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REVIEW

A comprehensive review of indirect solar drying techniques integrated with thermal storage materials and exergy-environmental analysis

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Abstract
Food processing industries generally use fossil fuels for heating and drying applications leading to increased carbon footprints in the atmosphere. The carbon emissions can be significantly reduced with the use of solar energy. Various solar drying techniques are used to dry agricultural products; however, drying can only be done during the sunshine hours. Outside the sunshine hours, drying can be performed using thermal storage materials in which thermal energy is stored during sunshine hours and utilized during non-sunshine hours. This paper aims to deliver the significance of different thermal storage materials for improving solar drying efficiency. Also, a comparative study on various modes of drying practices like natural and forced convection, with and without thermal storage materials, is presented mainly for indirect solar dryers. The crucial parameters affecting the drying rate, such as initial moisture content, air velocity, air temperature, type of food products, solar collector, and dryer efficiency, are reviewed, tabulated, and significant findings are highlighted. The challenges of using both sensible and latent storage materials were also discussed. The overall drying efficiency of the indirect solar dryers can be increased up to 25% over sun drying, and the collector efficiency can be enhanced up to 70% with thermal storage materials. A significant reduction in drying time of 6 h was noticed with thermal storage materials. The maximum solar collector efficiency of 70% was found with forced convection systems, whereas only 30% was achieved with natural convection systems. Exergy efficiency for most of the recently developed indirect solar dryers was more than 50%, which implies that the developed techniques can still be improved by minimizing the exergy losses. When the exergo-environment analysis was compared with other solar dryers, embodied energy of the indirect solar dryer was much lower when compared with other solar dryers. Therefore, the energy utilization and CO_2 emission by the indirect solar dryer is significantly low. This review will guide the researchers to design efficient indirect solar driers and collectors for future applications so that net zero emission can be achievable shortly.

Keywords Solar drying · Forced convection · PCM · Sensible heat storage · CO_2 mitigation · Embodied energy

Extended author information available on the last page of the article

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1 Introduction

The energy for drying agricultural products comes from various sources such as solar energy, natural gas, biomass and fossil fuels. In the developed world, 10 to 20% of total industrial energy consumption depends on thermal drying methods (Belessiotis & Delyannis, 2011). The practice of solar energy utilization in the agricultural sector has a potential scope for minimizing the cost of operation since the earth receives solar radiation abundantly. Thirugnanasambandam et al. (2010) reported that the planet gets 7500 times more solar radiation than is needed by the world's energy consumption. Therefore, when solar radiation is used to dry agricultural products, it can replace conventional drying methods using fossil fuels and natural gas. Also, the use of renewable energy sources has increased due to variations in the price of fuels, depletion of traditional fuels and other environmental factors. Greenhouse gas emission is another major problem in the industrialized world. In the past decades, the energy demand has increased significantly, and fossil fuels mainly meet the need. Globally for the last ten years, electrical energy consumption has been steadily growing by over 3%. As far as developing countries are concerned, CO_2 emissions have increased from 18 to 22 Gt between the year 2010 to 2019 (Ahmadi et al., 2021). According to the International Energy Agency (IEA) analysis, global CO_2 emission has increased to the highest peak in history after the pandemic (COVID-19). The CO_2 emission by coal, natural gas and oil contribute around 15.3, 7.5, and 10.7 billion tonnes, respectively. The equivalent diesel requirement to generate 1MWh of electricity is 291 kg (Nassar et al., 2021). As a result, the use of fossil fuels positively impacts CO_2 emissions (Tailon et al., 2021). On the other hand, food processing industries consume large amounts of energy from electricity and heat. Therefore, the food processing industries can reduce a large amount of CO_2 emissions by using solar-powered machines.

In the postharvest phase, drying agricultural products is a basic unit that needs much energy. Drying increases food products' shelf-life by protecting against the attack of insects, microorganisms and pests during storage. After drying, the agricultural products can be stored for the off-season. Drying refers to the moisture removal from the product to the predetermined level. It is a complex process that includes a Physico-chemical and thermo-physical process, and it is governed by heat and mass transfer laws and affects the final quality of the product. It may also remove volatile materials present inside the solid material. Different drying methods are available for fruits and vegetables: freeze drying, radiation drying, microwave drying, fluidised bed drying, superheated steam drying, osmotic drying and convection drying (Abhay et al., 2017). All these dryers depend on external power sources.

Traditionally, agricultural products were sun-dried; in recent decades, solar-dried products are emerging and fetching good market value. Solar radiation is a gift from nature and an environmentally friendly energy resource that requires sizeable open space and mainly depends on the sunshine hours. The rodents, birds, insects, litter and dust may contaminate the sun-dried products. It is also affected by climatic conditions and natural calamities. The other drawbacks of direct sun drying are loss of the active compounds of the food materials, bleaching of the colour, non-uniform drying and time consuming. However, it is hygienic if the food products are dried in the proper innovative solar drying setup.

Adopting solar drying techniques for preserving fruits and vegetables can minimize the emission of environmental pollution like carbon monoxide, carbon-di-oxide and nitrites as well as fossil fuel costs. This technique can be adapted to any fruit and vegetable. Various researchers have developed novel solar drying techniques for different fruits like grapes (Srivastava et al., 2021), apples (ElGamal et al., 2021), pineapple (Gilago et al., 2022), fig (Ekka et al., 2021), bananas (Lingayat et al., 2020), strawberry (Rodríguez-Ramírez et al., 2021), pomegranate (Abhimanyu et al., 2020), mango (Mongi et al., 2022), sweet cherry (Ouaabou et al., 2020), pear (Hind et al., 2022) and sliced orange (Atalay, 2019). Also, solar drying techniques can be used in drying vegetables such as potatoes, bitter guard, carrots, onions, and tomatoes and non-vegetables such as drying shrimp and meat. The performance of the solar drying technique can be improved by incorporating a Thermal Storage Material (TSM) in the solar drying systems (Mugi et al., 2022). Generally, TSM helps to store heat energy during day time and release heat during the off-sunshine hours.

Various researchers have developed novel indirect solar dryers to improve drying efficiency. Sharma et al. (2021) reviewed PCM-integrated indirect solar drying techniques. Reported that paraffin wax was most commonly used PCM mainly utilized during off-sunshine hours. Srinivasan et al. (2021) reviewed thermal storage materials integrated with solar dryers. It was concluded that applying a thermal storage material controls the temperature fluctuation inside the drying chamber. Using Sensible Heat Storage materials (SHS) like pebbles, rock, sand and brick with a thickness of 1 to 5 cm was practical. Some advantages of using SHS materials are low cost, higher specific heat capacity and availability. Some researchers have used desiccant materials as SHS material because of their exothermic reaction. It was kept outside during the daytime for sensible heating and then placed in the drying chamber at night. It was reported that solar dryers integrated with solar water heaters, heat exchangers, and other auxiliary heaters are highly complex and result in colossal capital investment; however, they can provide heat during sunshine hours.

Abed et al. (2022) reviewed advancements in integrating PCM with different solar collectors. The performance of PCM with a flat plate solar collector, a solar collector with the evacuated tube, a PV solar collector, a solar cooker and a parabolic trough collector was evaluated. It was reported that PCM as a working fluid in the evacuated tube solar collector enhances the efficiency of the solar collector. Metallic mesh made up of stainless steel and aluminium or using heat transfer fluid as PCM slurry significantly affects the heat transfer rate. Yi et al. (2022) reviewed the different concentrating (parabolic and non-parabolic trough) and non-concentrating (solar PV and PV/T) type solar dryers. It was reported that the V-grooved type solar collector creates turbulence in the airflow passage, increasing the convective heat transfer rate. The inlet and outlet temperatures were measured for both v-grooved and flat plate solar collectors. Mainly the temperature of a v-grooved type solar collector was 13.6 to 15.4% higher than the same of flat plate solar collector. Also, the solar collector with a parabolic trough was found capable of exacting more solar energy when compared to a flat plate solar collector. The expected operating temperature of a parabolic solar collector may range from 60° to 240 °C (Azwin et al., 2021). However, when the operating temperature goes beyond 75 °C, the active compound of the food material to be dried may be destroyed.

During the past few years, many researchers have developed innovative designs of solar dryers integrated with thermal storage materials, comparative studies with different configurations, numerical analysis with experimental data, and performance under different heat transfer modes. Also found a few reviews focused on the application of solar dryers in industry, particularly on a large scale. Further, most of the review focuses on the recent advancement in solar dryers, classifications of the solar dryer and thermal storage materials. However, more discussions are needed in reporting combined effects on the performance of solar dryers and collectors embedded with thermal storage materials. Moreover, no reviews are available in open literature reporting the CO_2 emissions from the drying process and discussing the exergy environmental analysis of different solar dryers, which are critical to achieving zero carbon emission. Therefore, this study reviews the latest developments in solar collectors integrated with sensible and latent storage materials and the challenges. Additionally, this study compares the CO_2 emissions from various energy resources and solar driers used in the food industry. Besides, the exergy environmental analysis of different solar dryers has been reviewed and presented. The main objective of this review is to propose the future direction for research and development in the design of indirect solar dryers and solar collectors.

1.1 Solar drying techniques

Solar drying techniques are mainly classified into (I) Direct, (II) Indirect, and (III) Mixed mode solar dyer.

1.1.1 Direct solar drying techniques

The food products are kept in the drying chamber covered with transparent polyethene film or glass in the direct-type solar drying technique. The drying chamber may be a cabinet, greenhouse or tent type (Hicham et al., 2018). The dryer surfaces are generally coated with black paint to absorb maximum heat (Messaoud et al., 2019). The solar radiation falls on the cover material (glass), which transmits, partially reflects, and is later absorbed by the black-painted surface (Ghasem et al., 2012). The heat absorption increases the temperature inside the dryer, and the food products get heated. In this way, the short-wave radiation from the sun is converted into long-wave radiation inside the dryer, which causes the greenhouse effect. The schematic diagram of the direct-type dryer is illustrated in Fig. 1.

1.1.1.1 Limitation

- Discolouration of dried products (Letícia et al., 2021)
- Limited usage due to small capacity (Sharma et al., 2021)
- Moisture accumulation on the covering material (glass) makes transmissivity less. (Prakesh et al., 2016)

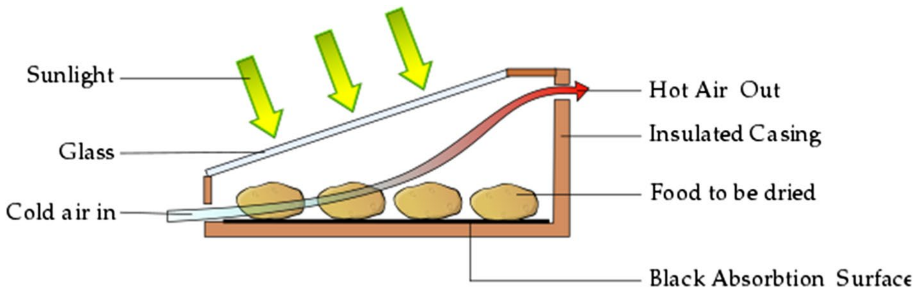

Fig. 1 Direct solar drying technique

1.1.2 Mixed mode solar drying technique

This system utilizes solar radiation through the drying chamber and the solar collector. The drying chamber is made of a transparent sheet of glass that enables the absorption of solar radiation. The incidence radiation on the solar collector gets absorbed and enhanced by the black paint. The absorbed energy heats the air and drives it towards the drying chamber (Chandrakumar & Jiwanlal, 2013). Also, the incidence of radiation heats the drying chamber. The moist air escapes through the outlet vent, and the ambient air gets inside through the inlet vent and gets heated by the absorbed solar radiation (Fig. 2). The performance of this dryer will directly depend on the efficiency of the solar collector (Arumugam, 2021, Rani and Tripathy, 2021).

1.1.3 Indirect solar dryer (ISD)

The indirect solar drying techniques consist of a solar collector with an absorber plate, drying chamber and chimney. The solar radiation incidence on the flat plate solar collector is trapped by the absorber plate in the solar collector and increases the air temperature inside the collector. The heated air is circulated to the drying chamber, and this circulation may be either natural or forced mode convection mode. This way, the moist air is sent out to the atmosphere through the chimney. The working of Indirect Solar Collectors is presented in Fig. 3. In this paper, an extensive review was done on Indirect Solar Dryers (ISD). A literature review shows that the indirect type solar dryer gives a better quality product, especially retention of the colour, and has better overheating control among the different types of solar dryers.

