale applications for the success of the developed drying systems. The automation of the complete drying process can improve the quality of material and drying efficiency. By considering all these advantages of solar-based drying systems, the government and private sectors should encourage the researchers.

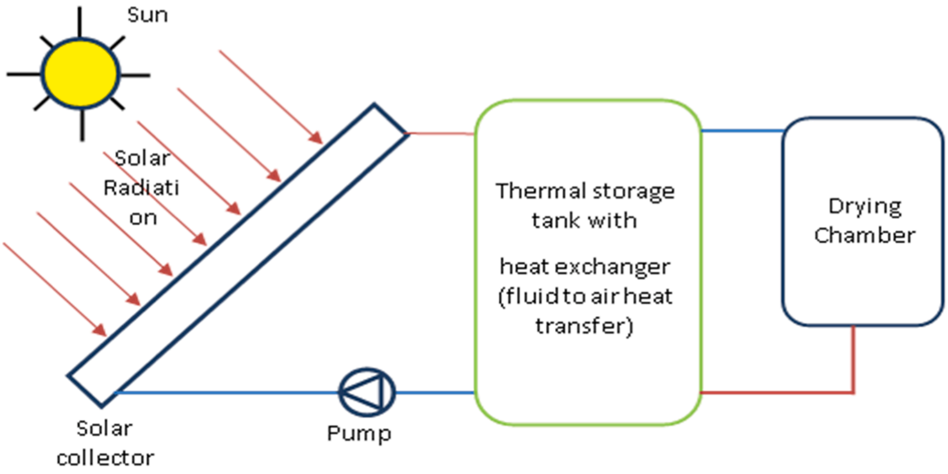

Fig. 5. Solar drying systems assisted with solar water heater and water–air heat exchanger.

8. Conclusions

Solar drying concept is an emerging technology for drying industries such as the food, automobile, paper, and allied products, rubber, sugarcane, sewage and industrial waste. Available literature reviews on solar dryers contributed more to the agricultural sector. This work reviewed the contribution of solar dryers of all industries. The presented review focused on industries where drying is involved during their production processes. Industrial drying process systems were analyzed concerning the type of material, existing solar drying technologies, required temperatures for drying, etc.

The required drying period of the product was different for different industries and their materials. The essential drying factors for all the industries were moisture content (MC) of the product, temperature, velocity, humidity of drying air, and geographical location. The solar dryers assisted with thermal energy storage (TES) systems helped to decrease the total time required for drying. Also, the addition of the TES system increased the system performance, energy, exergy, solar-to-electric conversion efficiencies. The use of hybrid solar dryers (such as dryers with LPG water heaters, diesel burners, and biomass-fueled air heaters) helped to satisfy the electrical power requirement so that the dryer could work round-a-clock. Forced convection solar dryers (FCSD) gave better performance compared to NCSD setups, but they needed little artificial energy for running the fan or blower. FCSD setups could run with zero electrical power using solar photovoltaic panels to run fans or blowers.

Solar-based drying technology is a promising area of research. The commercialization of solar dryers is increasing day by day for different drying applications in industries. More researches on different applications further help industries to make their setups so that society can enjoy its outcomes. This article helps scientists and researchers for finding the opportunity in solar-based drying systems for different industries and making feasible drying operations.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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