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A review on indirect type solar dryers for agricultural crops – Dryer setup, its performance, energy storage and important highlights

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HIGHLIGHTS

- Literature data of different indirect type solar dryers (ITSD) were discussed.
- ITSD with sensible and latent heat storage system was reviewed.
- ITSD with roughened solar collector was extensively reviewed.
- Chemical pre-treatment, payback period and economic analysis were discussed.
- Important findings and summaries of ITSD were listed and tabulated.

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Active and passive solar dryers
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Pay-back period

ABSTRACT

Inadequate preservation techniques and poor storage provisions lead to deterioration in the quality of agricultural products. Advanced processing techniques have been used to reduce postharvest losses of agricultural goods. Drying is a processing technique used for food product preservation. Drying by solar energy is an ancient food preservation technique. Solar dryers of various sizes, capacities and designs are available for drying applications in agricultural industries. Indirect type solar dryer (ITSD) is one of the prominent dryers used to dry food products and this type of dryer with its unique features, types, and different technique incorporated to improve its performance has not been investigated so far in any detail. The purpose of this work is to review the features and benefits of ITSD. A commonly used classification of different types of solar dryers is also presented. Heat transfer enhancement on ITSD and the influence of pre-treatment before drying are also effectively reviewed. Payback period and cost analysis of ITSD are discussed. Important findings on ITSD have been reviewed, discussed and tabulated. The most dominant parameters affecting the drying rate are air temperature and velocity, followed by solar radiation, type of product, initial moisture content and total mass of the product. Passive solar dyers were easy to fabricate compared to active dryers. The drying rate of pre-treated foods was high and the quality of the product remained intact after drying.

1. Introduction

To sustain the balance between population growth and food supply, food losses during harvesting and marketing should be minimized. The quality and quantity of agricultural produce suffer due to poor processing methods and shortage of storage facilities. Many developing countries suffer considerable losses on the agricultural front. It is mentioned that post harvesting loss of fruits and vegetables in developing countries is about 30–40% of total production [1]. Drying is one of the important preservation techniques for fruits and vegetables. Removing water by drying is the oldest technique used in many applications such as wood pulp drying for making paper, drying for food preservation and drying building materials [2]. The energy for drying comes from various sources, namely, fossil fuel, electricity, natural gas, biomass and solar energy therefore, the topic of this review work comes under the application of applied energy. These thermal drying methods account for 10–20% of total industrial energy consumption in the developed world [3]. Fossil fuels pollute the environment and the guarantee of limitless availability of such fuels is doubtful [4]. Solar energy is efficient and an effective source which provides long-term actions for

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Nomenclature

A_c	area of collector, m^2
AH	absolute humidity of air, %
C_p	specific heat, kJ/kg·K
db	dry basis
DPSD	double pass solar dryer
h	specific enthalpy, J/kg
h_{fg}	latent heat of vaporization, kJ/kg
I	solar radiation, W/m^2
ITSD	indirect type solar dryer
LH	latent heat, kJ/kg
m, $\dot{m}_a$	mass flow rate, drying rate, kg/s
m_i	initial mass of product, kg
m_d	mass of the dried product, kg
m_w	mass of water, kg
MC	moisture content, %
OSD	open sun drying
P_f	fan power, W
P_t	total energy input to the dryer, kWh
PV/T	photovoltaic-thermal
q	power absorbed by the drying load, kW
q'	power absorbed by the air, kW
Q	energy required for drying,
RCCD	rotary column cylindrical dryer
RH	relative humidity, %
SAC	solar air collector
SAH	solar air heater
SEC	specific energy consumption, kW h/kg
SH	sensible heat, kJ/kg
t	time, s
t_{save}	time saved
TES	thermal energy storage
T	temperature, ˚C
wb	wet basis

Greek symbol

η_c	collector efficiency, %
η_d	dryer efficiency, %
η_{ex}	exergy efficiency, %
η_p	pick-up efficiency, %
ϕ	relative humidity ratio

Subscript

a	air
as	adiabatic saturation
co	collector outlet
f	final, fluid
i	inlet

sustainable development. The earth receives abundant solar radiation. Using available solar radiation, it is possible to replace conventional method (using fossil fuel, natural gas) of drying to preserve vegetables and fruits for a very long time.

Removing water from food to prevent bacterial growth is a method of food preservation known as drying. Drying is a complicated process with unsteady heat and mass transfer, or physical or chemical transformations which can affect the product quality [5]. It involves simultaneous heat and mass transfer processes as the product is heated and then the moisture is removed [6]. Different drying methods are available such as convective drying, indirect drying, di-electric or microwave drying, freeze drying and natural air drying [7]. Solar energy is frequently used for drying and in recent decades solar drying has become popular. Solar drying is abundantly available, free of cost and is an environmental friendly energy source. The food is dried in open air called open sun drying (OSD). It is the oldest and traditional method of drying where the material to be dried is spread over the ground or on mats, or on trays allow them to dry throughout the day. But OSD has a lot of disadvantages as the materials are put in open air, therefore, the food material is easily contaminated by dirt, dust, pollution, damage by animals, birds or insects and their dropping, degradation through exposure to direct sun radiation, storm, and dew, additional losses during storage due to insufficient or non-uniform drying. These all are lead to infestation by fungi, bacteria and other microorganism causing the spoilage of the material [8]. Both open and industrial methods of drying have some disadvantages but some innovative techniques are used to solve the problems and all are discussed in this review.

Solar dryer is mainly used for drying fruits and vegetables and the final product is clean and hygienic, if necessary provisions [9] are made in the setup. It also saves energy and occupies less space. The main importance of solar dryer is, it protects the environment by not releasing carbon monoxide, carbon di-oxide, oxides of nitrogen and other smokes as internal combustion engine and power plants release. It also enhances the stability of the product, minimizes packaging problem and also reduces weight and cost of transportation [10]. A lot of food products can be dried through solar drying. Fruits such as grapes, apples, pineapples, banana, dates, beets, mangoes, etc., and vegetables such as tomatoes, onions, potatoes, carrots, etc., and grains such as wheat, rice, maize, corn, etc., herbs and spices such as chillies, tulsi, garlic, neem, ginger, etc., and cash crops - flowers, coffee, tea, etc., as well as fish and meat may be preserved through drying [11].

Solar energy for drying has not been widely commercialized yet due to expensive investment, limited time and intensity of incident radiation, low skilled manpower for drying operation and poor maintenance of equipment. The main and primary reason however is that solar dryers were not designed keeping economic viability in mind. A variety of solar dryers with different types and sizes create uncertainty in the mind of users. Therefore, it is important to collect all the details of solar dryers of different types so that their usefulness for different applications may be taken into account. Among the different types of dryer, indirect type solar dryer (ITSD) has better product quality on the dried product than OSD and direct type solar dryer as it can provide the required temperature, better control over drying, retention of product color, nil damage to crops, and is highly recommended for photo-sensitive materials such as lemon, cucumber, papaya, etc. Though the available literature has certain data on ITSDs, no study as yet has contributed with specific reference to data of ITSDs, its features, types, ITSD with energy storage techniques, performance of ITSD, its cost analysis etc. This review work overcomes the above limitations and extensively reviews the studies on ITSD to draw significant conclusions. The paper also reviews ITSDs based on different designs, operating parameters and method of energy storage. The classifications based on the nature of air flow i.e. natural or forced convection, number of pass which includes single pass, double pass, triple pass solar air collector are also discussed. Corrugations or roughness over absorber surface for heat transfer enhancement are thoroughly reviewed. This review paper helps one understand the different types of ITSD for drying different agricultural products, different design details and performance parameters evaluation of setup, thermal energy storage material used in ITSD and their performance, and cost analysis of the setup. This is an application of renewable energy on small and large scale by industries and also by farmers; therefore this topic is of potential interest to readers.

2. Classification of the solar drying system

The main classification of solar drying system is mentioned in Fig. 1. According to the utilization of solar power, the drying system is classified into two groups; open sun drying (OSD) and controlled solar drying. These two groups are extensively discussed in the sections that follow.

2.1. Open sun drying (OSD)

Following are some types of OSD,

Open sun drying (OSD) in ground– the materials to be dried are spread on the ground or into thin layers of trays, mat, concrete floor, therefore, the product is exposed to open wind and the sun.
Rack type (shade type) [12] - In this method, series or parallel racks are provided to keep the moist food material to be dried.

Conventional methods are advantageous as OSD is independent of other sources of energy; there is no extra provision needed to dry the product; it is the cheapest drying method and requirement of skilled labour is not necessary.

But there are some disadvantages of OSD, which inspired researchers to look for alternative ways to OS drying.

- The risk of damage to the product by birds, insects and animals.
- Product degradation because of direct exposure to sun irradiation and storm.
- Degradation of product due to rain, air humidity and dew.
- The quality of product being degraded by dirt, dust and atmospheric pollution.
- Loss due to over-drying.
- Spoiling of product due to the growth of micro-organisms.
- Losses due to non-uniformity or insufficient drying during the process of drying.

2.2. Controlled solar drying

In both the cases, open and rack type, controlling the drying parameters such as temperature, velocity, humidity etc. is difficult. It has a number of advantages such as good quality products, lower drying period, dust free products and large scale products [13]. But new innovative dryers are available in the literature where controlling the drying parameters is possible. In the solar drying of agricultural goods, food quality depends on the working fluid temperature, humidity, velocity, etc. [14]. It is possible to control these influencing parameters using various methods. Also, in controlled solar drying, it is possible to store solar energy in two forms of heat, such as sensible heat (SH) and latent heat (LH), which can be utilized during the night to continue the drying for a certain period of time. These controlled solar drying systems are classified as follows;

2.2.1. Direct type solar dryers

In the direct type solar dryer, transparent glasses are used to transmit solar radiation directly to the food products [15]. In these dryers, convective losses must be reduced and therefore, drying chamber temperature can be increased. Some direct solar dryers are; box type or solar cabinet dryer or glass roof solar dryer [16] and greenhouse dryer [17].

Advantages are:

- Low contamination in the product due to enclosure provieded by transparent cover.
- Protection from rain, dew, etc.
- Better product quality than in OS drying.
- Simple and less costly to fabricate than indirect dryer for the same capacity.

Disadvantages:

- Quality and color of the product deteriorate when the product is directly exposed to sunlight.
- Improper removal of vapor moisture results in slower drying rates.
- Smaller capacity and therefore, useful only for applications on a small scale.
- Glass cover transmissivity reduces after some time as moisture condensation occurs inside glass cover.

2.2.2. Indirect type solar dryer (ITSD)

Two methods of ITSD are noticed from the literature; they are (a) natural circulation type and (b) forced circulation type [18]. Fig. 2 shows the further classification of ITSD.