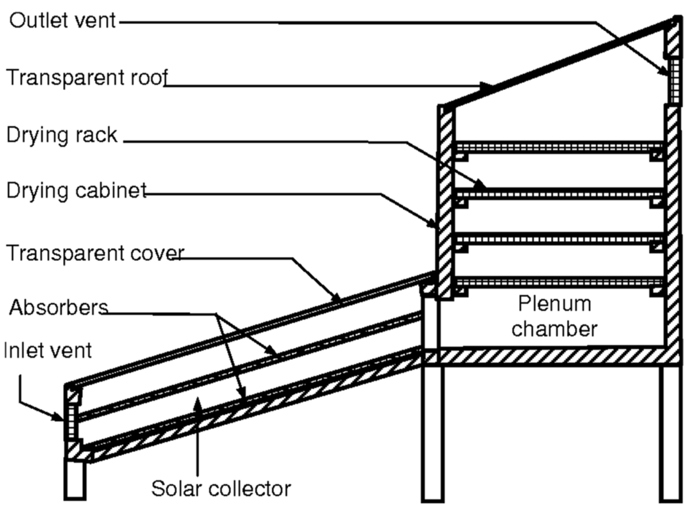

Fig. 2 Mixed mode solar dryer

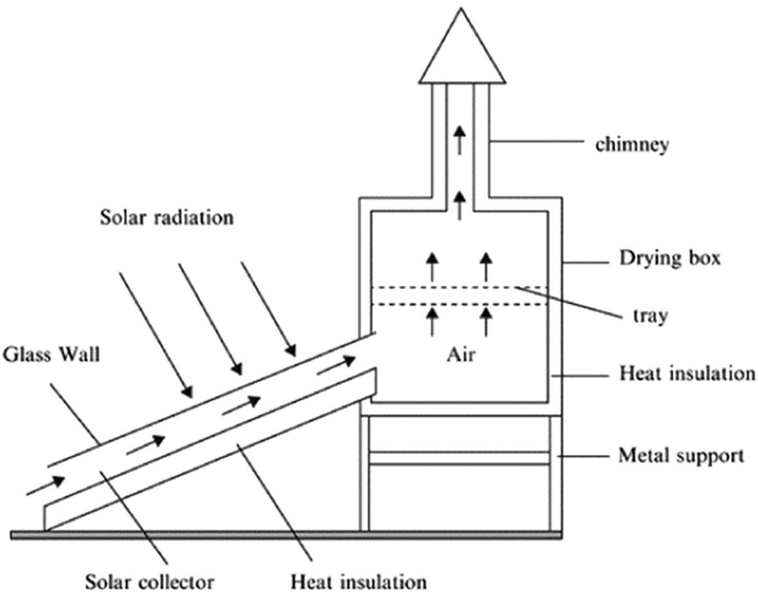

Fig. 3 Indirect solar dryer

1.2 Thermal storage materials (TSM)

During the non-sun shine hours, rainy and cloudy days, the dryer performance is greatly affected. Also, due to the extended drying time, the food products' quality declines, and the food materials may be attached by microorganisms (Amer et al., 2010). Integrating solar dryers with a thermal storage system can reduce the drying time of the food materials as well as the drying efficiency can also be improved. TSM can be classified into sensible heat storage and latent heat storage materials.

1.2.1 Sensible heat storage materials (SHS)

The materials that can store excess heat from solar radiation can be called sensible heat or natural thermal storage materials. Several SHS materials are cited in the literature, such as sand, limestone, brick, aluminium, rock, iron and gravel. These SHS have excellent thermal stability (no degradation or weight loss), thermal reliability (no change in the thermal characteristics) and chemical stability (no decay/ no change in chemical composition) (Mugi et al., 2022). It can be understood that highly thermal conductive particles like carbon fibres, graphite foam, and expanded graphite can improve the thermal efficiency of solar energy devices. Table 1 shows the list of sensible heat storage materials and their thermal properties. It was found that aluminium and granite have the highest heat capacity. The amount of sensible heat stored in the materials can be calculated using Eq. 1 (Srinivasan et al., 2021)

$$Q = mC_p\left(T_f - T_i\right) = \rho C_p V\left(T_f - T_i\right) \quad (1)$$

Table 1 Sensible heat storage materials and their thermal properties (Velraj, 2016)

SHS material	Specific heat (J/kg. K)	Density (kg/m^3)	Heat capacity × 10^{-6} (J/m^{3}K)
Aluminium	896	2707	2.4255
Brick	840	1698	1.4263
Clay	879	1458	1.2815
Concrete	880	2000	1.7600
Granite	892	2750	2.4530
sandstone	712	2200	1.5664
Stone, limestone	900	2500	2.2500
Stone, marble	800	2600	2.0800

where Q—Amount of heat storage, m—mass of the product (kg), C_p—Specific heat (J/kg/K), T_f—Final temperature, T_i—initial temperature, ρC_p—Volumetric heat capacity of the solid material (J/m^3/K), V—volume (m^3). Mugi et al., 2022 reported that Sensible storage materials could store heat energy up to 108 MJ/m^3 for heating and cooling applications.

1.2.1.1 Solar collector integrated with SHS Solar collector efficiency can be improved by increasing the convective heat transfer coefficient between the flowing air and the absorber plate. The flowing air turbulence increases when sensible heat storage materials are kept below the absorber plate. Also, the heat transfer rate due to convection increases because of the void space between the packed bed materials. El-Sebaii et al. (2007) (Fig. 4) conclude that a more convective heat transfer rate filled bed with low porosity should be placed above the absorber plate, and also using gravels can be better compared with limestones. Secondly, to increase the thermo-hydraulic efficiency, the system should be maintained with less pressure drop.

El-Sebaii et al. (2002) reported that the sensible storage material, mainly using sand, accelerated the drying time by 12 h. This SHS was placed between the absorber plate gap and the back cover insulation. The nocturnal moisture re-absorption value was found to

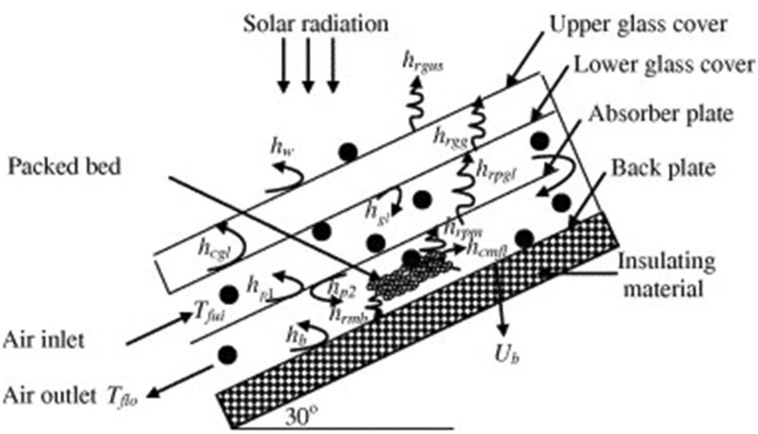

Fig. 4 Double glass, double pass solar air collector with sensible storage material

be – 7.0% and – 13.9% during the first and second nights, respectively. The negative values showed that the drying process was continuous through the night. Vijayan et al. (2020) developed the flat plate solar collector with a corrugated absorber plate made of galvanized iron sheet and coated black. The glass cover was placed 30 mm above the absorber plate to decrease the heat loss coefficient. The pebbles of 30 mm size were packed between the gap of the absorber plate and the back plate to store the sensible heat (Fig. 5). The solar collector outlet temperature was found to be 45.3 °C at peak solar insolation time.

Using an SHS with locally available material, the cost of operation of the solar dryer can be reduced. Mugi et al., 2022 reviewed various naturally available sensible storage materials like gravel, rock, sand, pebbles and granite and found that the working temperature ranged from 20 to 1200 °C. The thermal conductivity of these materials ranged from 1 to 10 W/mK. The factors which affect the retention and discharge time of SHS materials are the range of working temperature, storage system capacity, thermo physical properties of the materials, thermal diffusivity and density. Ahmad and Prakash (2020) reported that black-coated gravels are more energy efficient than gravel and sand. It also depends on the shape and size of the gravel. Cetina-Quiñones et al. (2021) reported that the limestone and beach sand's charge and discharge energy were 910 kJ and 736 kJ, respectively. It was also found that the drying time can be reduced up to 3 h using limestone and beach sand as SHS material in ISD.

Challenges in using SHS in solar dryer

- The volume of solar dryer increases due low energy density of SHS materials
- The design parameters to find the required amount of SHS material is difficult compared to LHS Since the heat transfer rate of the former depends upon the void fraction, size and RH.
- When pebbles and stones are used as SHS material, there will be more pressure drop at a higher flow rate as well as these materials have low thermal conductivity.

1.2.2 Latent heat storage materials (LHS)

When the materials change phase, i.e. from liquid to gas or solid to liquid or vice versa, during the constant temperature, there is absorption or release of heat from the material (Pause, 2019). The heat energy stored in these materials depends on the endothermic reaction, conversion extent and the amount of material used. LHS materials can store high

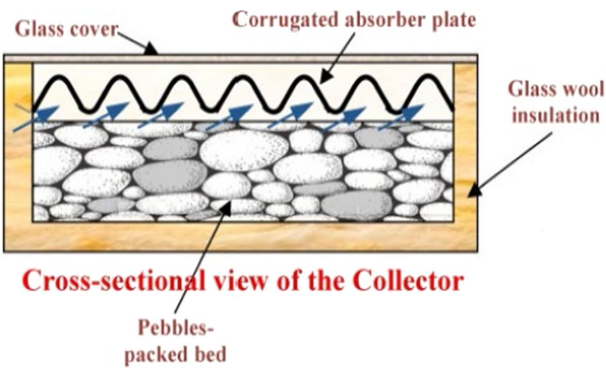

Fig. 5 Single plate-corrugated absorber plate with SHS material

energy density per unit volume and per unit mass at a constant temperature. The amount of heat energy stored in the LHS material can be calculated using Eq. 2 (Srinivasan et al., 2021)

$$Q = m\left[C_{ps}\left(T_p - T_i\right) + L + C_{pl}\left(T_f - T_p\right)\right] \tag{2}$$

where Q—Amount of heat energy stored, m—mass (kg), C_{ps}, C_{pl}—Specific heat of solid and liquid materials $(J/kg/K)$, T_p—phase change temperature, T_i– initial temperature, T_f —final temperature, L—Latent heat of fusion (J/kg).

When the phase change materials (PCM) reach a specific temperature, the phase change takes place. However, the PCM temperature remains constant mainly during latent heat absorption or release. Therefore this property of absorption and release of latent heat in a controlled way helps PCM to be used in different products to enhance thermal performance. Table 2 shows the properties of different types of PCM. Desirable properties of phase change material include (Lalit et al., 2011):

- The high heat of fusion and heat capacity
- High density and high heat conductivity
- Stable, inert and non-toxic

There are some main criteria for choosing the PCM.

- Based on the environmental factors
- Low greenhouse gases emission
- Reduce global warming
- Based on Economic aspects
- Easy availability of the material
- Low cost
- Less operator cost
- Based on thermodynamic properties
- High thermal conductivity,
- More thermal stability,
- High latent heat and specific heat capacity
- Based on chemical properties
- Non-toxic and non-flammable
- No supercooling effect
- High chemical stability and low volume expansion

PCM can be classified into organic, inorganic, eutectic mixtures and bio PCM. Organic PCMs are non-toxic, chemically inert and non-corrosive. Paraffin wax is the most commonly used organic PCM. The melting and solidification temperature was 10 and 20 °C higher than the actual drying temperature of the product. At the same time, paraffin wax's drawbacks are its high volume and low thermal conductivity. Most inorganic PCMs are corrosive to metals, and the main disadvantage is that they undergo supercooling (Banavath et al., 2021). The energy density of the eutectic mixture PCM is higher than the other organic PCMs. Bio PCMs are derived from organic-based materials with more significant specific heat and latent heat of fusion (Muruganantham et al., 2010). Zakir et al. (2016) reviewed the performance of different PCM types. It was found that paraffin and

Table 2 Properties of different types of PCM

PCM	LH (kJ/kg)	Specific heat (J/ kg.K)		Thermal Conductivity (W/mK)	Density (kg/m3)	Phase change temperature (°C)	Authors
		Solid	Liquid				
Paraffin (14 kg)		2100(T < 60);2000(T > 60)		0.2516	800	60	Mingyang et al. (2021)
RT 70 HC	260	2000	2000	0.2	880	69–71	Pingrui et al. (2021)
Wood Alloy/Expanded graphite composite	113.1 J·cm-3	0.22–0.0.85 J/g/K		65	4.4 g.cm3	70.5	Zhaowen et al. (2017)
RT 35 HC	240	2 (kJ/kg.K)		0.2	880	35	Rubitherm (2015)
Glycerol trimyristate	154.3					32	Nihal and Emel (2012)
Dodecyl carbonate	200					17.3	Nihal and Emel (2012)
Tetradecyl carbonate	227					31.8	Nihal and Emel (2012)
Hexadecyl carbonate	219					43.1	Nihal and Emel (2012)
Octadecyl carbonate	223					46.4	Nihal and Emel (2012)
Palmitic acid	185.4			0.162	850	64	Sari and Kaygusuz (2002)
P116-wax	209	2.89	2.89	0.14	786	46.7	Adline and Qarnia (2009)
Magnesium nitrate hexahydrate/graphene composite	122.8 kJ•kg^{-1}			0.34–0.99		89	Hui et al. (2021)
SP-21EK	170	2000		0.5		21–23	Khalid et al. (2021)
Mixed organic PCM	222			0.2		2–7	Fan et al. (2019)
Paraffin		3890	2940	0.21	850	56–60	Aymen et al. (2017)

salt hydrates showed better performance. The durability of paraffin wax was found to be 14 years (Banavath et al., 2021). Using multiple PCMs with decreasing melting temperatures can be more efficient (Hoseinzadeh et al., 2018). Encapsulation of high thermal conducting nanoparticles with the PCM can significantly improve the thermal conductivity of the PCM (Karunesh et al., 2016).

1.2.2.1 Solar collector integrated with LHS Eman et al. (2006) experimented with the effect of variations in solar energy and different flow rate of water on discharging and charging paraffin wax as a PCM integrated with a solar collector. During the release of sensible heat, the solid–liquid phase gives an elliptical shape; during the latent heat release, it offers a circular shape in the discharging process. Also, during the charging process, the distance from the wax container increases the heat transfer coefficient decreases. Fan et al. (2019) investigated the performance of antifreeze characteristics of PCM integrated with flat plate solar collectors mainly when the daily average temperature reaches below 5 °C. Bin et al. (2018) developed composite PCM using 3% expanded granite and 97% erythritol and found that the storage efficiency of solar collectors reached up to 39.98%. It was inferred from the simulation results that due to the more thermal conductivity of the composite PCM, the temperature field was uniform mainly during the charging process. Alva et al. (2006) developed composite PCM using paraffin wax (65%) and graphite integrated with a solar collector (Fig. 6). Simulations done by the lumped capacitance method predicted that the PCM reaches the melting temperature (89 °C) in 196.3 min. Also, the mass flow rate directly influences the solidification of the PCM. Aymen et al. (2017) investigated the performance of solar air collectors integrated with PCM in the indirect type solar dryer (Fig. 7). The relative humidity inside the dryer was 17–34.5% lower than the atmospheric humidity, and the temperature inside the dryer was 4–16 °C higher than the atmospheric temperature, mainly at night time. Onkar et al. (2021) reported that the drying time was reduced by 35–38% using PCM containers in flat plate collectors (Fig. 8).

Anan et al. (2020) gave a conceptual design and numerical analysis of a flat plate solar collector integrated with PCM and geothermal energy for drying food products (Fig. 9). This hybrid energy technology can dry food up to 20 h per day with 20.5% higher efficiency when compared with existing flat plate solar collectors using numerical simulations. Theoretically, after sunset, the outlet temperature can be 15.9–13.4 °C for 12 h more than the ambient temperature.

Radouane and Hamid (2019) studied the thermal performance of nanoparticle-enhanced PCM (RT50 + Al_2O_3) integrated with a flat plate solar collector. The effect of nanoparticles on the first phase of the charging process was low. In the melting stage, natural convection develops in the nano-enhanced PCM and nanoparticle volumetric fraction increases. It improves sensible heat storage and collector efficiency and enhances nanoparticle-enhanced PCM's melting rate. Saw et al. (2013) added 1% 20 nm copper nanomaterials with paraffin wax to develop nano-enhanced PCM integrated with the solar collector

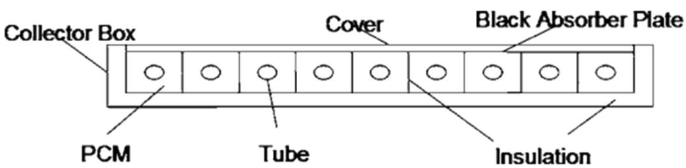

Fig. 6 PCM solar collector

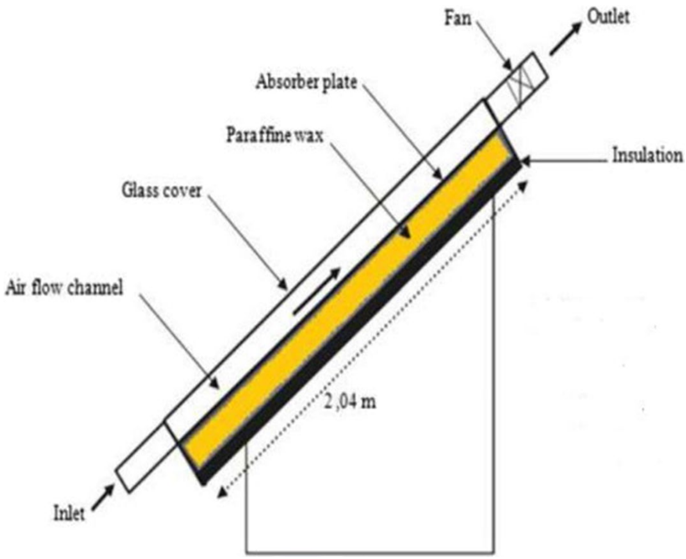

Fig. 7 Solar air collector with PCM

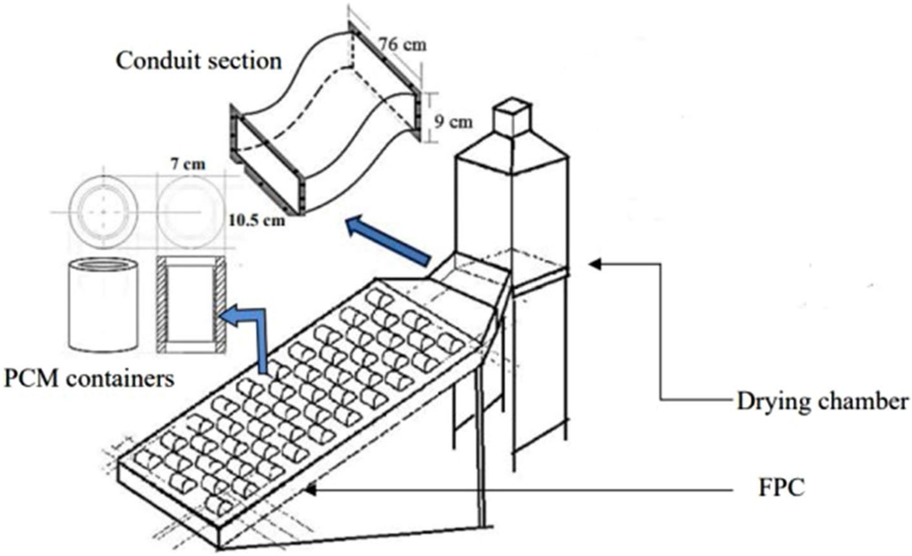

Fig. 8 Flat plate solar collector with PCM containers

(Fig. 10). With the dimension of 1.2 m × 1.2 m solar collector, the collector efficiency was found to be 8.4%. Madhankumar et al. (2021) developed ISD with fins inserted in LHS. Paraffin wax-filled cans were inserted with aluminium strips (fins) to increase the heat conductivity of the LHS. The pick-up efficiency of the dryer ISD inserted with fins in the LHS

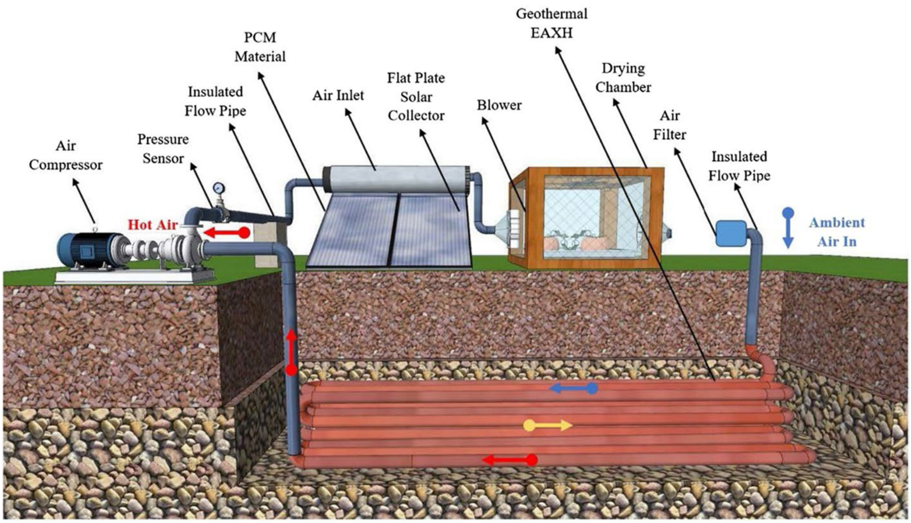

Fig. 9 Conceptual design of geothermal hydrid PCM

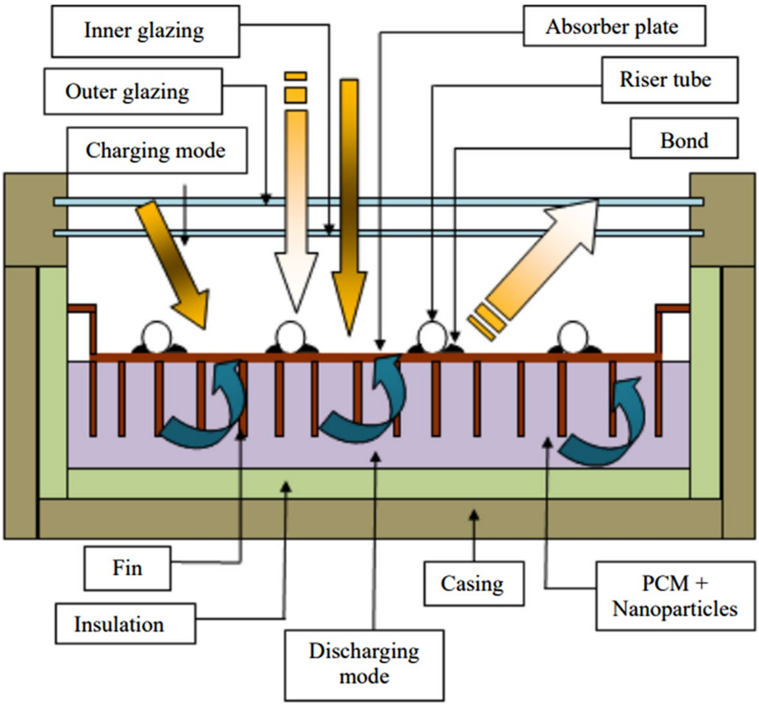

Fig. 10 PCM integrated solar collector

was the highest among all other treatments. The maximum exergy efficiency of 79% was achieved using fins in PCM.

Challenges in using PCM

- The heat transfer rate is low from the storage material to the working medium.
- As the thermal conductivity is low, PCM's charging and the discharging rate is low.
- The design of storage materials, fins, encapsulated materials and nano-particles in PCM can help to improve the heat transfer rate.

2 Classification of indirect solar dryer

Indirect solar dryers are divided into natural convection (NC) and forced convection (FC), as presented in Fig. 11. Researchers and scientists have developed several indirect solar dryers for different agricultural products. Few of the natural and forced convection indirect type solar dryers with and without thermal storage systems have been explained in this paper.