(a) Natural circulation type: It is also recognized as passive solar dryer because of the natural circulation of air due to thermo-syphon effect. Food is heated because of hot air and then the moisture

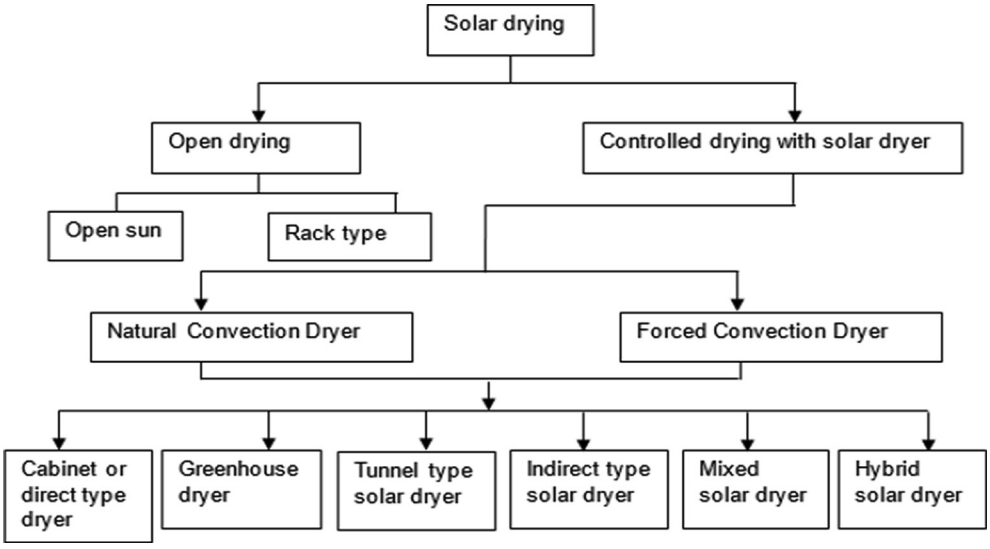

Fig. 1. Classification of solar dryer system.

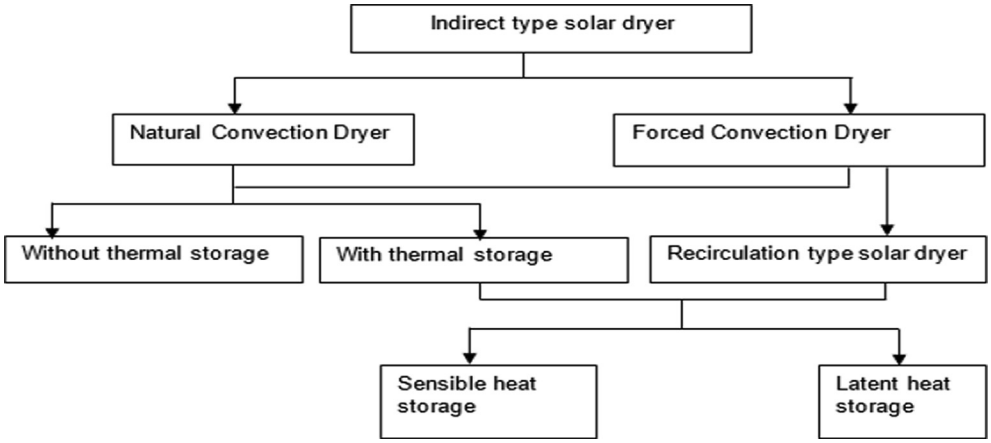

Fig. 2. Classification of indirect type solar dryer (ITSD) system.

contained in the product is eliminated to outside air through the chimney which is placed at the top of the drying chamber by natural air circulation. Some of these types are:

i. Conventional ITSD: It consists of a solar air collector (SAC) to heat the inlet air and a chamber to keep the food to be dried [19].
ii. ITSD with chimney: The main components of this type are: SAC, drying cabinet and a chimney to create the draft force [20].
iii. ISTD with chimney and heat storage system: These dryers are provided with chimney to create draft and storage material for storing solar thermal energy which can be utilized during night or when there is no sunlight [21].

(b) Forced circulation type (Active mode) – Here, as electric fan or blower is used to force the air, into or out of the dryer. So controlling the drying rate is possible in this type of dryer. It is also categorized in the same way as natural circulation type with the addition of a fan or blower. Some other types of solar dryers are: solar dryer with greenhouse collector and tunnel type dryer with integral collector [22].

2.3. Mixed mode type solar dryer

It has the advantages of both direct type and indirect type dryer. Heat energy is absorbed by the product directly from the sun as well as indirectly from the SAC [23,24].

3. Working principle and performance parameters of ITSD

Solving the problems of open and direct type solar drying, different designs of ITSD have been developed and tested, and these have a number of advantages and some disadvantages.

Advantages:

- Better product quality as it gets the required temperatures.
- Better control over drying and better product quality than sun drying.
- Higher moisture pickup per kg of dry air.
- Retention of product color as it is not exposed to ultraviolet radiation.
- Better performance than other conventional type of dryers.
- Absence of heat damage to crops.
- Particularly recommended for photo-sensitive materials such as lemon, cucumber, papaya, etc.
- Greater efficiency than direct solar drying.

Disadvantages:

- The intensity of solar radiation varies with respect to time; so thermal storage is needed and so is auxiliary energy source during cloudy days and in the evening.
- Solar radiation has low energy density and hence a large surface is required for the collector.
- High initial investment and energy costs.

3.1. Working principle of ITSD

The ITSD, shown in Fig. 3, consists of two main components; drying cabinet where materials are kept on trays and solar collector set-up which consists of a glass plate and absorber plate. Hot air is then allowed to flow over the food material to be dried; therefore, the food is heated and the moisture is removed. The drying chamber is provided with wire mesh trays to keep the product to be dried.

Solar collector set-up consists of an absorber plate and a glass cover which is coupled with the drying chamber at a particular inclination, which depends on the latitude of location. The absorber is selectively coated with black color for maximum solar radiation absorption. When solar radiation is incident on glass cover, a number of heat transfer mechanisms occur; part of radiation is reflected back to atmospheric air, another part is transmitted through the glass cover, a part is transmitted from glass cover to the atmosphere (transmission loss), some amount of energy is absorbed by the absorber plate and a certain quantity is transferred by convection to heat the air which passes into the chamber. The food product in the drying cabinet absorbs the heat and loses moisture. Basic theory for calculating the efficiency of ITSD is discussed in the next section.

3.2. Flat plate collector efficiency

Performance of the solar flat plate collector is based on factors such

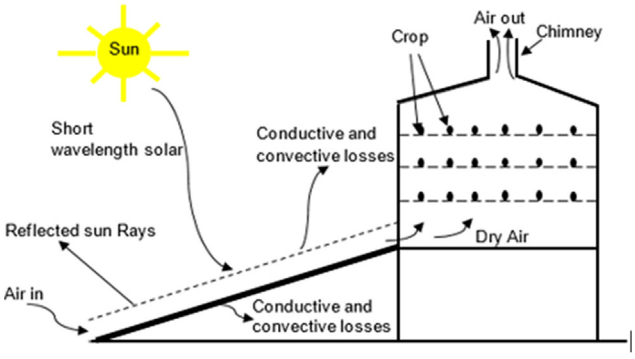

Fig. 3. Schematic view of the indirect type solar dryer (ITSD).

as speed, surrounding temperature, humidity, etc. Collector efficiency [25] is estimated using the equation below:

$$\eta_c = \dot{m}_a C_p (T_{co} - T_i)/A_c I \quad (1)$$

where m_a is air flow rate (kg/s), T_i and T_{co} are the collector inlet and outlet air temperature (°C), A_c is collector area (m^2), C_p is the specific heat and I is incident solar radiation (W/m^2).

3.3. Drying and psychrometry

Food drying process involves reduction of moisture to acceptable limits. Moisture content must be reduced at a certain level for long-term preservation which may vary with different fruits and vegetables. Energy required for drying, Q_d [26] is estimated using:

$$Q_d = m_a C_p (T_{co} - T_f) = m_w L_w \quad (2)$$

where m_w is mass of water removed in kg, L_w is latent heat at a mean temperature $[(T_{co} + T_f)/2]$ in J/kg, and T_f is the temperature at exit of the chamber in °C.

Amount of water removed (m_w) throughout the drying is,

$$m_w = m_i (MC_i - MC_f)/(100 - MC_f \quad (3)$$

where m_i is initial mass of product (drying load) in kg, MC_i and MC_f are initial and final moisture content of the product. Moisture content in the product can be estimated using [27,28],

$$\text{Moisture content, wet basis (wb)}, MC_i = (m_i - m_d)/m_i \quad (4)$$

$$\text{Moisture content, dry basis (db)}, MC_i = (m_i - m_d)/m_d \quad (5)$$

where m_i is initial mass of the product before drying, m_d is mass of the dried product.

Initial moisture content of the food product is generally estimated using hot air oven method where wet product to be dried is kept at 105 °C for 24 h time duration to get complete dried product [27].

If m_w is the amount of water that evaporates in time (t), the power absorbed by the product (q) is given by;

$$q = m_a C_p (T_{co} - T_f)/t \quad (6)$$

During air heating in the collector, specific enthalpy of air rises from h_i to h_{co} and humidity ratio $\phi_i = \phi_{co}$ remains constant. In the drying chamber, drying air absorbs the moisture from the product and hence humidity ratio changes from $\phi_{co,}$ and ϕ_f.

The mass of air needed for the moisture removal process can be calculated using:

$$m = m_w/(\phi_f - \phi_{co}) \quad (7)$$

The thermal power needed to heat the air from the absorber plate (q') is given by,

$$q' = m(h_{co} - h_i) = \eta A_c I \quad (8)$$

3.4. Drying efficiency

It is the proportion of energy supplied which is utilized by the wet product to eliminate moisture from the product. Drying efficiency can be estimated as,

$$\text{For natural convection, Drying efficiency (\%)}, \eta_d = m_w h_{fg}/A_c I \quad (9)$$

$$\text{For forced convection, Drying efficiency (\%)}, \eta_d = m_w h_{fg}/(A_c I + P_f) \quad (10)$$

where h_{fg} is the latent heat of vaporization (kJ/kg), P_f is the fan power.