2.1 ISD-NC without thermal storage material (TSM)

Cesar et al. (2020) designed a drying chamber with a mobile, opaque polycarbonate cover that works as both mixed mode solar drying (MSD) and indirect mode solar drying (ISD) system. Sun's rays were allowed to pass through the opaque cover for mixed-mode drying and covered for indirect-mode drying. MSD and ISD dried products at 17 h and 26 h, respectively. The efficiency of the solar collector, overall dryer efficiency and drying efficiency were in the range of 52.30–55.45%, 10.66% and 8.80%, 10.66% and 8.80% for MSD and ISD, respectively. The drying chamber temperature at 13:00 was 65–70 °C and 55–60 °C for MSD and ISD, respectively.

Lingayat et al. (2020) estimated exergy analysis by drying bananas in an ISD dryer Fig. 12. The setup had a flat plate solar air collector with a glazed glass window tilted at 30◦ angle. The collector plate was V-shaped and corrugated with an aluminium sheet at the bottom. The drying chamber has four plastic mesh trays and a chimney. The efficiency

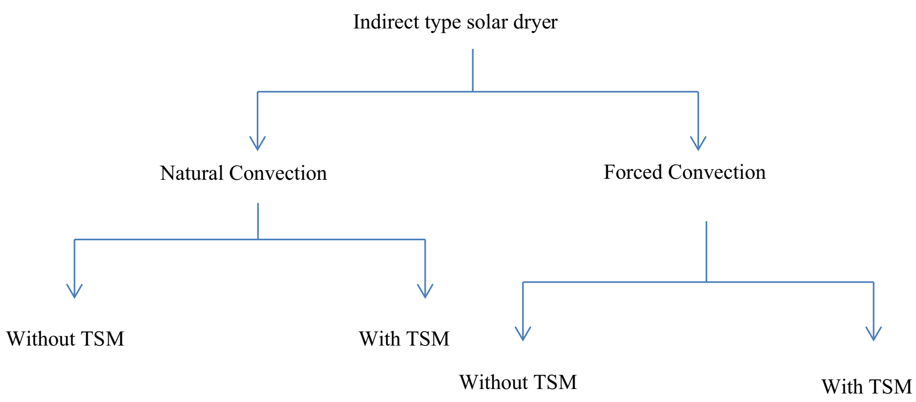

Fig. 11 Classification of ISD

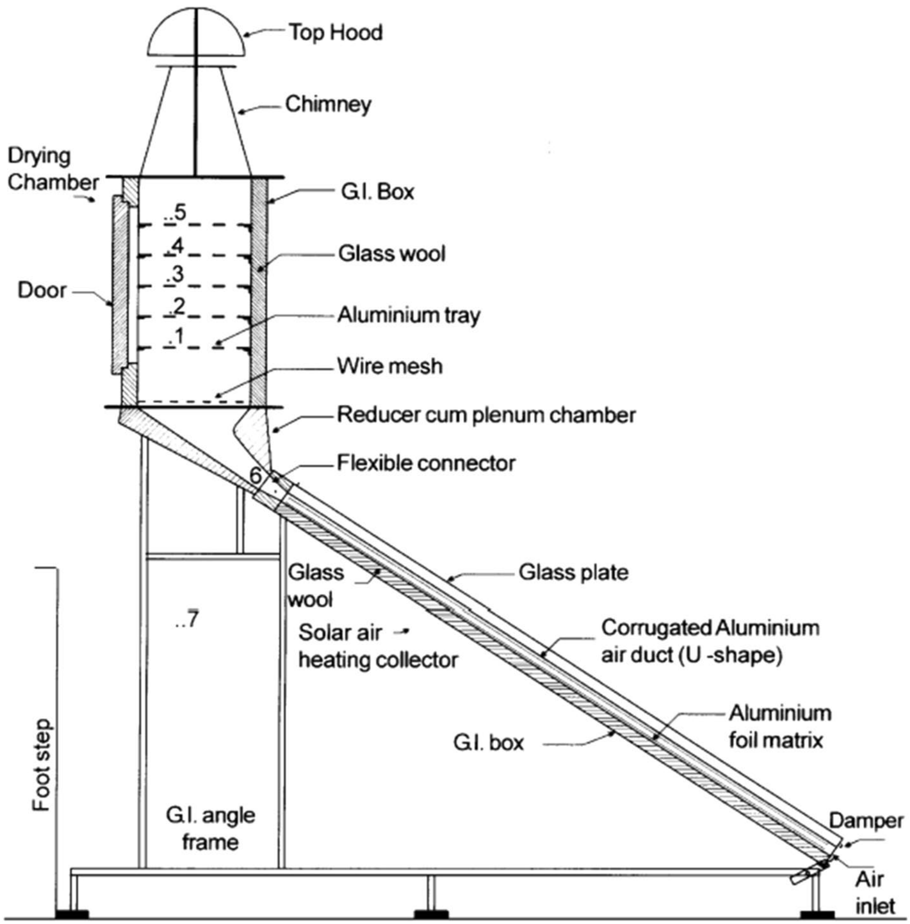

Fig. 12 Indirect type natural convection solar dryer

of the drying chambers and collector was found to be 17.73% and 38.23%, respectively. Exergy loss during the drying was estimated to be 3.36 to 25.21 kJ/kg.

Pangavhane et al. (2002) designed and developed an indirect solar dryer. The collector has a U-shaped corrugated absorber painted matte black with a leak-proof aluminium air duct below it. The air inlet of the collector had shutter plates that prevented airflow during the night. The collector has a wire mesh at its inlet to avoid insects. The experiment was conducted using sliced pretreated seedless grapes. The total days required for drying was five days. The efficiency of the solar air collector ranged from 48 to 56%. The drying time was reduced to 43% while improving the raisin quality compared to the open sun drying.

Simate (2003) compared MSD and ISD techniques and noted that the length of solar collector needed for an indirect solar collector (3.34 m) was almost twice when compared to the mixed mode solar dryer (1.8 m) for the same capacity of the product. In addition, it was noted that the drying cost and initial cost of the mixed mode of the solar dryer were higher than the indirect solar dryer. In contrast, the product quality was superior in the ISD than in MSD.

2.1.1 Merits and demerits ISD-NC without TSM

2.1.1.1 Merits

- The dried product has superior quality
- Construction and design are simple
- No external energy is required to operate the system

2.1.1.2 Demerits

- Drying time was increased compared to other methods
- The length of the solar collector should be more to increase the collector efficiency. The collector's performance always influences the drying system's performance.
- The Drying rate cannot be controlled

2.2 ISD-NC with TSM

The different techniques of solar food dryers getting the quality dried product is by indirect solar dryer (Sharma et al., 2021). The main advantage of using the TSM in solar dryers is to increase the effectiveness of the solar dryer by working during off-sunshine hours. Singh and Mall (2020) developed an ISD-NC with PCM for banana slices (Fig. 13). Using the PCM, the ISD effectively worked 5 h after the sunshine hours. The banana slices with the initial moisture content of 73.2% w.b were reduced to 20% w.b in 18 h. To study the drying characteristics of banana slices Pabis model and the Modified Henderson model were found to be the best fit. The efficiency of the solar collector was estimated to be 66.32%.

For drying herbs, especially to retain colour and flavour, Dilip and Parthiban et al. (2015) developed an ISD-NC with TSM. It mainly consists of a flat plate solar collector, packed bed for thermal storage, drying chamber and ventilation system.

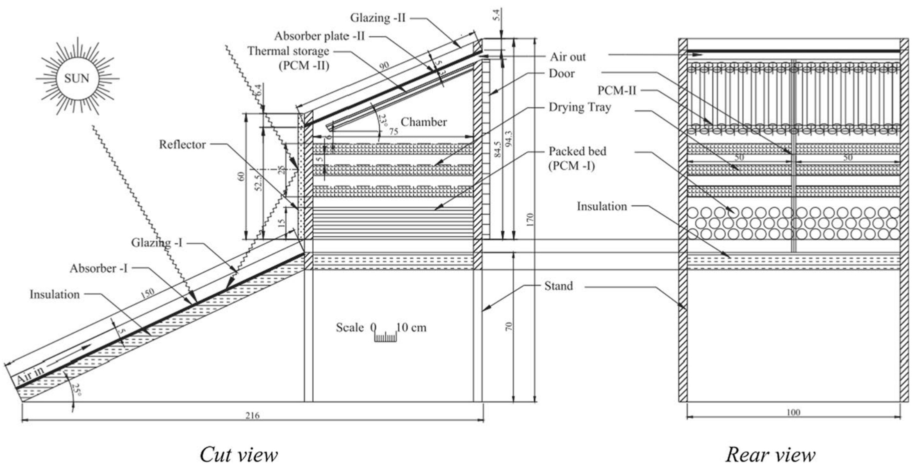

Fig. 13 Indirect natural convection solar dryer with PCM

The dryer capacity was 12 kg, and the PCM used was 50 kg. After sunset, the dryer could operate for the next 5–6 h by releasing the sensible and latent heat. However, it was observed that the temperature difference of around 6 °C higher than the ambient temperature after sunset.

Baber et al. (2020) designed a passive flat plate solar collector for drying mushrooms with paraffin wax as the TSM. The collector aspect ratio, depth, and volume were 2, 0.25 m^2 and 0.5 m, respectively. There was a difference of 24.6 °C between the dryer inlet and ambient temperature at 13.30 pm. It was reported that 36.36% drying time was reduced compared to open sun drying temperature. The sliced mushroom reached the equilibrium moisture content after 21 h from the initial moisture content of 91.05% (w.b).

El-Sebaii et al. (2002) designed an ISD-NC with a flat plate solar air heater and sand as the TSM under the absorber plate to improve the drying process. To enhance the quality of the products, pretreatment with 0.3% NaOH and 0.4% olive oil for 1 min was given. In addition, the products were chemically pre-treated with boiling water containing 0.4% olive oil and 0.3% NaOH for 60 secs. Both storage material and pre-treatment techniques significantly reduced the drying time. Experiments were conducted using three conditions: seedless grapes, figs, apples, tomatoes, green peas and onions. Results showed that the inlet temperature in the drying chamber was found to be in the range of 45.5–55.5 °C, and drying efficiency in the range of 53.9–16.2%.

Furthermore, the storage material causes additional moisture loss during nighttime. The chemical pretreatment was effective in small-sized products like grapes and peas, whereas larger products like onions, apples, figs, and tomatoes are better dried when cut into pieces over unsliced fruits. Shalaby et al.(2014) noted that using the TSM in solar drying systems enhances efficiency and reduces heat loss.

2.2.1 Merits and demerits of ISD-NC with TSM

2.2.1.1 Merits

- Dryer temperature can be maintained for 5–6 h after sunset
- The most commonly used PCM was paraffin wax
- Simple in construction
- Reduced heat loss
- Exergy losses can be reduced

2.2.1.2 Demerits

- Difficult to control the drying rate
- The solar collector's volume is larger when sensible heat storage materials are used since heat storage capacity is directly proportional to the volume of the solar collector. Also, the heat storage capacity of TSM is generally limited.
- The charging and discharge rate is low as the thermal conductivity of TSM is low.
- Inorganic TSMs are highly corrosive, unstable, inappropriate re-solidification and supercooling ability
- Organic TSMs are inflammable and generate fumes if overheated

2.3 ISD-FC without TSM

Etim et al. (2020) designed and constructed an active mode indirect solar dryer for drying cooking bananas and examined the effect of air inlet area on the dryer's performance. Fifty-two dryers were considered, with four different air inlet shapes (square, rectangle, circular and triangle) at five levels. The drying efficiency range for square, rectangular, circular, and triangular-shaped inlet dryers was 21.14 to 30.65%, 14.23 to 31.67%, 14.30 to 28.71%, 15.24 to 31.84%, respectively. The dryers with circular-shaped inlets showed the highest average drying efficiency of 25.45%. Results show that the moisture content was reduced within 9 to 16 h from 68.97% to 12% (w.b). In addition, this system helped reduce drying time by 40% compared to open-air drying.

Vijayan and Arjunan (2015) studied the dryer performance of an indirect forced convection solar dryer with potato slices (Fig. 14). The mass flow rate of the dryer was 0.058 kg/s, and it reduced the moisture content from 85% to 14% in 4 h. The product dried using the dryer was of better quality and colour than the traditional sun drying technique. The instantaneous thermal efficiency of the collector was in the range of 20% to 32%.

Akpinar et al. (2008) worked with long green peppers, drying them with an indirect forced convection solar dryer and also studied the mathematical model of the drying curve. The forced convection solar dryer dried the product in 104 h, whereas open sun drying took 152 h; thus, using the dryer effectively reduced the drying time by two days. The drying chamber temperature at the inlet was between 43.9 to 64.8 C and 33.6 to 56.7 C at the outlet. Moreover, the highest wind speed was recorded to be 3.2 m/s. As a result, long green peppers of 4 g of water per g of dry matter were reduced to 0.10 g of water per g of dry matter. Modelling on a thin layer forced convection solar dryer by logarithmic model gave a drying curve with R of 0.98.

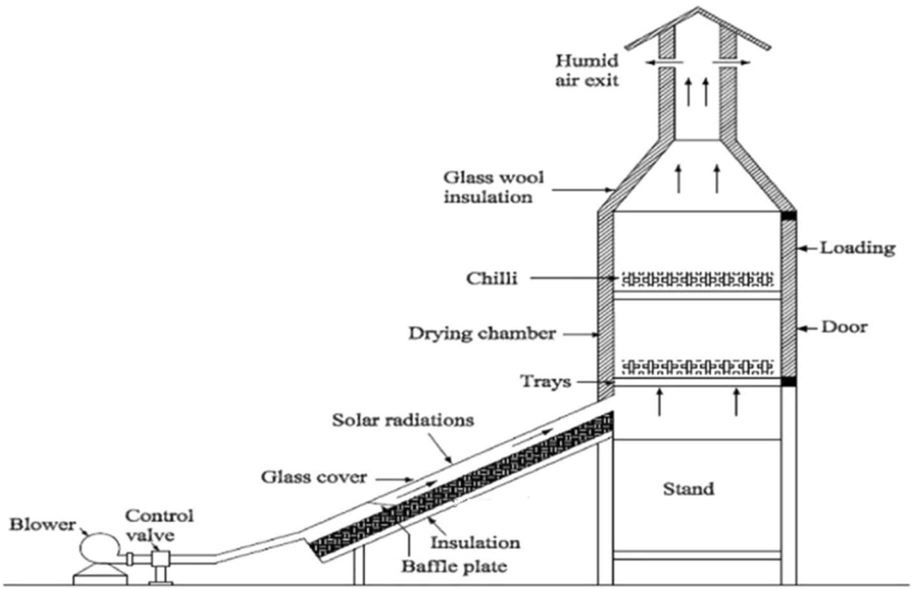

Fig. 14 Indirect type forced convection solar dryer

Bharadwaz et al. (2017) evaluated the performance of an indirect solar dryer with a blower using green apple slices. The maximum temperature inside the drying chamber was 51 °C. The thermal efficiency of the collector was 35.33%, and the thermal efficiency of the dryer was found to be 13.8%. The mass of water removed from the product by the solar dryer was 164.2 g, while open sun drying removed 155.4 g of water. The product dried in the solar dryer also had a higher dry matter and lowered organic matter, thus making it more suitable for preservation.

Subramaniyan et al. (2021) analysed the performance of a forced convection solar dryer with ground nuts. The initial moisture content of 25–30% was reduced to 10% (w.b). The mass flow rate of air was found to be in the range of 0.022 kg/s to 0.044 kg/s. There is more moisture reduction at 0.022 kg/s mass flow rate than at 0.044 kg/s mass flow rate. The dryer's efficiency decreased when the mass flow rate was lower than 0.022 kg/s. A maximum dryer efficiency of 39.2% and maximum average collector temperature of 322.3 K were found at the optimized mass flow rate of 0.022 kg/s.

2.3.1 Merits and demerits of ISD-FC without TSM

2.3.1.1 Merits

- The food products' drying time is less than natural convection drying.
- Uniform drying can be achieved with quality products compared to open sun-dried products.
- The drying rate can be controlled

2.3.1.2 Demerits

- Needs external power to operate fan or blower
- Design and fabrication are complex compared to natural convection dryer
- Cannot be operated outside the sunshine hours
- The efficiency of the drier was affected due to a higher air flow rate

2.4 ISD-FC with TSM

The performance evaluation of ISD-FC with paraffin wax in shell and tube heat exchanger as a TSM was conducted using red chilli (Rabha & Muthukumar, 2017). Solar air collectors with two double pass enhanced the efficiency of the collector. Figure 15 shows the ISD-FC with TSM. Paraffin wax in the shell and tube heat exchanger helped to reduce the air's temperature variation while drying and supplying dry air after sunset. The dryer temperature ranges from 36 to 60 °C. The moisture content of red chilli was brought down to 9.7% (w.b) after four days.

Arun et al. (2020) developed an active multi-tray ISD with TSM for banana and bitter gourd. Paraffin wax was used as a thermal storing unit. The influence of the tray arrangement on the slice thickness, mesh size, tray spacing, and mass flow rate was studied. The bitter gourd and unripe banana had an initial moisture content of 1328% (d.b) and 180% (d.b), respectively. Furthermore, the tray arrangement pattern facilitated uniformity in drying the banana and bitter gourd within 10 and 18 h, respectively.

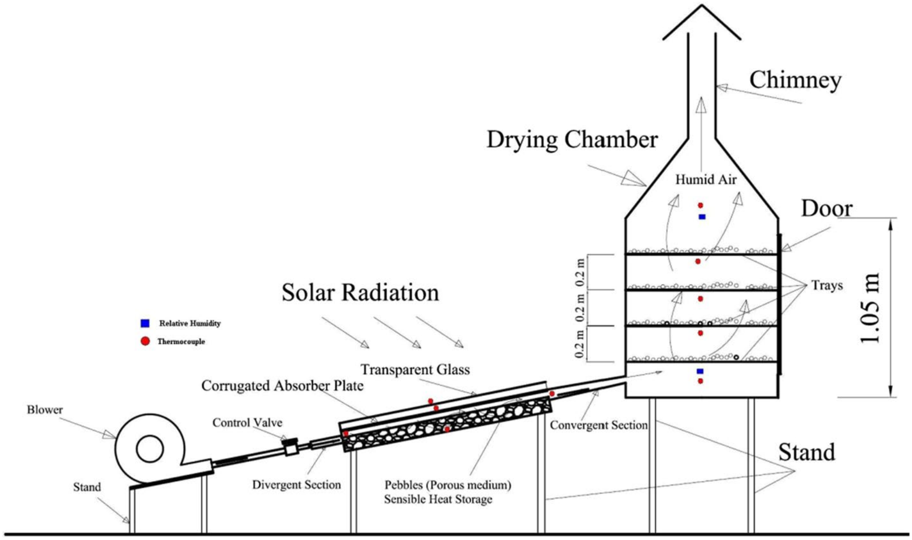

Fig. 15 Indirect forced convection solar dryer with TSM

Bhardwaja et al. (2020) developed an ISD with SHS material and PCM. In the absorber plate, iron scraps with gravel were packed along with copper tubes containing engine oil, serving as the SHS medium. The PCM used was paraffin RT-42. A medicinal herb was used for drying investigation, and it was found that the moisture content was reduced from 89 to 9% in 120 h. However, the medicinal herb's essential oil and bio-active compounds were retained and good.

Vignesh et al., (2021) investigated the drying of potato slices in the ISD using paraffin wax as TSM. The blower was working at the mass flow rate of 0.065 kg/s. It was found that the presence of PCM significantly increased the drying two hours after the sunshine. The moisture content of potatoes reduced from 81 to 13% without PCM in the solar dryer, whereas moisture content reduced to 8.2% with PCM. A summary of different indirect mode type dryers with and without TSM is shown in Tables 3 and 4.

2.4.1 Merits and demerits of ISD-FC with TSM

2.4.1.1 Merits

- Dried products can retain essential oil contents as well as bioactive compounds.
- Dryer temperature can be maintained even after sunset.
- Best suitable for agricultural products with high moisture content

2.4.1.2 Demerits

- It needs electric power to operate the fan/blower
- Fabrication is complex compared to natural convection dryer

Table 3 Summary of ISD-NC/FC without the TSM

Authors	Dryer type	Design parameters	Product dried/ drying period	Operating parameters	Important conclusions
Margarita et al. (2017)	Forced convection Tunnel-type ISD with solar air heater and centrifugal fan	Solar collector area is 1.22 m^2 Drying chamber horizontal rectangular tunnel $6 \times 0.3m^2$	Red chilli Initial M.C-75.3% and 83.1% (w.b) Final M.C—0.057–0.90 kg of water/kg dry matter Drying time—16 h Air velocity—1.4–2.6 m/s	The temperature inside the dryer maintained at 31–45 °C Solar air heater tested at from 2 to 8 m/s	50–70%—Solar collector thermal efficiency The drying characteristics of red chilli were the best fit with the Page model
Lingayat et al. (2020)	Passive ISD	Corrugated v-shaped copper plate solar collector	Banana slices Exergy loss of solar collector ranged from 2.64 kJ/kg to 26.10 kJ/kg	The temperature of drying air varied from 38 to 82 oC	Collector efficiency was found to be 33.14% Average exergy efficiency was found to be 21.57% With time exergy efficiency increases
Pangavhane et al. (2002)	ISD-NC	Solar flat plate air heater—U-shaped corrugations with aluminium fins The drying chamber was made of aluminium sheets covered with glass wool	Raisins soaked at 2.5% K2CO3 for 3 min Drying time- 4 days	The average dryer temperature was 50 to 55 °C Drying time reduced by 43%	It was reported that when the ambient temperature rises, the airflow rate also increases because of thermal buoyancy inside the collector Pretreated grapes reduced the drying time by improving the water permeability
Lingayat et al. (2017)	ISD-NC	V-shaped corrugated absorber plate in solar flat plate collector Collector area-2m2	Banana Slices Initial M.C—77% Final M.C—16–31% Drying time 24 h	Collector outlet temperature ranged from 61.2 to 44 °C	The solar collector's thermal efficiency was estimated as 31.50%

Table 3 (continued)

Authors	Dryer type	Design parameters	Product dried/ drying period	Operating parameters	Important conclusions
Simate (2003)	Comparison of mixed mode and ISD-NC	Collector length for ISD and mixed mode drying was 3.34 m and 1.8 m, respectively, for 90 kg capacity	Maize M.C reduced to 13.7% dry basis	Grain temperature inside the indirect type dryer showed up to 48 °C, whereas for the mixed mode, the temperature was raised to 65 °C	It was concluded that indirect drying showed the typical deep bed drying behaviour During the first five hours of heating, grain temperature was lower than the ambient temperature in the indirect dryer
Fadhel et al. (2011)	Forced Convection Thin layer drying	Heat collector with Zinc sheet, air flow divider, air flow inlet and outlet compartments	Banana slices—426 g Initial M.C—80%	Air temperature at the inlet of the dryer—62.8 °C After five hours of drying moisture ratio reached 0.733	The drying characteristics of banana slices were the best fit with Wang and Singh model
Hedge et al. (2015)	Active type Low-cost ISD	Solar flat plate air heater: Two configuration 1. Top flow: airflow in between absorber plate and glass cover 2. Bottom flow: airflow in between bottom insulation and absorber plate Air gap in collector—5 cm	Banana slices—1.5 kg Initial M.C—77.2% Final M.C—29.63% Drying time—16 h	The maximum air outlet temperature was 45 °C when the ambient temperature was 34 °C At the air flow rate of 1 m/s	Results showed that the efficiency of top flow configuration was 27.5% The bottom flow configuration had a 38.21% efficiency This drying method showed better colour, shape and taste

Table 3 (continued)

Authors	Dryer type	Design parameters	Product dried/ drying period	Operating parameters	Important conclusions
Matavel et al. (2021)	Passive ISD	The volume of the drying chamber—1 m^3 Airflow on both sides of the collector absorber plate	Amaranth leaves and maize M.C of amaranth leaves reduced from—83.4%—10.5% M.C of maize 26% to 14% Drying time—5 days	Drying chamber temperature ranged between 27 and 38 °C	It was found that quality attributes were good 40% of people rated excellent quality in terms of texture, colour and aroma
Sansaniwal and Kumar (2015)	Natural Convection	Solar collector 1.3 m^2 Drying chamber 0.0977 m^3 Through PVC pipe, hot air from the solar collector enters the dryer	Ginger Initial M.C—76% Final m.c—8%	The moisture removal rate is high when the coefficient of convective heat transfer is high	Collector efficiency was found to be 14.97–16.14% It was found that the best fit model for predicting the drying characteristics was the Modified page model
Vijayan and Arjunan (2015)	Forced Convection	Solar collector area—2m^2	Potato thickness 4 mm Moisture content reduced from 85% to 14%	Mass flow rate—0.058 kg /s	The drying period was around 4 h, whereas the open drying period was 5 h