3.5. Pick-up efficiency

Pick-up efficiency is efficiency related to drying air which is a measure of the moisture removal capacity from the product and calculated as [22]

$$\eta_p = \frac{AH_o - AH_i}{AH_{as} - AH_i} \quad (12)$$

where AH is absolute humidity. Specific energy consumption (SEC) is the ratio of total energy input (P_t) to the quantity of water removed from the wet product.

$$SEC = \frac{P_t}{m_w} \quad (13)$$

4. Review of indirect type solar dryer (ITSD)

Scientists and researchers have developed solar dryers for many types of agricultural goods to solve the problems of traditional sun drying and have been continuously working to improve these dryers. Some of the natural and forced type ITSD with and without thermal energy storage (TES) system is reported in the section. ITSD without TES system is simple in design and useful for drying food after sunshine hours.

4.1. Natural convection ITSD

A lot of experimental studies have been carried out in ITSD by considering a simple flat plate SAH and drying chamber. Air is circulated naturally without any external devices such as fan or blower etc. Natural circulation reduces additional cost and maintenance of fan. A review of some ITSD with collector and single pass flat plat collector has been carried out in this section and the results obtained during the drying in natural convection ITSD are explained. This type of collectors is simple in design and easy to fabricate (Fig. 3).

Parikh and Agrawal [28] carried out the experiments and analyzed the double shelf cabinet dryer attached with flat plate collector in Jaipur, India. The analysis was done for green chilli (Capsicum annuum) and potato (S. tuberosum) chips. Glass and polycarbonate sheets were used as glazing cover for enhancing dryer efficiency. The efficiency increased from a range of 9–12% to 23.7% with glass glazing as a cover sheet and 18.5% using polycarbonate sheet. Therefore the drying time decreased drastically.

Maiti et al. [29] designed, developed and tested an ITSD (natural convection) solar dryer fixed with reflectors. It was reported that when using a reflector, collector efficiency increased from 40% to 58.5% with no load condition during peak values of solar irradiation in the month of January at Bhavnagar, Gujarat (India). The system was used for drying a popular Indian wafer called 'papad'. 1 kg of papad was dried from an initial moisture content of 4.88 to a final 12% moisture content (wb) with a drying efficiency of 4.12%.

Pangavhane et al. [13] developed a natural circulation ITSD which consists of SAC and drying cabinet for grape drying. The collector set-up consisted of absorber plate with dark painted fin, collector glass and necessary insulation at the bottom. U - Shaped corrugations over the absorber were placed parallel to airflow direction to enhance heat transfer. The bottom side of absorber plate was fitted with aluminium fins (0.15 mm thick) to create more turbulence of air flow, so that maximum amount of heat could be transferred to air. At the inlet of collector, shutter plates of size 4 mm thickness and 0.08 m × 0.4 m were used to restrict the air flow at night time to avoid drying because of higher relative humidity. The entire unit was placed in a galvanised iron sheet (0.9 mm thickness) box. 43% reduction in drying time was observed compared with OS method. Traditional shade and OS method of drying take 15 and 7 days respectively, while multipurpose natural circulation indirect dryer took 4 days with good quality raisins.

Stiling et al. [30] developed a setup for Roma tomatoes drying. The setup was built with and without the concentrating solar panels (CSP). Results showed that the dryer with CSP had 10 °C higher temperature

and 7.4% faster drying rate than dryer without CSP. Abhay et al. [31] developed an ITSD for drying crops. It consisted of an SAC, a drying chamber and a chimney. Flat plate SAC was provided with a V-shaped roughened absorber plate. The drying chamber was provided with four trays at equal distance one above the other. Experiments were performed on banana for analyzing its drying characteristics. Banana was dried from an initial MC of 78% to a final MC of 0.1633, 14.04%, 17.46%, 23.76%, and 29.76% (wb) at Trays 1, 2, 3, 4 and OSD, respectively. They estimated the average thermal efficiencies of the drying chamber and collector cover and these were: 22.38% and 31.50%, respectively. It was observed that the temperature of drying air was the most influential factor during drying operation.

Essalhi et al. [32] developed an ITSD for drying grapes and compared the results with OSD drying. Grapes were dried from an initial MC of 79.8% (wb) to a final MC of 20.2% (wb) in 120 h. Drying curve for grapes was fitted with different available models and the best drying model was found. Effective moisture diffusivity of grapes was 2.34×10^{-11} m^2/s. Sanghi et al. [33] developed a CFD model using Ansys software for corn drying in natural ITSD. Air velocity, RH and temperature profile inside the chamber were estimated. Simulated results were validated with experimental results. Similarly, 7.45 kg of tomato slices were dried in a flat plate ITSD dryer [34]. MC of tomato slices was reduced from 93.81% to 6.54% in 26 h. Collector efficiency and drying efficiency of ITSD were estimated to be 55.45% and 8.80%. Tedesco et al. [20] designed and simulated a natural convection ITSD with a chimney. Three separate portions of ITSD (solar collector, dehydration chamber, and chimney) were modelled and flow parameters were estimated using numerical simulations. Simulation results were compared with experimental results of apple drying process.

Details of the studies on ITSD with flat plat collector are presented in further paragraphs and a highlighted list is provided in Table 1.

From the above studies, it is recommended to use ITSD for drying agricultural products; ITSD being photo-sensitive, it protects the material from dirt, dust, animal and bird attack. The heat gained by drying air can be increased with increase of SAC dimensions such as length, width, flowing air gap and tilt angle. Also from Table 1, it is observed that the time required for drying is less in ITSD compared to OSD. CFD analysis can be carried out for visualizing air velocity and temperature distribution within natural convection ITSD chamber to find dead zone which reduces dryer performance. Possible modifications can be done in the chamber before starting the work. Also, food products can be kept where active zone is found in the chamber.

The maximum capacity of natural convection ITSD dryer is only 7.45 kg [34] which is used for tomato drying. All other studies are made with small scale prototypes as these studies suggested a small quantum of production. It shows that this topic needs much data on large scale solar dryers. So, it can attract commercial manufacturers and buyers such as farmers, who grow food for local markets and small scale food processing units. The natural convection dryers take more time to dry food products, and therefore such models may be ideal for low MC food materials such as yam slices, green chilli, cauliflower (Brassica oleracea), onion (Allium cepa), banana and sapota (Manilkara zapota) slices which can be dried within 8 h of sunshine hours. Other higher MC fruits and vegetables cannot be dried continuously as it results microbial activity. In some cases [13], the dryers work for more than a day, while the food products are stored in some reservoirs at night. These foods are dried consecutively in day time and stored at night time. It creates rotting and structural failure, so it is difficult to maintain quality. Also, studies on the performance improvement of natural convection ITSD dryers are not noticed in literature; therefore, this area needs to be investigated more by researchers and industries. The other difficult task in natural convection ITSD is controlling temperature and air velocity inside the dryer.

4.2. Forced convection setup ITSD

In forced convection solar dryer, fan or blower is used to enhance the air flow rate through the duct. It helps to maintain the temperature inside the system by controlling the air flow rate at the inlet [35]. Review on forced convection ITSD is presented in this section.

4.2.1. Forced convection ITSD with single pass SAC

In this section, forced convection ITSD with a single pass flat plate collector is briefly reviewed. Fig. 4 shows the single pass forced convection ITSD dryer used for drying fruits and vegetables.

Kadam and Samuel [36] used forced convective V-grooved SAC for cauliflower (Brassica oleracea) drying. The maximum rise in temperature was reported as 13.5 °C at collector outlet. The average thermal efficiency of collector was calculated to be 61.5%. It was concluded that thermal efficiency and drying rate can be improved by optimizing the air flow rate.

Al-Juamily et al. [37] fabricated an ITSD with a blower for air supply. Two V-grooved absorber plates and a glass cover were provided in the collector. One of the vegetable varieties (beans) and two fruit varieties (grapes and apricots) were dried. It was noticed that the MC of beans was reduced from 65% to 18% (wb) in 1 day. Similarly, for apricot, the moisture percentage was reduced to 13% from 80% in 1½ day and that of grapes to 18% from 80% in 2½ days. The temperature of hot air was found to be the most influencing factor in the drying process which reduced the drying time.

A setup of forced convection ITSD with the provision of electric heating was developed for studying the dying kinetics of olive leaves such as Chemlali, Chemchali, Zarrazi and Chetoui [38]. Experiments were conducted at 40, 50 and 60 °C with the flow rate of 0.0556 m^3/s. It was found that the page model had better agreement with the experimental drying curve. Moisture diffusivities and activation energy were estimated and they were in the range of 2.95×10^{-10}–3.60×10^{-9} m^2/s and 52.15–83.60 kJ/mol, respectively.

El-Beltagy et al. [39] conducted experiments on the solar dryer for drying strawberry (Fragaria Xananassa) slices. Experiments were conducted with different shapes of pre-treated strawberry. Strawberry was pre-treated with different solutions such as 1% sodium metabisulphite and 1% citric acid, 1% ascorbic acid and 1% citric acid, 1% citric acid

Table 1
Performance of ITSD having flat collector reported by some authors.

Load (kg)	MC (wb%)		Time (t) (h or day)		Time Save (day)	Flow rate/velocity	T_o °C	Efficiency (%)	
	MC_i	MC_f	OS	ITSD				η_c	η_d
Grapes [13]	77.75	14.53	7 days	4 days	3 days	0.0126–0.0246 kg/s	51.9 to 64.6	48–56	–
1 kg potato chips [28]	28	12.05	–	8 h	–	–	55	–	18.2
2 kg green chilli [28]	–	–	–	–	–	–	52	–	23.7%
1 kg papad [29]	83	12	–	5 h	–	0.0367 kg/s	65	49.45	4.12
2 kg banana [31]	78	18.05	–	–	–	1 m/s	62	31.50	22.38
0.384 kg grapes [32]	79.8	20.2	25 days	15 days	10 days	0.7 m/s	46.8	–	–
7.45 kg Tomato [34]	93.81	6.54	–	26 hr	–	0.028 kg/s	62	55.45	8.8

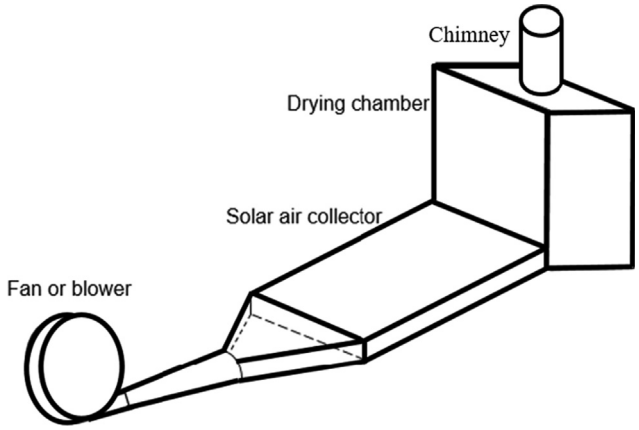

Fig. 4. Forced convection indirect type solar dryer setup.

and 2% sodium metabisulfite. The result showed the drying times required to reach 10.15%, 11.58%, 0.1031%, and 15.61% wet basis MC were 24, 28, 26, and 20 h for discs, halves, quarter sized and a whole strawberry, respectively. It was found that the process of pre-treatment and slicing reduced the drying time without affecting the chemical composition of strawberry.