Table 4 Summary of ISD-NC/FC with TSM

Authors	Dryer type	Operating /Design parameters	Product dried/ drying period	Thermal storage materials	Important conclusions
Vijayan et al. (2016)	Forced convection Thin layer drying	Corrugated absorber plate—solar flat plate collector—$2m^2$ Mass flow rate—0.0636 kg/s	Sliced bitter guard Initial M.C—92% Final M.C—9% Drying time—7 h In open sun drying—10 h	Porous sensible heat storage—Pebbles kept near the air passage of the solar collector for a height of 60 mm	Drying and Collector efficiency was 19% and 22%, respectively Moisture extraction rate was maximum with 0.215 kg/kWh Two-term model and Midilli–Kucuk model gave the best fit
Shalaby and Bek (2010)	ISD-FC	Flat plate solar air heaters The mass flow rate ranged from 0.0664 to 0.2182 kg/s Collector area 3.32 m^2	*O. basilicum and T. neriifolia*-medicinal plants Drying time is 12 h for *O. basilicum* and 18 h for *T. neriifolia*	12 kg Paraffin wax at melting point 49 °C Kept in insulated plastic containers 32 copper tubes vertically distributed to increase the surface area	It was noted that there was a 2.5 to 7.5 °C higher temperature inside the dryer after sunset To minimize the heat loss, PCM was placed in the drying chamber
Singh and Mall (2020)	Natural convection Thin layer drying	Flat plate Collector area—$0.72m^2$ Drying temperature −40.5 °C Average drying rate—0.131 kg of water/kg of dried product/h	Banana slices—400 g Initial M.C—73.2% (wb) Final M.C—20% (wb) Drying time 18 h	Paraffin wax Mass −4.2 kg PCM layer thickness–1 cm Placed in between the bottom of the casing and absorber plate	Average dryer efficiency was in the range of 9.88–2.98% Average collector efficiency was found to be 66.32% Two models gave the best fit: Modified Henderson and Pabis model

Table 4 (continued)

Authors	Dryer type	Operating /Design parameters	Product dried/ drying period	Thermal storage materials	Important conclusions
Dilip and Parthiban (2015)	Natural convection	Flat plate solar collector area—1.5m^2 A reflector was placed adjacent to the drying chamber Maximum dryer temperature reached 50 °C	Leafy herbs—12 kg Pretreatment with 0.5% sodium bi-carbonate for 5 min to maintain colour and flavour Initial M.C—4.8 (d.b). Final M.C—0.11 (d.b)	Paraffin wax Mass—50 kg Placed above and below the drying chamber Packed in 48 cylindrical tubes	It was noted that compared with ambient temperature, there was 20 °C more temperature in the PCM bed Dryer thermal efficiency was around 28.2%
Wafa et al. (2018)	Forced convection inside the solar dryer in the Sahara environment	Duct parallelepiped shape The volume of the drying chamber was 90×60×15 cm^3 Drying chamber—made of double-wall wood resins	Camel meat—4 kg The maximum temperature reached in the drying chamber—67 °C	Pebble bed—placed in a cavity of solar collector Shape—triangular Mass—40 kg	The logarithmic model and Midilli-Kucruk model were found to be the best fit Dryer efficiency ranged from 18.34% to 15.52%
Baber et al. (2020)	Natural Convection	Assumptions: Steady state condition The mass flow rate ranged from 0.02–0.9 kg/s The ratio of the dryer area to the surface area of the collector should range from 1–2	Mushroom (blanched at 70 °C for 3 min)– 7.5 kg Initial Moisture content—85–92% (wb) Final moisture content—5–7% (wb) Max. temperature reached in the inlet of the drying chamber—56–57 °C	Paraffin wax Placed in a cylindrical shape container The PCM was placed horizontally with an absorber plate	A difference of 24.6 °C was found between the drying chamber and ambient temperate at 13.30 pm The moisture ratio reached zero after 21 h of drying

Table 4 (continued)

Authors	Dryer type	Operating /Design parameters	Product dried/ drying period	Thermal storage materials	Important conclusions
El-Sebaii et al. (2002)	Natural Convection	Solar air heater area—$1m^2$ The capacity of the drying chamber is 10 kg Inlet air temperature in drying chamber—45.5–55.5 °C	Seedless grapes, onions, apples, figs, tomatoes, peas Pretreatment kept in boiling water with 0.3% NaOH and 0.4% olive oil for 1 min	Clay, granite and sand Placed in between the absorber plate and back insulation	Resulted after 60 h of drying, seedless grapes reached an equilibrium moisture content Daily drying efficiency decreased with an increase in drying time No significant difference in the chemical pretreatment
Arun et al. (2020)	Forced Convection	Double pass flat plate solar collector The capacity of the dryer is 20 kg The dryer is made up of SS-304, and at the top mica sheet was placed to block the solar radiation	Banana and bitter guard Initial M.C of banana—180% (db) and bitter guard—1328% (db) Drying time banana—10 h, bitter guard—18 h	Paraffin was (60 °C) Kept in cylindrical macro-encapsulated unit—6 kg Placed below the absorber plate	It has resulted in a reduction in exergy loss with a rise in mass flow rate The energy utilization ratio was in the range of 45.3% to 47.9%
Vignesh et al., (2021)	Single-pass ISD-FC	Drying chamber—steel plate Dryer inlet temperature—62 °C	Sliced potato Moisture content reduced from 81% to 8.2% Drying time 9 h	Paraffin wax Placed beneath the absorber plate in five compartments (5 kg)	Resulted that the moisture removal rate has been increased by 5.1% per day After sunset, the dryer temperature was maintained for two hours
Vijayan et al. (2020)	Flate plate solar collector Corrugated absorber plate Forced convection	Collector area—2 m2 Collector inlet temperature 1-8 °C higher than ambient temperature	Sliced bitter guard (4 kg) Moisture reduction from 92% to 9% Drying time 7 h At mass flow rate—0.063 kg/s	Pebbles 30 mm size Kept in between the back insulation and absorber plate	The average pickup effectiveness of the dryer was 17.12–54.29% Exergy efficiency was in the range of 28.27% to 40.68%

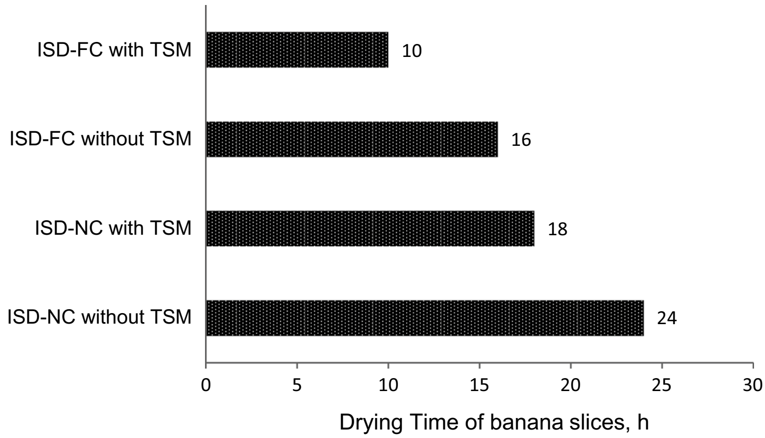

Fig. 16 Comparison of drying banana slices using different methods of ISD

3 Comparison of ISD-NC/FC with and without TSM

The drying rate was faster with the forced convection type than with the natural convection type. Figure 16 shows the time taken by the banana to dry in different modes. Without TSM, forced convection showed 33% enhancement compared with natural convection. At the same time, TSM forced convection showed 44% enhancement compared with natural convection. The fig shows that using the TSM, banana slices' drying time can be decreased to about 6 h. Therefore, using the ISD-FC with TSM was the best method for drying banana slices with a drying time of 10 h.

4 Recent advancement in solar drying techniques

The operating temperature of the flat plate solar collector used in the ISD system ranges from 30 to 70 °C. However, few developments have been made to increase the operating temperature of solar drying techniques.

4.1 Parabolic concentrators

Parabolic concentrators with a sun tracking system can improve the system's performance. Azwin et al. (2021) reported that parabolic concentrators could be used for large-scale applications of solar dryers. The operating temperature of this collector ranges from 60 to 240 °C. Lamrani et al. (2019) studied the performance of an indirect hybrid dryer for drying wood using compound-type parabolic concentrators. The environmental analysis showed that energy consumption by the auxiliary heaters could be reduced, and thereby the CO_2 emission can be reduced to 34% per year.

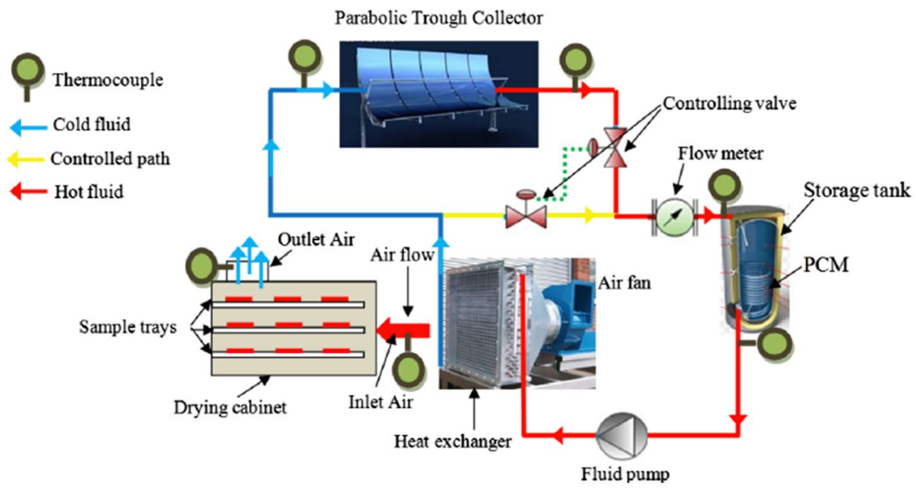

Fig. 17 Solar dryer integrated with Parabolic solar collector

4.1.1 Parabolic concentrators with nano-fluids

Alimohammadi et al. (2020) developed a solar dryer for drying apple slices. It was integrated with a parabolic solar collector, PCM, heat exchanger and sun-tracking sensor (Fig. 17). The study was conducted with different working fluids such as nano-fluids, engine oil, glycerin and water. It was reported that overall performance efficiency increased by 20.2% when engine oil was used.

4.2 Jet impingement technique

The solar air heater's thermal performance can be increased using the impingement jet technique, as it creates more turbulence in the airflow passage. Underneath the absorber plate, a wavy or corrugated plate was introduced with holes which provide jet-impinging velocity. It can increase heat transfer to air and improve thermal efficiency (Chauhan & Thakur, 2014). Satyender et al. (2020) constructed a metal perforated corrugated plate for jet impingement and found enhancement in thermal and thermos-hydraulic efficiency (Fig. 18).

4.3 Nanoparticle on absorber plate

Absorber surface properties can be altered by coating with nano-particles and improving absorptivity. It may be due to the increase in the specific heat capacity with an increase in the volume fraction. The maximum absorber plate temperature recorded was 96.85 °C with 0.04%CuO nanoparticle coating on the solar collector (Sivakumar et al., 2020). The extreme solar absorptivity of 855 W/m2 was recorded at 1 pm. Using Cuo nanoparticles for coating the absorber plate increases the solar absorptivity to 14.12%. Also, the solar

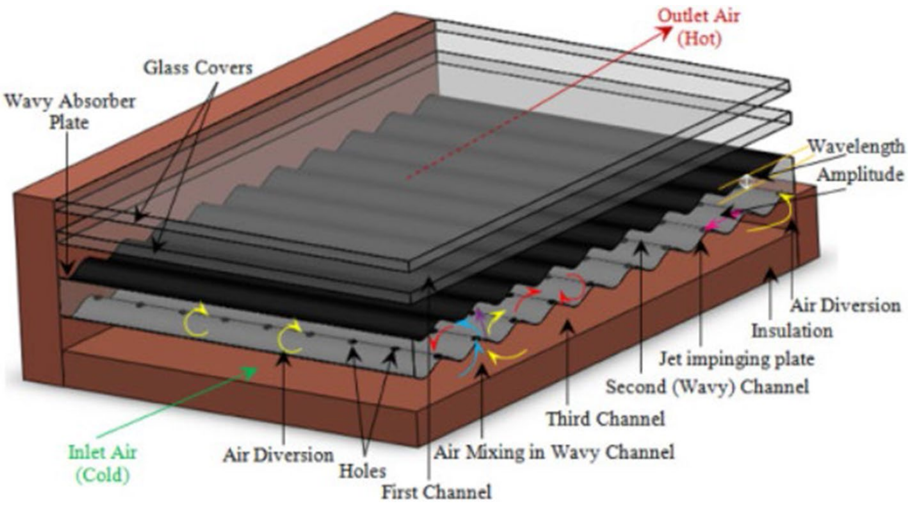

Fig. 18 Flat plate solar collector intergrated with jet impingement technique

collector outlet temperature can be enhanced by 7.81% compared to the conventional flat plate solar collector.