Hybrid ITSD with solar reflector was developed by Hossain et al. [40] for drying of 20 kg half cut tomato. The temperature at the outlet of the collector was found to be 30 °C more than ambient temperature. 20 kg of the sample were dried up to 2 kg per batch with the drying efficiency of 17–29%. Solar reflector helped to increase the efficiency of the collector by 10%. They suggested pre-treatment should be performed before drying with 8 g/L sodium metabisulphite to prevent microbial growth if the drying temperature is below 45 °C

Usub et al. [41] developed a force convection ITSD of tunnel type dryer for silkworm pupae drying. Pupae were dried from the initial MC of 81.39% to final MC of 13.04% (wb) in 6.22 h at a mass flow rate of 0.32 kg/s. Drying curves were compared with different available models and it was found that Midilli–Kucuk model was a better fitting model. Maximum effective moisture diffusivity was 2.7696×10^{-10} m^2/s.

Singh [42] developed a forced convection ITSD for thin layer silk cocoon (Bombyx Mori) drying. It consisted of a drying chamber with several trays for cocoon loading and an SAH. Cocoon moisture percentages were reduced to 12% from 60% (wb) at different air temperatures between 50 and 75 °C. He performed an energy analysis and found that the consumption of electrical power was very low which was mentioned in terms of Net Present Value.

Sundari et al. [43] experimented with active ITSD consisting of an evacuated tube collector, and a drying chamber with chimney and blower. The performance of the system was studied for bitter gourd (Momordica Charantia). The MC of bitter gourd was reduced to 6.25% from 91% (wb) in 6 h when compared with 10 h in OS drying. Also drying rates as well as moisture ratio were calculated and compared with OSD drying. It was noticed that better quality product was obtained than that of OSD drying.

Boughali et al. [44] developed a hybrid solar–electrical dryer. Experiments were performed in the winter season, with and without load, and the thermal behavior, effect of high mass flow of air on collector performance and drying efficiency were analyzed. It was reported that the average efficiency of the system was in the range of 13–31%, 12.5–33% and 2.5–47.5% for air velocities of 1, 1.5 and 2 m/s, respectively.

Akbulut and Durmus [45] used mulberries (Morus) to study the performance of ITSD. Energy and exergy analyses were performed during the drying of mulberry slices. The result was estimated for seven different air flow rates which were varied between 0.0015 and 0.0361 kg/s. The result showed that there was a decrease of drying time with an increase in flow rate of air. The effective moisture diffusivity was estimated and its value varied between 3.47×10^{-12} and 1.46×10^{-9} m^2 s^{-1}. They also concluded that the higher mass flow rate of air helped to reduce exergy losses.

Midilli [46] studied the drying behavior of pistachio (both shell and unshelled) samples using ITSD and OS drying. The experiments were performed on 100 g of raw and unshelled pistachio in both conditions. It was observed that samples of pistachio dried in ITSD took 6 h at 50 ± 10 °C temperature with 29% final MC. Dried sample in OS method took more time to dry and it was observed that the dried pistachio had poor quality due to dust and insects.

Sreekumar [47] used 46 m^2 SAC for the application of drying 200 kg fresh pineapple slices (0.5 cm thick). Maximum temperature of 76 °C was achieved at the collector outlet. Pineapple slices were dried up to final MC (< 10%) from an initial MC of 82% within 8 h. Karsli [48] analyzed the performance of four different ITSDs. Two were finned collectors having 75° and 70° fin angles, one was a base-collector setup and the fourth was a collector setup with tubes. The efficiency of each collector was estimated using first and second laws of thermodynamics and comparisons were made. It was found that the collector with 75° fin angle had the highest efficiency. The first law and second law efficiencies were estimated and they were in the range of 26–80% and 27–0.64%, respectively.

Dissa et al. [49] conducted experiments on the drying of 8 mm thick mango cut pieces. The final MC achieved from the result was 13.79% (wb). They developed correlations for the drying rates of shrinkage and the critical water content of mango. El-Sebaii and Shalaby [50] developed a forced convection ITSD. Experimental analysis was carried out for the drying of thymus and mint. Thymus was dried from an initial MC of 95% (wb) to final MC of 11% (wb) for a drying time of 5 h while mint was dried from an initial MC of 85% (wb) to final MC of 11% (wb) for a drying time of 34 h.

Mohanraj [51] developed a solar-ambient hybrid source heat pump dryer and analyzed its performance for copra drying. Specific moisture extraction rate was estimated to be 0.79 kg/kWh. Experimental results showed a reduction in moisture content of copra from 52% (wb) to about 9.2% (wb) in 40 h and this was a far better method of drying compared to other methods.

Tomatoes were dried in solar crop dryers with solar concentrator from an initial MC of 90% to final MC of 10% (wb) [52]. Effect of solar concentrator on the drying rate of tomatoes was studied. It was observed that the drying time was reduced to 21% compared to the dryer without concentrator. Quality analysis was carried out on dried tomato slices and it was found that there were no changes in quality in dryer with and without concentrator.

Hegde et al. [53] evaluated dryer performance while drying various agricultural products. The performance was evaluated for banana slices. Two different airflow configurations were considered with air flow velocity varying from 0 to 3 m/s; one was the top flow where airflow between absorber and collector cover and the second one was bottom flow where air flow happened between the absorber plate and the insulated plate. From the result, it was found that for the same the solar input, bottom flow provided 2.5 °C higher temperatures to the drying chamber than the top flow. The efficiency of top flow and bottom flow configuration was calculated as 27.5% and 38.21%, respectively. Also, it was found that the dried banana's color, taste and shape did not change at an air flow velocity of 1 m/s compared at 0.5 and 2 m/s.

Daghigh et al. [54] designed and analyzed the performance of heat-pipe evacuated tube collector for water heating and drying application. Water recovery system was used for the dryer to enhance the overall system performance. Maximum air temperature available for the dryer observed was 45.5 °C.

Koua et al. [55] conducted drying experiments using ITSD on cocoa beans. They investigated different parameters such as heat and mass transfer coefficients, shrinkage, density, porosity, which were essential to understand the drying behavior of cocoa beans. The results showed

that shrinkage decreased and porosity increased with decrease in MC. Density of cocoa beans reduced from 825.1 to 696.25 kg/m^3 during the drying process. Also, mass transfer coefficients, in cocoa beans drying, increased from 1.88×10^{-7} to 7.88×10^{-5} m/s, respectively. Effective moisture diffusivity values varied from 5.49×10^{-10} to 4.26×10^{-10} m^2/s.

Condorí et al. [56] developed two solar dryers and experimented with vegetables in Huacalera, Argentina. Each dryer consisted of a bunch of 10 solar flat plate collectors and a tunnel typed drying cabinet of 450 kg capacity. The total area of the collector plate was 92 m^2. The experiment was performed approximately for 16 h with onion slices to achieve the final MC of 8.26% from an initial MC of 81% (wb). The optimum collector efficiency was noticed at 0.4 kg/s for low temperature experiments. Optimum value was achieved at 0.23 kg/s when the air temperature was more than 50 °C. Investment return rate was found and it was 13 months. Fterich et al. [57] developed forced convection mixed solar dryer and performed the experiments with tomato slices. The dryer consisted of photovoltaic-thermal air collector (PV/T) and a drying chamber provided with trays. PV panels were provided with aluminium tube at the bottom for air flow and spread into upper gap which helped to cool the PV panel. MC of tomato was reduced from 91.94% to 22.32% for tray 1 and 28.9% (wb) for tray 2.

Wang et al. [58] presented forced convection ITSD with auxiliary heating source for mango drying. The system consisted of a fan, an automatic control system, evacuated tube SAC and drying chamber. The effect of drying air temperature on the performance of the system and drying behavior of mango slices was investigated. Average thermal efficiency was estimated and it ranged between 30.9% and 33.8%. The specific moisture removal rate was estimated and it was 1.67 kg water/kWh at a temperature of 52 °C. The moisture was reduced from 77.38% to 20% (wb). A similar forced convection study was performed by Téllez et al. [59] for drying red chilli.

Shrinkage behavior and its influence on the microstructural change of dates at three ripening stages (namely khalal, rutab and tamr), were analysed during forced convective ITSD by Seerangurayar et al. [60]. The microstructural analysis of date tissue was performed and compared with OSD and greenhouse tunnel dryer. The structure of the food is good in ITSD dryer compared to other two methods. The drying methods and ripening stages significantly affect shrinkage of dates. The correlations were developed in terms of quadratic equation for volumetric shrinkage of dates as a function of MC. A similar type of ITSD and its experimental analysis was carried out for drying Khalas dates at three ripening stages to find the drying kinetics, color and texture [61].

Experimental investigation of evacuated tube based ITSD was carried out during the drying of Phyllanthus Emblica (anvla), aloe vera and Aegle Marmelos (Indian bael) [62]. The maximum efficiency of the dryer was estimated to be 55%. The dried products obtained were free from contamination by insects, flies, birds and micro-organisms. SAC of ITSD was designed and developed from aluminum cans and its performance was investigated for drying of tomatoes at different flow rates (0.0042–0.0125 m^3/s) [63]. Aluminum cans helped to increase the efficiency of SAC from 25 to 63%.

More studies of drying and performance parameters of forced convection ITSD setups are listed in Table 2.

It is found that forced convection ITSD provides uniform distribution of airflow through trays and within the drying chamber. It helps to improve the heat and mass transfer between air and material; hence the drying rate is enhanced compared to natural ITSD and OSD. The thermal efficiency of the dryer depends directly on solar radiation and also the humidity in the air, which was not controlled during experiments. Controlling airflow rate is possible by adjusting the fan or blower speed. Numerical analysis may help to find the optimum airflow which can give better thermal efficiency. η_d increased up to 47.5% (Table 2) in the forced convection ITSDs which is low in natural convection setup (4–23.7%) (Table. 1).

Huge production is possible in forced convection ITSD setups as was evident when 200 kg pineapple [47], 450 kg of onion slices [56], 24 kg mango [58] and 50 kg of silk cocoons [42] were dried in this dryer. These dryers can be used to dry high and low MC agricultural products. If the product does not reach the required MC on the first day, the drying process can be continued by providing auxiliary heaters. It increases the production cost, but the quantum of food going waste can be reduced. The drying time saved is almost 40% in bitter gourd drying [43], 86% in mulberry drying [45] and 73% in silk cocoon drying [42] while compared with OSD drying. It's a huge success in forced convection ITSD dryers compared with OSD dryers, therefore this is an effective technique to dry food products quickly.

Forced convection ITSD needs to be further investigated numerically to enhance the performance of the system. The possible areas are; heat transfer enhancement in SACs, heat loss calculation in dryer and SAC, insulation required and thickness, uniformity of exposure of hot air in the drying chamber, etc. These studies will help to improve the performance of forced convection ITSDs further.

4.2.2. Forced convection ITSD with multi-pass SAC and recirculation of working fluid without TES

In some cases, instead of using single pass, multi-pass passage was provided in SAC for the flow of working fluid. This helps the working

Table 2
Performance of the force convection ITSD with single pass collector reported by some authors.

Load (kg)	MC (wb %)		Time (t)		t_{save} (h or day)	Air flow rate	Efficiency (%)		T_c (°C)
	MC_i	MC_f	OS	ITSD			η_{ic}	η_d	
Cauliflower [36]	92.05	5.92	–	28 h	–	4.81 kg/s	54.5	16.5	–
Beans [37]	65	18	–	1 day	–	0.8 m/s	–	–	–
10 kg grapes [37]	80	18	–	1½ day	–	0.3 m/s	65	–	20
10 kg Apricots [37]	80	13	–	2 ½ days	–	0.3 m/s	60	–	33
11.78 gm strawberry [39]	88.3	18.5	–	20 h	–	–	–	–	46.8
50 kg Silk cocoon [42]	60	12	70 h	19 h	51 h	480 m^3/h	–	8.8–9.2	50–75
bitter gourd [43]	91	6.25	10 h	6 h	4 h	1.47 m/s	–	–	101
Tomato [44]	93.4	11	–	11 h	–	–	–	2.5–35	50
Mulberry [45]	80	8	120 h	6–17 h	114–103 h	1.5,7.8,14,20,26,33,36 g/s	–	–	–
100 g shell pistachio [46]	70	26.95	> 6 h	6 h	–	1.23 m/s	–	–	50 ± 10
100 g unshelled pistachio [46]	70	29	> 6 h	6 h	–	1.23 m/s	–	–	–
200 kg pineapple [47]	82	10	8 h	–		1.2 m/s	52.55		40–67.3
Banana [53]	77.2	34.98	–	16 h	–	0.0338 m^3/s	29.63	4.96	45
4 kg mango [49]	80	13.79	–	3 days	–	0.022 kg/s	35.04		33.38–52.58
450 kg onion slices [56]	–	–	–	16 h	–	0.06 kg/s	30	30–35	50
24 kg mango [58]	77.38	20	–	13 h	–	0.07 kg/s	53.5	33.8	52
Dates [60]	–	–	–	–	–	0.05 m^3/s	–	–	29–62

fluid to harness more heat from the heated absorber. Fig. 5(a), (b) and –(c)– show the prototype of double-pass, triple-pass and recirculation type arrangement SACs. Several investigatots have used multi-pass SAC to increase the temperature of the air at its outlet.

Fudholi et al. [64] constructed a dryer with double pass solar dryer (DPSD) for seaweed drying. Red seaweed was dried from 90% to 10% (wb) MC in 15 h. It was mentioned that the dryer with double pass collector had a system efficiency of 35% and the same with single pass was 27% at 500 W/m^2 of average solar radiation and at 0.05 kg/s.

Banout et al. [65] developed a DPSD for chilli (C. Annuam) drying. This system reduced red chilli's MC to 10% from 90.21% (wb). Drying efficiency was estimated and it was 12.52% greater than that of the cabinet type dryer. The required 10% (wb) MC was obtained with system efficiencies of 24.04% and 11.52% for DPSD and the cabinet dryer, respectively. Also, the color value of products obtained by DPSD was better than that of cabinet drying and OS drying.

Fudholi et al. [66] analyzed a DPSD with auxiliary heating facility for red chilli drying. Red chilli was dried from 80% to 10% (wb) in 33 h at the mass flow rate of 0.07 kg/s and at an average solar radiation of 420 W/m^2. The efficiency of the collector and drying unit was 28% and 13%, respectively.

Sarsavadia [67] developed forced convection ITSD for analyzing the effect of different temperature, airflow and air fraction on the total energy requirement for onion slices drying. The drying system was

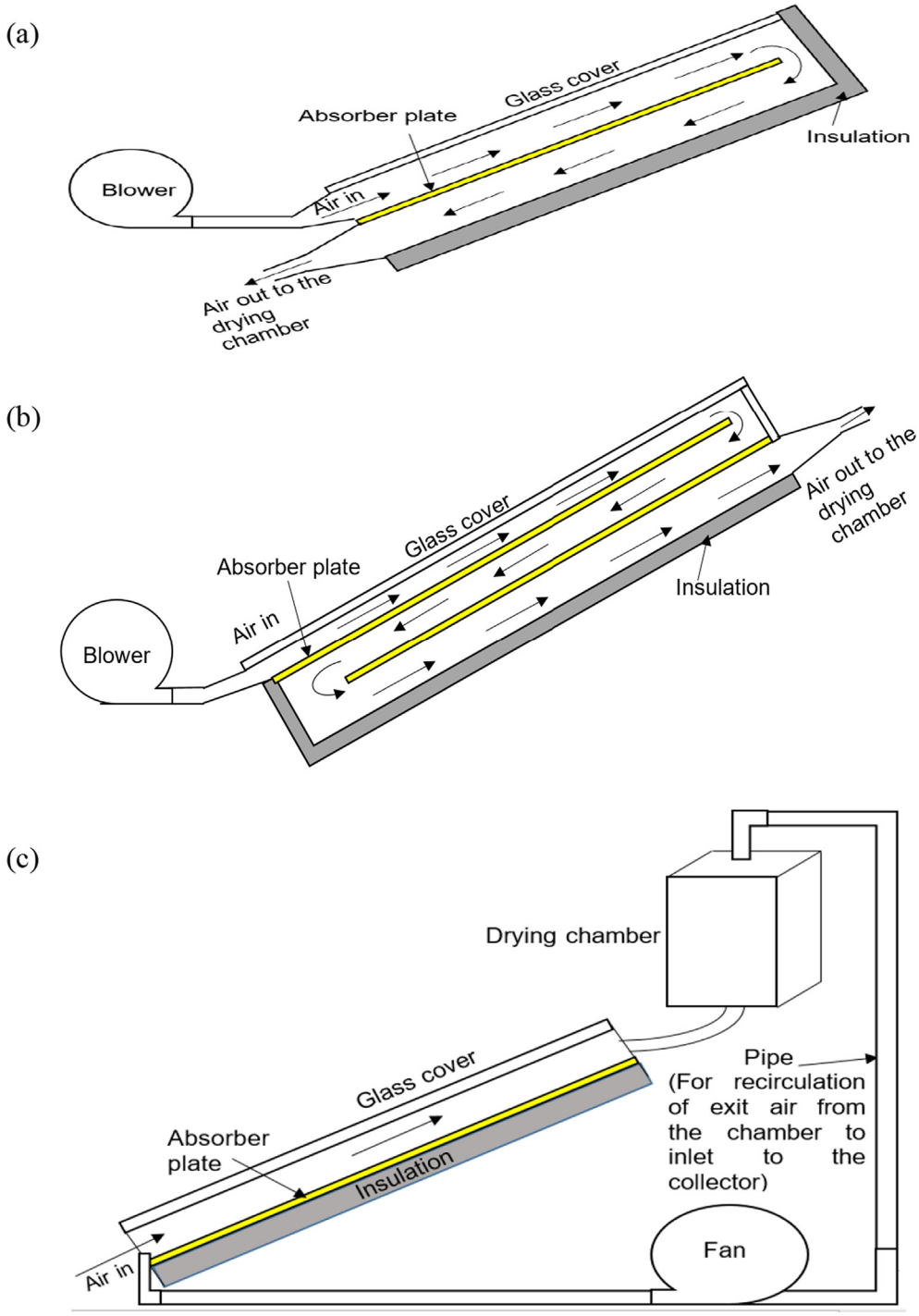

Fig. 5. (a) Double pass, (b) triple pass SAC and (c) recirculation type ITSD.

provided with SAC and it had corrugations and triangular obstructions over the absorber surface. The system had provision for recycled exhaust air. The experiment was performed for air flowrate of 0.135, 2.43 and 5.25 kg/s and air temperature of 55, 65, 75 °C. 90% of air was recycled during the drying experiments. A provision was in the set-up to conduct the experiments without recirculation of air. Onion slices were dried from an initial MC of 86% (wb) to a final MC of 7% (wb). Consumption of energy by SAH, electrical heater and blower for the system with no recycling of air was calculated and they were in the ranges of 24.5% and 44.5%, 40.2% and 66.9% and 8.6% and 16.3%, respectively and the same parameters were in the range of 22.4% and 40.9%, 33.6% and 62.6%, and 11.2% and 37.2%, respectively, for recirculation of air in the system. It was observed that the total energy saved was 70.7% because of recirculation of working fluid (air). It was concluded that the total energy requirement was increased when the air flow rate increased. Also, when air temperature increased, energy requirement decreased.

Chan et al. [68] developed a novel recirculation type drying chamber integrated with solar collector. The main components of this set-up were: centrifugal blower, transparent structure, feed hopper and pneumatic conveyor. A transparent system was used as a drying chamber which included hopper with the vortex. The set-up was tested with 104 and 200 kg of rough rice. Results showed that at a temperature of 50 ± 0.2 °C and RH of 21.73%, it took 5 h for 104 kg of rice to reduce the MC in them from 28.4% to 14.3% (wb). At the same time, 200 kg of rice required 8 h to reduce the MC in them from 27.6% to 14.3% (wb) with the same temperature and humidity maintained as in previous case. Drying efficiency was estimated and it was 22.4% for 104 kg and 31.7% for 200 kg, respectively. Similar analyses were carried out by Mokhtarian et al. [69] for the drying of pistachio where it was dried from an initial MC of 40–5% (wb). It was found that the drying time of pistachio was reduced by 30% using recirculation of air compared with the system without recirculation of air.

Komilov et al. [70] designed a unit comprising SAC and a heat storage system. Commercial paraffin was used as TES material. Existing air from the dryer was re-circulated through SAC and it was found that the overall efficiency of the system improved. It was concluded that experimental unit shortened the drying process by 4–5 times than air and OS drying, and the finished product was of high quality. It was concluded that the availability of solar energy storage and circulation led to the productivity and efficiency of the unit being increased by 1.5–2 times compared with similar units without storage and recirculation system.