4.4 Nanoparticles in thermal storage materials

The main drawback of using PCM is its low thermal conductivity research is being done to enhance the thermal conductivity of the PCM using nanoparticles. For example, paraffin wax with 10 w.t% nano graphite improves the thermal conductivity to 0.93 W/mK. Further, Wu et al. (2021) reported that using 5% carbon nanotubes with paraffin wax enhances enthalpy and thermal conductivity by 6.3%. Also, using single-wall carbon nanotubes with phase change composite improves the thermal conductivity to 0.87W/mK. Abdelkader et al. (2021) reported that the overall thermal efficiency of carbon nanotube-based ISD was 12.2–19.6%.

5 Exergo-environmental analysis

Exergy is the system's highest amount of work when in contact with an equilibrium environment. It is one of the predominant indicators to achieve environmentally sustainable, efficient, economical energy use, mainly in the drying systems. Exergy identifies the decrease in the thermodynamics losses. The exergy balance equation can be written as.

Exergy = internal energy – entropy + work + momentum + gravity + radiation emission.

This equation can be simplified by neglecting momentum and gravity and substituting enthalpy for the internal energy terms. Now the steady flow equation for exergy can be written as (Madhankumar et al., 2021).

For inflow

$$E_{xin} = m_a C_p \left[(T - T_1) - T_1 ln\left(\frac{T}{T_1}\right) \right] \quad (3)$$

For outflow

$$E_{xou} = m_a C_p \left[(T_2 - T_1) - T_1 ln\left(\frac{T_2}{T_1}\right) \right] \quad (4)$$

where m_a is the mass flow rate of air (kg/s), T is the temperature at the exit of the solar collector, T1 is the Temperature at the entry of the solar collector, and T_2 is the temperature at the drying chamber exit. Using the Grassmann diagram Halil and Eda (2021) (Fig. 19) demonstrated the exergy inflow and outflow in the indirect solar dryer system for drying strawberries.

The exergy efficiency (η_{Ex}) of the ISD can be expressed by

$$\eta_{Ex} = \frac{E_{xin}}{E_{xou}} \quad (5)$$

The sustainability index also assesses the influence of exergy losses and efficiency to improve drying operations and sustainable development. For example, Atalay (2019) reported that the waste exergy ratio was higher during the sunshine hours than in the experiment performed with TSM (Table 5).

Exergy efficiency is one of the critical indicators for finding the effectiveness of the solar dryer system. Mainly the exergy efficiency increases with an increase in the drying time due to nearer exergy inflow and outflow rates. Indirect solar dryers with fins in the phase change material gave the highest exergy efficiency among all other design configurations of indirect solar dryers. However, the exergy losses can still be minimized with a better design of solar collectors with thermal storage material to commercialize on a large scale.

5.1 CO_2 emission from the food industry

The usage of non-renewable energy sources in industries significantly impacts CO_2 emissions (Salazar-Núñez et al., 2022). In the food processing industry, the drying unit mainly depends on fossil fuels to meet the energy requirements. In Lybia, a case study was conducted in the refinery unit and power plants. The total CO_2 emission from the oil factory in Lybia was estimated at 983 kg CO_2/MWh. It contributes around 26% to the production of

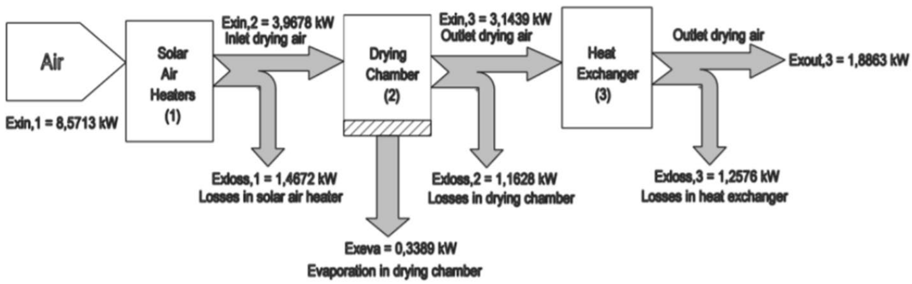

Fig. 19 Exergy inflow and outflow of solar dryer represented in Grassmann diagram

Table 5 Exergy analysis on Indirect Solar dryers

Authors	Type Dryer	Exergy Loss in Solar collector	Exergy Loss in the drying chamber	Exergy Efficiency of the dryer	Sustainability index	Waste Exergy Ratio
Lingayat et al. (2020)	ISD	2.64 kJ/kg to 26.10 kJ/kg	3.36 to 25.21 kJ/kg	21.57%		
Vijayan et al. (2020)	ISD	9.185 W		28.27 to 40.68%	1.63	0.65786
Atalay (2019)	ISD		0.14199 KW	59.4% and 63.34%	2.15–3.17	0.395
Madhankumar et al. (2021)	ISD			8.66% to 79.02%	1.74	
Halil and Eda (2021)	ISD		0.22866 kW	64.43%		
Dash et al. (2022)	ISD			72.08%		
Sharma et al. (2022)	ISD			46%	1.55–2.39	0.41–0.67
Vishnuvardhan and Chandramohan (2021)	ISD- Natural Convection	3053.76 to 29,043.2 J/kg	0.84 to 664.63 J/kg	51.85%		0.481
Vishnuvardhan and Chandramohan (2021)	ISD-Forced	1885.5 to 17,443.73 J/kg	0.2 to 327.76 J/kg	56.12%		0.438
Abdelkader et al. (2021)	ISD			47.3%		
Abhay and Chandramohan (2021)	ISD		2.72 to 17.60 kJ/kg	25.48%		
Çiftçi et al. (2021)	ISD			43.04—56.11%		0.43- 0.56
Gilago et al. (2022)	ISD			57.07%		

total greenhouse gas emissions. Guo et al., (2023) and Sun et al., (2022) reported that, on average, China's annual growth rate of CO2 emission increases by 11%. Ma et al. (2012) stated that in Taiwan, the energy consumed by 76 food processing sectors was 69,540 L of fuel oil and 2,136 tons of LPG. By efficiently using 40% solar dryers, the energy consumption by conventional methods can be reduced to 27% to 80%. Solar dryers can replace the use of fossil fuel.

Rajarajeshwari et al. (2018) reported that for drying the food products like apples, tomatoes, onions, pineapple and tapioca, the energy required was in the range of 0.43–0.57 kWh. When using an infrared and vacuum dryer, the energy requirement was 3.08 and 12.83kWh, respectively (Ali et al., 2011). It was reported that using microwave drying units continuously in the food processing industry leads to the emission of 529 kg of CO_2/year. Mohammed et al. (2020) evaluated the greenhouse gas emissions from different commercially available dryers like hot air dryers, hybrid hot air-infrared, hybrid hot air-microwave and continuous multistage dryers. The emission of greenhouse gases like NOx, CO_2 and SO_2 were estimated to be 357,336.6, 1974.21 and 5210.02 g from the continuous multistage dryer. It found that the greenhouse gas emissions increased with an increase in temperature as well as the airflow velocity of the dryer. Overall, 34% of the CO_2 has been emitted from the food industry. Figure 20 represents the CO_2 emission from different types of commercially available dryers. The Fig shows that the different types of dryers used in food processing industries emit a significant amount of CO_2 into the atmosphere. An industrial batch type dryer emits 13261 g of CO_2 to remove one kg of water, followed by an industrial horizontal dryer (7289 g of CO_2/kg of water)and deep bed dryers (1646 g of CO_2/kg of water).

5.2 CO_2 emission mitigation

Effective environmental and energy conservation systems can be designed by the exergo environmental analysis (Buchgeister, 2010). For calculating exergo-environment analysis, CO_2 mitigation values and environmental impact analysis of the dryer are necessary. In

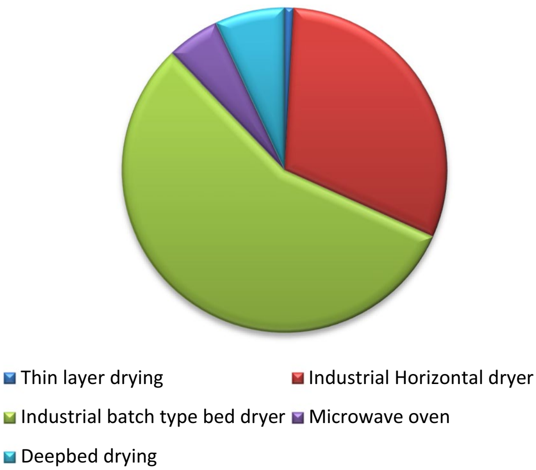

Fig. 20 CO_2 emission/kg of water for different types of dryer. (Source: Rajarajeshwari et al. (2018))

addition, the total energy consumed by the system can be estimated by the environmental impact analysis.

The energy payback period (EPT) can be calculated by the formula (Vijayan et al., 2020)

$$EPT = \frac{Embodied\ Energy\,(kWh)}{Annual\ Energy\ Output\left(\frac{kWh}{year}\right)} \tag{6}$$

Embodied energy is the production of energy during the lifecycle of a system during construction, production, maintenance and transportation. This concept will help to evaluate the energy-saving substances which can save time and energy. Annual thermal energy output can be calculated using the formula:

$$Annual\ thermal\ energy\ output = Daily\ thermal\ output * N_d \tag{7}$$

where N_d is the number of sunny days/year.

Daily thermal output from the solar dryer can be estimated using the formula:

$$Daily\ thermal\ output\,(kWh) = \frac{Moisture\ evaporation\,(kg) \times h_f}{3.6 \times 10^6} \tag{8}$$

where h_f is the latent heat of evaporation (J/kg).

Each crop's drying time varies according to its moisture content. Therefore for each crop, energy derived from solar radiation was estimated along with the replaced fossil fuel. Based on the utilization efficiency (n_i) of various fuels, carbon oxidised fraction (COF_i) during combustion and their carbon emission factor (CEF_i) it was possible to find the gross CO_2 emission (GE_c) mitigation by the use of a solar dryer as shown in expression in Eq. (9): (Atul & Tara, 2005)

$$GE_C = \sum_i f_i\left(\frac{f_{es}Q_{dry}UE_{dry}}{n_i}\right)CEF_iCOF_i\left(\frac{44}{12}\right) \tag{9}$$

where f_{es} = fraction of solar energy required for drying.

f_i = Fraction of crop currently being dried by $\boldsymbol{i}^{th}$ fuel.

Q_{dry} = Amount of produce taken for solar drying (kg).

UE_{dry} = Useful energy required for drying.

The useful energy required for drying can be calculated using the following Equation (Merlin et al., 2020):

$$UE_{dry} = \frac{1 - M_f}{1 - M_i}Cp_{rc}\left(T - T_{ae}\right) + \frac{1 - M_f}{1 - M_i}H_{fg} \tag{10}$$

where, M_i—Initial moisture content (w.b).

M_f—Final moisture content (w.b).

T—Drying temperature (°C).

T_{ae}—Ambient temperature (°C).

H_{fg}—Enthalpy of moisture evaporation at the drying surface (MJ/kg/°C).

Cp_{rc}—Specific heat $(MJ/kg/C)$ of wet crop.

The net annual CO_2 emission mitigation can be obtained from the following Eq. (11):

$$NE_c = \left\{ \sum_i f_i \left(\frac{f_{es} Q_{dry} UE_{dry}}{n_i} \right) CEF_i COF_i \left(\frac{44}{12} \right) \right\} - \left(\frac{EMA_a}{T} \right) \quad (11)$$

EM = Embodied CO_2 emission in the solar dryer (kg/m^2).