Ezeike [71] designed a modular drying system with a triple-pass simple flat plate air heater, a dehumidification system and drying chamber. The top compartment was provided with baffle plates for uniform distribution of hot air. Dehumidification chamber was provided with silica gel desiccant to withstand the drying process during rainy or low incident radiation time. The system was tested with yam slices and paddy. Yam slices were dried to 10.66% from 64.90% (wb) in 31 h and paddy to 5.31% from 25.93% (wb) in 10 h, respectively. It was observed that the collector exit temperature was in the range of 90–101 °C with an average air velocity of 3.5 m/s. The average collector efficiency was estimated and they were in the range of 73–81%.

Blanco-Cano [72] developed a theoretical model on ITSD for maximum possible evaporation rate from food products by assuming vaporization of free water. A mathematical model was developed for estimating the temperature and the specific humidity of drying air. Results showed that the evaporation rate depended on the ratio of total drying area to the cross section area of the drying chamber.

Godireddy et al. [73] developed a mathematical model for solar drying of green peas. Moisture distribution was estimated at various drying temperature and different drying times. The influence of temperature on drying time was studied. It was observed that to achieve the final MC of 20% from an initial MC of 75%, green peas were dried for 7.31, 6.03, 4.63, 3.98 and 3.7 h at temperatures of 45, 50, 60, 70 and 75 °C, respectively.

Aktas et al. [74] analysed the drying kinetics of grapes using double pass SAC in ITSD and estimated its performance. Maximum thermal efficiencies of double pass SAC were estimated to be 79.85%. The effective moisture diffusivity was estimated and it was in the range of 9.15×10^{-11}–1.04×10^{-7} m^2/s.

Blanco-Cano et al. [75] used thermo-gravimetric analysis to determine the drying kinetics of Granny Smith apples at different temperatures in the range of 20–50 °C at intervals of 5 °C. Drying curve for apple was generated and compared with existing models. Akpinar et al. [76] presented a mathematical modelling of apricots drying in ITSD with rotary column cylindrical drying (RCCD). Apricots were dried from the initial MC of 74.8% (wb) to 16% (wb). Slimani et al. [77] proposed an ITSD which consisted of double pass PV/T hybrid SAC. They developed a numerical model for SAC of ITSD. They estimated the electrical and overall dryer efficiencies and they were 10.5% and 90%, respectively, at a mass flow rate of 0.0155 kg/s.

A detailed report of multi-pass SAC ITSD studies and their performance parameters are listed in Table 3.

It is found that for multi-pass solar dyers, the fabrication cost is significantly higher than for single pass SAC. Also, more design procedures are needed compared to single pass SAC dryers. The drying cost (which involves operation, maintenance and labour costs) per kilogram of the product is small in multi-pass SAC than single pass dryer because of lower drying time in multi-pass setups. Also, it is found that the specific energy consumption varies with the type of product used, drying time and capacity of the dryer. The drying chamber temperature of multi-pass dryers is in the range of 47–101 °C (Table 3) whereas it is in the range of 20–101 °C (Table 2) for single pass ITSD dryers.

In this specific area of multi-pass dryers, there is a sound need for numerical analysis as this area offers rich possibility of using numerical problems to improve the system performance. The contact area of hot

Table 3
Details of forced convection ITSD with multi-pass collector setup and drying and performance parameters.

Load (kg)	Number of passes	MC (wb %)		Drying time (h or days)	mass flow rate, (kg/s)	SEC (MJ/kg)	Efficiency (%)				T_c °C
		M_i	M_f				η_c	η_d	η_p	η_{ex}	
40 kg red seaweed [64]	Double pass	90	10	15 h	0.05	9.43	35	27	95	1–93	–
38.4 kg red Chilli [65]	Double pass	90.21	10	32 h	0.221	–	61.62	24.04	22.04	–	51.89
40 kg red chilli. [66]	Double pass	80	10	33 h	0.07	18.94	28	13	45	–	57
2.27 kg Onion slices [67]	Partial Recirculation	86	7	–	0.135	–	24.5–44.5	–	–	–	75
104 kg rough rice [68]	Partial Recirculation	28.4	14.3	5 h	–	10.7	–	31.7	–	–	50.1
200 kg rough rice [68]	Partial Recirculation	27.6	14.3	8 h	–	9.475	–	47.5	–	–	47
yam slices [71]	Triple-pass	64.90	10.66	31 h	–	–	73–81	–	–	–	90–101
rice paddy [71]	Triple-pass	25.93	5.31	10 h	–	–		–	–	–	
Pistachi[69]	Double pass	40	5		0.106						
20 kg Curcuma zedoaria [121]	Double pass	76.09	8.47	31 h	0.042	3.15	48.2	21.9	–	–	

air is huge in multi-pass dryers than single-pass dryers; therefore, there is enhancement of heat transfer, at the same time the possibilities of heat losses are more. Modelling the problem and running numerical simulations, heat losses can be identified so that an engineer can work further to reduce heat loss. Corrugations can be provided on the absorber plate to increase the turbulence effect and thereby increase the heat transfer coefficient between the absorber plate and air. Circular, triangular and square shaped corrugations can be used on both sides of the absorber plates. The type and dimensions of the corrugations can be optimized by modelling the problem and performing numerical simulations.

4.3. ITSD with heat energy storage

ITSD with heat or thermal storage system is useful for continuing the drying process after sunset so that processing time can be reduced significantly [78]. Solar heat can be stored in the form of SH and LH in the thermal heat storage devices as shown in Fig. 6(a), (b) and –(c)–. In Fig. 6(a) TES material is stored below the absorber plate. As TES material is directly in contact with the absorber plate, the heat energy is conducted from the absorber plate to TES system. In Fig. 6(b) TES material is placed in the heat exchanger or storage tank. Solar flat plate water heater is used to heat the water. This heat is transferred from water to TES material which acts as a heat exchanger. The heat stored in the heat exchanger can be utilised for heating the air for drying food products. TES material is kept at the bottom of the drying chamber as can be seen in Fig. 6(c). Hot air from the collector flows through the storage system where heat is absorbed by TES material and it can be utilised in off-sunshine hour [79]. In this section different ITSDs provided with heat storage system are reviewed.

4.3.1. ITSD with sensible heat (SH) storage materials

A forced convection ITSD setup was developed for copra drying by Mohanraj and Chandrasekar [80]. The set-up consisted of SAC, drying chamber and a centrifugal fan for forced air circulation. An inclined SAC (25° with horizontal) was provided with glass glazing while a black painted copper absorber plate below the glass cover with sand as SH storage material was filled between the gap of absorber plate and the layer of insulation (100 mm gap). The MC of copra was reduced to 7.8% (wb) for bottom tray and 9.7% for top tray in 82 h from 51.8% initial moisture. Dried copra was graded, such as 6% milling grade copra (MCG3), 18% (MCG2) and 76% (MCG1) as per the Bureau of Indian Standards. The solar dryer thermal efficiency was calculated as 24%.

Nabnean [81] designed and presented a dryer system for cherry tomatoes with heat storage system. Cherry tomatoes were osmotically dehydrated before solar drying. The dryer consisted of 16 m^2 of area SAC (water type), water heat storage system, heat exchanger and drying cabinet with a capacity of 100 kg. The cabinet dimensions were: width of 1.0 m, length of 3.0 m and height of 1.4 m. This study was made with a temperature variation of 30–65 °C. It took 4 days to dry 100 kg of tomatoes. Tomatoes were protected from insects, dust and rain during drying. The efficiencies of SAC were found to be in the region of (21–69%). Payback period was estimated and it was 1.37 years. The dryer can be used in tropical countries and it is useful for materials which are sensitive to solar radiation.

Potdukhe and Thombre [82] developed an ITSD with thermal storage system which was fitted with an absorber. Experiments were performed on fenugreek leaves (Trigonella Foenum-graecum) and chillies (Capsicum Annuum). Thermic oil was used as an energy storage material. Drying and collector efficiency was 21% and 34%, respectively. The required drying air temperature was maintained for a longer time period than usual because of the energy storage system. Thermic oil increased the system cost by approximately 10%, though, there was a 40% saving in drying time.

Shanmugam and Natarajan [83] built and tested desiccant integrated ITSD provided with a centrifugal blower. A desiccant bed with mirror arrangement was additional part of the dryer, and the bed was placed at the top of the dryer. 20% vermiculite, 10% calcium chloride, 60% bentonite and 10% cement were used in desiccant material and moulded in the shape of cylinders which acted as TES device. The performance of the drying system was analyzed while drying 20 kg of pineapple slices and green peas. The system was provided with reflective mirrors and a study was made to find the effect of reflective mirrors. It was observed that the mirror reduced the drying time by 4 h and 2 h for pineapple and green peas, respectively. The drying efficiency and pick-up efficiency varied in the range of 43–55% and 20–60%, respectively. It was concluded that desiccant with reflective mirror increased the drying potential considerably. Vlachos et al. [84] designed and tested tray dryer unit, where water was used as heat storage medium and carried out the experiment at full load, no load and with different climatic situations. Water was packed in 25 sealed metallic containers (5L each). Drying efficiency was estimated at 45% for the first 2 h. The food product dried completely at a satisfactory rate.

Jain [85] analyzed a crop dryer having an inclined multi-pass SAC with TES. Granite grits were used as storage material, which was placed below the absorber plate. The system performance was analyzed for drying paddy. The impact of the length and breadth of a collector,

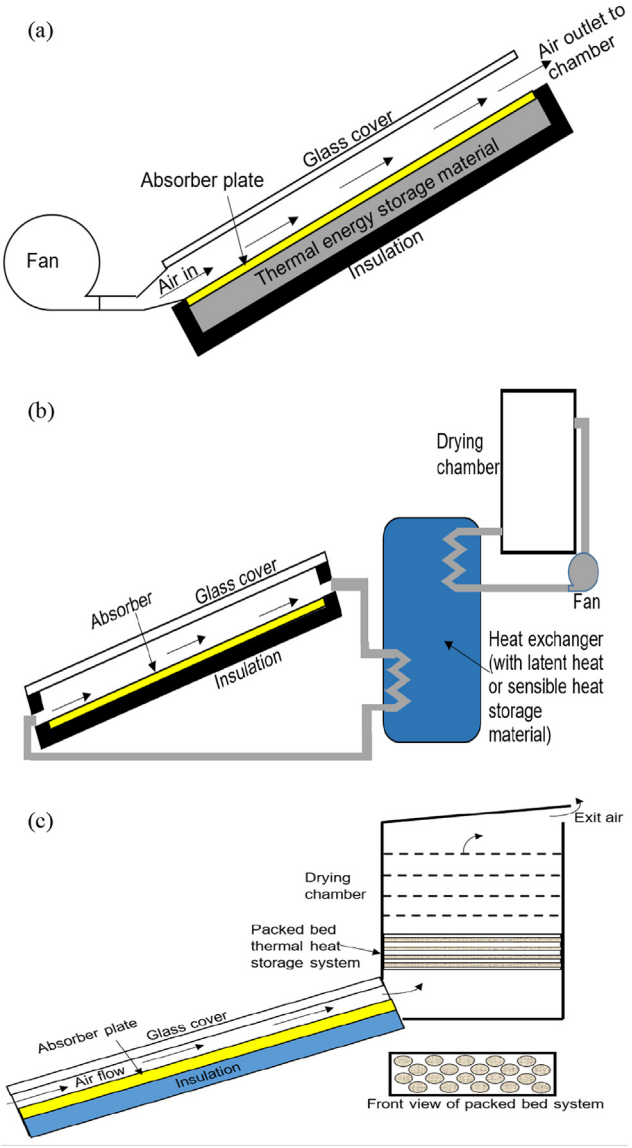

Fig. 6. Solar air collector with thermal storage material (a) below the absorber surface, (b) in heat exchanger and (c) inside the drying chamber.

change in collector angle, and flow rate of the working fluid (air) on the crop temperature were investigated. It was found that the temperature of the crop increased when collector dimensions and angle were increased. Crop temperature variation created different drying rates on different trays of the setup. Thermal efficiency of the system increased with a rise in crop mass.

Jain and Jain [86] proposed an analytical model to test the performance of a flat plate SAC with the TES for crop drying in multiple trays. The experiment was performed while drying paddy and moisture evaporation rate for different grain bed depth was analyzed. TES helped to heat the drying air in the off-sunshine period. It was also found that the drying rate as well as humidity of drying air increased with increase in grain bed depth.

Drying phenomenon of coriander was studied by Chauhan et al. [87]. Drying condition was achieved by a SAC with rock bed TES and drying bed arrangement for a thin layer of grains. The experiment was carried out with and without considering TES. MC in coriander decreased from 73.82% to 53.27 in 2 days (more than 18 h) and 1 night (13 h) with rock bed and 3 days (approximately 27 h of day time) without rock bed in SAC. It was observed that during sunshine the drying performance of coriander was affected by the depth of a thin layer of grain (varies from 0.2 to 1 m). 0.2 m depth of thin layer showed better drying rate. It was also observed that, air velocity didn't have any impact on the drying rate. It was concluded that TES was a better option to enhance the processing time.

Jain [88] used two absorber plate collector setups (one in top of drying cabinet and in bottom) with TES material packed at the bottom of the drying chamber for drying 95 kg onions (Fig. 7). The influence of TES system with natural convection was estimated and analyzed. The system thus designed was able to reduce the moisture content from 86% to 21.26% in 24 h.

Kareem et al. [89] performed experiments on Roselle (Hibiscus sabdariffa) drying to study the characteristics of multi-pass SAC. The system was assisted with granite to store SH. Different efficiencies were estimated and these were: collector efficiency; 64.08%, moisture pickup efficiency: 67%, drying efficiency: 36.22% and system optical efficiency: 70.53%. The system took 21 h less than OSD took. Payback period was estimated to be 2.14 years.

Aboul-Enein et al. [90] used an analytical model for flat plate SAC by considering SH. This study was conducted for the climatic conditions of Tanta, Egypt. The influence of different design configurations such as length, width, air gap, air flow rate, and thickness on outlet of SAH was studied by considering different thermal storage materials (sand, water and granite). Results showed that the average temperature difference, after sun-set and between the times of exit air and fresh atmospheric air was 32.7, 21.8 and 29.0 °C for sand, water and granite, respectively. It was observed that the exit temperature of the air at exit decreased with increased air gap and volume flow rate of air. The optimum thickness of storage material was found to be 12 cm where improvements in performance were observed, which helped to continue the drying process during the night.

El-Sebaii et al. [91] used sand as thermal heat storage material which was placed below the absorber of ITSD. Experiments were conducted without and with sand for fruits (apples, figs and seedless grapes) and vegetables (onions, tomatoes and green peas). Chemical pre-treatment was carried out by dipping the cut pieces for 60 into the boiled water with 0.3% NaOH and 0.4% olive oil. It was noticed that the dying process reduced to 12 h because of the use of TES device. Chemical pre-treatment of seedless grapes helped to reduce the drying time by 8 h using TES device. It was mentioned that pre-treated food products reduced the resistance offered by the outside membrane against mass transfer. Vijayan et al. [92] also conducted a similar study for the drying of bitter gourd.

Chaouch et al. [93] developed an ITSD integrated with pebble SH storage setup. The storage setup was placed in two locations; one was below the drying chamber and the other was below the SAC. SH storage system helped to enhance the thermal efficiency of SAC and drying chamber by 28% and 11.8%, respectively. The system also got an extra hour of required heat after sunset. Performance analysis was carried out by drying camel meat. They suggested that Logarithmic and Midilli-Kucruk models were most suitable in July and November, respectively. The average efficiencies of 18.34% and 15.52% were noticed in July and November, respectively. They reported that pre-treated meat with salt helped to maintain the desired quality.

Satyapal and Chandramohan [94] developed a 2-D numerical model using ANSYS FLUENT 2015 for solar drying of agricultural product in ITSD incorporated with paraffin wax as PCM. Air flow and heat transfer analysis was carried out on a single set of concentric tube with finned copper tube (inner side) and plastic tube (outer side) containing PCM material. The temperature profile of the setup and distribution of melting and solidification fraction of PCM were calculated at different inlet temperature of air, flow velocities and time. It was found that drying process can be continued for about 4–5 h after sunset with the help of solar energy which was stored in PCM during sunshine. The maximum temperature achieved at the system outlet was 341.62 K. Quick melting (charging) and quick cooling (discharging) of PCM were observed for higher air flow velocity. They suggested that higher air flow velocity did not create any impact on ITSD system. Ramakrishna et al. [95] also reviewed some SH storage material used for different application which can be used for ITSD.

Properties of SH storage material used in ITSD are presented in Table 4. ITSD setups with SH and LH materials are reviewed in further sections.

Drying and their performance parameters of ITSD setups with energy storage materials are presented in Table 5.

Dryer with SH storage system helps to reduce drying time and improve the quality of the dried product. With TES system, it is possible to continue the drying process even at off-sunshine hours. The crops may face non-uniform drying rate in ITSD without TES system because of the non-availability of solar energy after sunset, which can be avoided in dryers with TES system and it is very essential for crop drying applications. Mathematical models can suggest the quantity of TES material required for a given mass of the material to be dried based on the temperature that is to be maintained inside the chamber.

There are some natural and inexpensive substances such as water [81,84,90], granite [85,86,89,90], rock [87], sand [90,91], dry brick, fire brick, waste concrete [95] and pebbles [96,97] which are used as ensible heat (SH) materials. There are some chemical materials (thermic oil [82] and desiccants [83] which are also used as TES materials for low temperature application such as food drying. The heat capacity (multiplication of density and specific heat) of the material is responsible for storing heat energy within the substance; therefore, it should be high for the selected storage materials for solar dryer. The design complications are less if the selected TES material is in solid

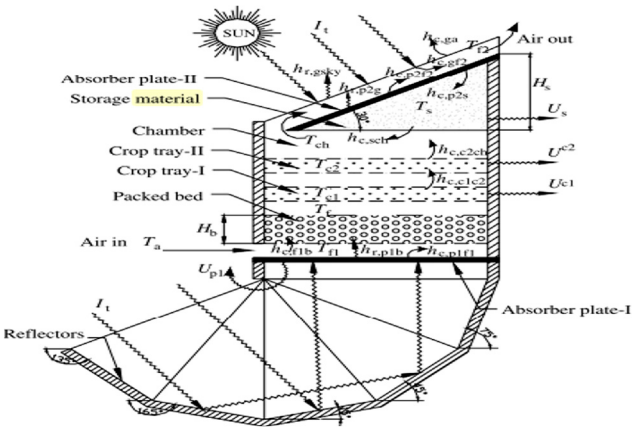

Fig. 7. Reverse absorber cabinet dryer [88].

Table 4
Properties of sensible heat (SH) storage material.

Material	Temperature (°C)	Density (kg/m^3)	Specific heat (J/kg)	Thermal conductivity (W/m·K)	Literature
Water	0–100	1000	4190		Nabnean [81], Vlachos et al. [84] and Aboul-Enein et al. [90]
Thermic oil	160	888	2400		Potdukhe and Thombre [82]
desiccant material	–	–	–	–	Shanmugam et al. [83]
Granite	–	2400	790	1.6–4	Jain [85], Jain and Jain [86], Kareem et al. [89] Aboul-Enein et al. [90]
Rock	200–300	2560	879	1	Chauhan et al. [87]
Sand	200–300	–	1.3	1	Aboul-Enein et al. [90], El-Sebaii et al. [91]
Dry brick	200–800	1600	840	0.5	Ramakrishna et al. [95]
Silica fire bricks	200–700	1820	1000	1.5	
Concrete	200–400	1900–2200	850	1.5	
Pebble stones	–	1920	835	–	Atalay [96], Vijayan et al. [97]

state. Water [81] or other liquid chemical substances [82] are used as TES material; therefore, the design and fabrication procedures of the dryer system become complicated.

By providing SH materials, the drying time is saved by up to 50% while drying fenugreek leaves [82] and copra [80] and 60% for drying Roselle (Hibiscus sabdariffa) [89] compared to OSD drying. 14.28% of drying time is saved during the drying of pineapple slices [8] in the dryer with SH storage facility compared to the dryer without storage. Similarly, the drying time saved for green peas [83] is 10.5% and bitter gourd [92] is 42.8%.

Drying efficiency (η_d) of single pass solar dryer is in the range of 2.5–35% (Table 2) during the drying of various food materials. The range of η_d increased from 13% to 47.5% (Table 3) in the case of double pass solar dryers and 13.5–55% (Table 5) in the case of solar dryers with energy storage SH materials. It shows the importance of TES system in solar food drying applications.