A_a= aperture area of the solar dryer (m^2).

T = life of the solar dryer in years.

Annual CO_2 mitigation of indirect solar dryers can be calculated using Eq. (12):

$$\text{AnnualCO2mitigation} = \left(E_{aout} \times L - E_{in} \right) \times 2.042kg \quad (12)$$

where,

L represents the lifetime of the indirect solar dryer (5,15, 25, 35 years),

E_{in}—embodied energy,

E_{out}—annual energy output.

Earned carbon credit can be calculated using the formula.

Earned Carbon credit = net mitigation of CO_2 in lifetime x Price per ton of CO_2 mitigation.

Ahmadi et al. (2021) reviewed that solar dryers have the capability of CO_2 mitigation up to 6.4 tons per month. Ayyappan (2018) developed natural convection solar greenhouse dryer for coconut and estimated the net CO_2 mitigation as 678 tonnes. A walk-in type solar thermal dryer was designed by Andharia et al. (2022) for drying 600 kg of fish. It was found that the embodied energy from the dryer was around 10,756 kWh, and the CO_2 emission was estimated to be 422 kg/yr, which was much lower than using any non-renewable energy sources. Merlin et al. (2020) developed a natural convection mix-mode solar dryer and estimated the annual CO_2 mitigation in Africa of around 1,280,148 tons. Tripathy (2015) concluded that using mixed-mode solar dryers can mitigate 23% of CO_2 emissions. Singh and Gaur (2021) estimated the CO_2 mitigation of the solar dryer developed mainly for high-moisture products like a tomato. It was inferred that during the entire life of the dryer, CO_2 mitigation was calculated as 169.10 tonnes. Vijayan et al. (2020) conducted an environmental impact analysis using the indirect forced convection solar dryer. It was reported that the energy payback period was about 2.21 years. Over the life span, CO_2 mitigation was estimated at 33.52 tons. Vipin and Anil (2017) developed an indirect solar drying system for drying fenugreek leaves. It was predicted that the carbon credit earned was in the range of 660–2061USD.

Exergo-environmental analysis of different types of solar dryers was carried out, such as greenhouse dryers, hybrid PVT greenhouse dryers, mixed-mode solar dryers, and indirect dryers (Table 6). The payback period of solar dryers ranges from 1.1 to 6.82 years which means that it is one of the economical drying methods. CO_2 mitigation differs with the dryer's capacity, the product's mass, the solar dryer's life, and the product's type. When the life of the solar dryer is more, the CO_2 mitigation is also increased, which means an increase in the use of solar dryers reduces the CO_2 emission. Azwin et al. (2021) also concluded that solar dryers could reduce 34% of the CO_2 emission to the atmosphere. Hicham et al. (2018) reported that drying 120 kg of peaches and cherries using the solar dryer for 60% of drying time can reduce the CO_2 emission of 20,500 kg/month and 26,850 kg/month, respectively. When the utilization of solar drying time increases, the payback period reduces. Figure 21 shows the embodied energy of the different types of the solar dryer. The embodied energy of the large-scale solar dryer is more due to the usage of an isoboard, aluminium tray and

Table 6 Exergy-environmental analysis of different types of dryer

Type of dryer	CO_2 mitigation	Carbon Credit earned	Payback period	Authors
Indirect solar dryer	20.128 tons	$100.642–$402.569	1.42	Madhankumar et al. (2021)
Greenhouse dryer	678 tons	$18,645	3.3 years	Ayyappan (2018)
Large scale Solar dryer	99.60 tons		6.82 years	Halil and Eda (2021)
Indirect forced convection solar dryer	33.52 tons	10,894 to 43,576	2.21 years	Vijayan et al. (2020)
hybrid photovoltaic/thermal (PV/T) greenhouse dryer	44.98 tons	47,674	3.06 years	Barnwal and Tiwari (2008)
Hybrid PVT-Based Greenhouse Dryer	140.97 tons	47,929.8–191,719.2		Prakash and Kumar (2014)
Indirect Solar dryer		46,982–187,931	4.36	Prakash and Kumar (2014)
hybrid active greenhouse solar dryer	169.10 tonnes		1.73 years	Singh and Gaur (2021)
forced convection mixed mode solar dryer	8.4 tons		3.75 years	Jasinta and Muthukumar (2021)
Indirect Solar dryer	6400 kg/month	780 $/month	10 months	Hicham et al., 2018
Indirect Solar dryer	391.52 kg/year	660–2061 USD	4.36 years	Vipin and Anil (2017)
Hybrid greenhouse dryer	46.28 tons	16,844.76 INR to 67,379.05 21 INR		Asim et al. (2021)
Direct/Indirect Solar Drying System	38.06 tons	INR 12,561.70–50,245.49		Prakash et al. (2017)
Solar tunnel dryer	10.9–13 tons	$162.880/year	2.1–2.36 years	Eshetu et al. (2021)
Greenhouse dryer by natural convection	33.04 tons	11,068–44,273	1.68 years	Prashant et al. (2018)
Greenhouse dryer by forced convection	36.34 tons	12,173–48,695	2.35 years	Prashant et al. (2018)
Modified greenhouse dryer Active mode	38.06 tons	12,561.70 INR to 50,245.49 INR	1.14 years	Prakash and Kumar (2014)

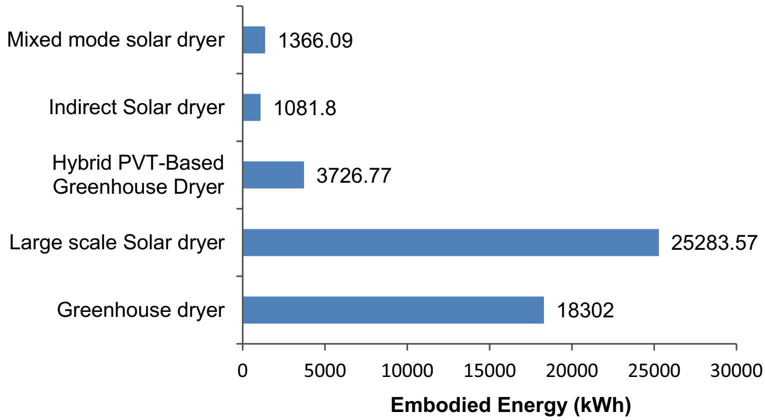

Fig. 21 Embodied energy of different types of solar dryer

fittings. At the same time, the embodied energy of the indirect solar dryer is only 1081 kWh which is much lower when compared with other types of the solar dryer. Therefore, it can be concluded that the construction of an indirect solar dryer utilizes less energy in terms of kWh. Thus CO_2 emission can significantly be reduced.

6 Limitations, future scope and challenges

Solar radiation is a freely available resource from nature. Therefore, it can be utilized efficiently for different agricultural unit processing, especially when drying food. However, the utilization of solar energy is limited due to various factors though solar energy is available in plenty. Therefore, more studies are required to understand the factors that hinder solar energy usage and some of the factors found in the literature are summarised below

- Limited studies on ISD's technical and economic feasibility with SHS/LHS are found in the literatures. Therefore, the concept of Techno-economical analysis is essential to commercialise the developed dryers, and the challenges in such analysis shall be cleared.
- The technology available to integrate the SHS and LHS in ISD is preliminary; hence, further study is required, particularly on the influence of solar radiation on the TSM.
- Studies suggest that the selection of LHS depends on the melting point of the TSM. Therefore, commonly available paraffin with a melting temperature range of 45–55 °C is primarily preferred in ISD. However, a systematic selection procedure based on various properties is necessary to find a suitable TSM for solar dryers and collectors.
- The latest studies reveal that the influence of parameters like the size and shape of nano-coated TSM is worth investigating as nano-structured TSM affects the heat transfer rate.
- Accurate results of charging and discharging TSM are needed to enhance the dryer's performance or efficiency. Artificial Intelligence based models can help in predicting the charging and discharging of TSM based on various properties.

Besides these challenges, there is plenty of opportunity to improve the performance of dryers and collectors with TSMs. Research can be focused on improving PCM's heat transfer ability by encapsulating it with nanomaterials. Also, more studies should be devoted to using the PCM for waste heat recovery applications. Then, this recovered waste heat can be converted to electrical energy. Further, to improve the performance of the ISD, efforts should be made to integrate Photovoltaic cells with TSM as it can store more thermal energy and increase conversion efficiency. Furthermore, some studies analysed the exergy efficiency of solar collectors and drying chambers; however, research can also be focused on eliminating the exergy losses in the solar collector and drying chamber. Finally, automation in the operation of the solar dryer can be developed to monitor the real-time data, such as temperature, humidity and airflow rate, inside the dryer and solar collector.

In addition, there is still more potential to improve the performance of solar collectors in the indirect dryer. The performance of the solar collector can be increased by

i. Using multiple reflectors in the collector
ii. Increasing the area of the collector
iii. Providing specialised coatings in the absorber surface to maximise the heat absorption
iv. Using the V or U-shaped corrugated absorber plates
v. The use of double or triple pass air collector
vi. Two-way airflow configuration, i.e. top and bottom flow in the absorber plate of solar collector

Currently, most of the dryers reported in the literature are small-scale prototypes with an average dryer capacity of 20 kg. However, there are many challenges ahead when converting them into large-scale dryers. The fundamental challenge that arises is low heat transfer in the PCM due to poor thermal conductivity. High thermal conductivity metal rods, heat pipes, nanoparticles and fins are embedded within the PCM to enhance the heat transfer in the same material. Adopting a similar technique in a large dryer is not feasible. Therefore, an effective heat transfer within the TSM is essential for the efficient charging and discharging of heat. Another challenge is that the volume of solar collectors required is enormous, and it occupies more space when the drier capacity is increased. Therefore, concentrated collectors, which occupy less space and extract more heat, can be suitable for higher-capacity dryers. In addition, energy consumption may increase when a heat transfer due to convection is envisaged in the dryer due to the active system used for air circulation. Overcoming these fundamental challenges is essential for developing indirect solar-based large dryers, and more research is needed to overcome these challenges. However, any developments on this indirect solar dryer will significantly reduce the carbon footprint, which is a welcome outcome.

7 Conclusion

This review focused on different types of indirect solar dryers with and without thermal storage materials, their design consideration, performance, efficiency, exergy, and exergo-environmental analysis of other solar dryers. The solar collector is an essential component in the ISD system; the efficiency of the solar collector is the key indicator for evaluating the dryer's performance. The maximum solar collector efficiency of 70% was found with forced convection systems, whereas only 30% collector efficiency was achieved with natural convection systems. Using the thermal storage material improves the dryer's efficiency as it can be operated in non-sunshine hours and reduces the drying time. This review found that TSM can decrease the drying time by up to 6 h. The efficiency of the solar collector can be further enhanced by encapsulating TSM with nano-structured/coated materials, which can improve the charging and discharging of heat. Also, advanced research is needed to integrate LHS and SHS in the design of ISD. Moreover, techno-economic feasibility studies are also necessary to successfully commercialise the ISD. According to the moisture content of the product, ambient temperature, relative humidity, the mass of the product and drying air velocity, the drying time varied from a different product. Natural convection indirect solar dryers are self-operated dryers with no control over the drying rate. At the same time, forced convection indirect solar dryers have reasonable control over the drying rate. Studies on the solar dryer's thermal efficiency alone are insufficient to pick out the preferred solar dryer system. Studies on exergy efficiency pave the way to reducing exergy losses and improving the solar dryer's performance. Thus the combined effect of renewable energy usage and minimizing exergy losses leads to sustainability. Exergy environmental analysis of different types of solar dryers shows that indirect solar dryers have the potential for achieving CO_2 mitigation by 2050 since the embodied energy is less and net CO_2 mitigation is around 33.52 tonnes. Therefore, as pointed out in COP 26, to reduce the net CO_2 emission to zero by 2050, solar dryers can replace the usage of non-renewable energy sources. It is an excellent alternative to protecting the environment from CO_2 emissions.

Data availability statements The authors would like to state that the data used in the present study are taken from the literature and are available within the article. The data taken from the literature are suitably cited.

Declarations

Conflict of interest The authors wish to state that the co-authors do not have any conflict of interest among them, and it is the new and collaborative work of Asha Monicka A, Pragalyaa Shree, Freeda Blessie. R, Humeera Tazeen, B. Navaneetham, S. Sheryl Andria and A. Brusly Solomon. Also, the authors would like to confirm that this work is not submitted elsewhere for publication.

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