4.3.2. ITSD with latent heat (LH) storage material

It is easy to design a solar dryer with SH storage and have low cost but the problem related to SH storage is low heat storage capacity per unit volume and it has non-isothermal characteristics during heat exchange. LH storage using phase change material (PCM) is a possible solution as it has high LH capacity and isothermal conditions can be maintained during melting and solidifying and it requires only a small volume [98]. The required properties of PCM are high specific heat, density, thermal conductivity and heat of fusion. Also, it should be non-toxic, chemically inert, of stable composition and economical [99]. Very limited data is available related to the application of LH storage in ITSD. In this section, LH storage incorporated in ITSD is reviewed.

Akmak and Yildiz [100] developed an ITSD consisting of an expanded surface SAC and SAC with PCM and drying chamber with swirl arrangement to reduce drying time. Experiments were conducted with and without swirl flow on seedless grapes to study the drying kinetics and to analyze the performance of the system at three different velocities. Moisture content reduction from 75% to 8.26% (wb) took 56 h with PCM and swirl, 80 h without PCM with swirl, 104 h without PCM and swirl and 200 h in OSD.

Shalaby and Bek [101] developed ITSD with PCM for TES. This study experimentally investigated for different ranges of mass flow rates of volatile oil herbs of Thevetia Neriifolia and Ocimum Basilicum under zero load condition, with and without PCM. The system produced drying air temperature was 7.5 °C more than atmospheric temperature after sunset. It was observed that 0.1204 and 0.0894 kg/s mass flow rates gave maximum temperature with and without PCM, respectively. The herbs reached final MC after 12 h for the system with TES system, but they took 18 h in the system without TES. It was concluded that a system with TES was suitable for drying medicinal plants which contain volatile oil.

Esakkimuthu et al. [102] developed an ITSD provided with an inorganic salt based PCM HS58. The ITSD dryer consisted of a SAH (with double pass V corrugated absorber), a packed bed type HS 58 unit tank, and a drying chamber. GI sheet with glass wool insulation was used for making TES tank. Polyethylene spherical balls filled with HS 58 were placed inside TES tank. Mass flow rate was maintained at 200 kg/h. The proposed system with PCM balls provided uniform temperature profile with low energy consumption.

Jain and Tewari [103] designed and constructed a solar crop dryer with TES. The dryer included a solar flat plate SAC, packed bed PCM energy storage, a chamber with a capacity of 12 kg for fresh leafy herbs and natural ventilation system. The thermal energy stored by PCM was effectively utilized for the next 5–6 h after sunset. The temperature was maintained at 6 °C more than that of atmospheric temperature till midnight. Dryer thermal efficiency was estimated and it was 28.2%. Also, economic analysis was made and it was reported that the payback

Table 5
Drying and performance parameters of ITSD with SH storage system reported by some studies.

Load (kg)	MC (wb%)		Drying time (h or days)			t_{save}	flow rate (kg/s)	Drying rate (kg water/kg dry matter-min)	Efficiency (%)			T_c °C
	MC_i	MC_f	OS	Without storage	With thermal storage				η_c	η_d	η_p	
60 kg copra from 160 kg nuts [80]	51.8	7.8	168 h	–	84 h	84 h	–	–	24	–	–	43
100 kg Queen cherry tomatoes [81]	59–62	15	–	–	4 days	–	–	–	21 to 69	–	–	30–65
1 kg fenugreek leaves [82]	–	–	2 days	–	1 day	1 day	–	–	34	21	–	–
2 kg of chillies [82]	–	–	15 days	–	4 days	11 days			34	13.4–15.2	–	
20 kg green peas [83]	80	5	–	21 h	19 h	2 h	0.035	2.3	–	43–55	15–45	
20 kg pineapple slices [83]	–	–	–	32 h	28 h	4 h	–	10	–	–	52–62	–
75.2–81.3 kg Roselle [89]	85.6	9.2	35 h	–	14 h	21 h	0.02–0.07	–	64	36.2	66.9	57
Onion [72]	57.84	21.26	–	–	–	–	0.032–0.046	–	–	–	–	70
4 kg Bitter gourd [92]	92	9	10 h	7 h	–	3 h	0.0636	–	22	19		40–50
Orange slices drying [96]	93.5	10.76		7	7.2	–	–	–	–	34.36		45.25

period was 1.5 years.

El-Khadraoui et al. [104] designed and constructed a solar dryer with TES system. The dryer consisted of a solar air panel, SAC with PCM provision and a drying cabinet. Experiments were performed to estimate the charging and the discharging behavior of PCM. The daily energy and exergy efficiency of the SAC with PCM cavity was 33.9% and 8.5%, respectively. It was concluded that SAC with PCM cavity produced a temperature difference of 4–16 °C inside the drying cabinet throughout the night. Also, RH in the drying cabinet was in the lower range (17–34.5%) than that of ambient RH.

Drying kinetics of sweet potato was analyzed by Devahastin and Pitaksuriyarat [105] for a system where paraffin wax was used as TES material. This system was provided with a temperature controller, a solar heater, a compressor and cylindrical acrylic LH storage device. It was concluded that at an air velocity of 1 m/s, LH storage could save approximately 34% energy during drying and the same was 40% at 2 m/s.

El-Sebaii and Shalaby [106] used ITSD for the drying of Thyme leaves (Thymus Vulgaris) using four different methods (drying whole leaves with and without PCM and drying of cut leaves with and without PCM. Leaves were cut in order to reduce drying time. When the ITSD was tested without PCM, Thyme leaves were dried from an initial MC of 95% (wb) to a final MC of 12% (wb) in 126 and 56 h for whole leaves and cut leaves, respectively. Hence cut leaves reduced the drying time by 70 h than whole leaves. When the ITSD was tested with PCM, Thyme leaves were reduced to a final MC of 11.97% (wb) for whole leaves and 11.77% (wb) for cut leaves in 84 and 28 h, respectively.

Bhardwaj et al. [107] performed an experimental study on ITSD incorporated with PCM (Paraffin RT-42) for the drying of Tagar herbs (Valeriana Jatamansi) at Himachal Pradesh (India). MC of rhizomes was reduced from 89% to 9% (wb) in 5 days. Results showed that 37.5% and 64.29% reduction in drying times were noticed using the system with PCM compared to heat pump drying. Also it was observed that dried rhizomes were superior in quality.

Baniasadi et al. [108] developed an efficient and cost effective mixed-mode solar dryer with LH storage to continue drying after the sunset. A fan was provided for air flow which was operated by photovoltaic panels. TES unit was made of copper coil and the PCM used was granulated paraffin (melting Temperature 70 °C). Fresh apricot slices were dried and the effect of TES system was studied by conducting experiments with and without TES system. It is reported that TES system helped to extend the drying process after sunset. Drying and thermal efficiencies of the dryer were 10% and 11%, respectively. Bhardwaja et al. [109] developed an ITSD integrated with SH storage material (engine oil) and LH material (Paraffin RT-42). Drying experiments were performed with Valeriana Jatamansi (Tagar). The product lost its MC from 89% to 9% (wb). Both SH and LH TES helped to improve the drying rate which was almost double when compared to dryer without TES and OSD. Drying time of 120 h, 216 h and 336 h were noticed in dryer with TES, without TES and OSD, respectively, to achieve the final MC of 9%.

Agarwal and Sarviya [110] used an ITSD dryer with paraffin wax in the shell and tube type LH storage system. The effectiveness of the use of PCM during the drying of potato slices and their drying kinetics was studied. The result showed that, during extraction of heat from LH storage, hot air temperature was in the range of 5–19 °C for approximately 10 h. Hence it was concluded that LH storage system was useful for drying application after sunset. Thermodynamic analysis on solar dryers during drying of garlic cloves was carried out by Shringi et al. [111] where the MC of garlic cloves was reduced from 55.5% to 6.5% (wb) in 8 h. The energy efficiency was in the range of 43.06–83.73%. Properties of some LH storage material used by different studies are reported in Table 6. Similar studies are found in Iranmanesh et al. [112], Reyes et al. [113] and Vásquez et al. [114].

It is found that charging LH storage material happens in natural convection as heat transfer takes place from hot air to PCM. PCM helps to maintain the drying air temperature almost constant as the fluctuation is low. It is a good characteristic in LH storage dryers which is difficult to achieve in other dryers even in SH storage system. Dryer with LH storage is suitable for drying medicinal plant as these leaves contain volatile oil [96,101,102,104]. It provides heat continuously to the drying cabinet even after sunset or when the intensity of solar energy is low. It reduces the processing time for drying and hence plays a major role in energy saving and enhances system performance. The selected LH storage material should be with low melting temperature. Most of the time, paraffin wax is preferred as LH storage material [68,96,100,102,105] because of its melting temperature of 55 °C, easy availability and low cost. Some studies used other inorganic salts such as HS-58 [102], calcium chloride [100] etc.

The temperature difference of up to 19 °C is noticed [108] in the drying chamber with ambient air by providing LH storage material; therefore, the drying process continued after sunset. 43% drying time was saved while drying seedless grapes [100] using LH storage material compared to the system without PCM. Similarly, 50% drying time was saved during the drying of herbs (Thevetia Neriifolia and Ocimum Basilicum) [101] and Thyme leaves [106]. 80% drying time was saved while drying Valeriana Jatamansi (Tagar) with and without PCM. The drying time saving of system with PCM was 180% compared with OSD method [109]. LH storage with forced convection setups increased the drying rate of sweet potato [105]. 34% energy was saved while the air velocity was maintained at 1 m/s and 40% energy was saved when the air velocity increased to 2 m/s. A maximum drying efficiency of up to 39.9% was achieved at the dryer with PCM and at the mass flow rate of 0.025 kg/s during the drying of apple slices [112].

Table 6
Properties of some latent heat storage material.

PCM	Melting Temperature (°C)	LH, (kJ/kg)	Specific heat (kJ/kgK)		Thermal conductivity (W/mK)		Density (kg/m^3)		Literature
			Liquid	Solid	Liquid	Solid	Liquid	Solid	
Paraffin wax	41–55	176	2.8	–	0.21		835	–	Komilov et al. [70], Agarwal and Sarviya [110]
Calcium chloride hegzahidrat	–	–	–	–	–				Akmak and Yildiz [100]
Paraffin wax 5.2 kg	49	173	–	–	0.167		790	–	Shalaby and Bek [101]
HS-58 Inorganic salt	57–58	250	2.5	–	–		1290	1400	Esakkimuthu et al. [102]
Paraffin wax 60 kg	35–54	196.1	2.44	2.35	–		786.1	833.6	Devahastin and Pitaksuriyarat [105]
Paraffin wax RT-42	42	165	2	–	0.2		880	760	Bhardwaj et al. [107]
Paraffin wax 59.5 kg	55	220	2.38	1.85	0.15	0.40	778	861	Reyes et al. [113]
—	87	180	2.65	–	0.5		1540	1630	Shringi et al. [111]

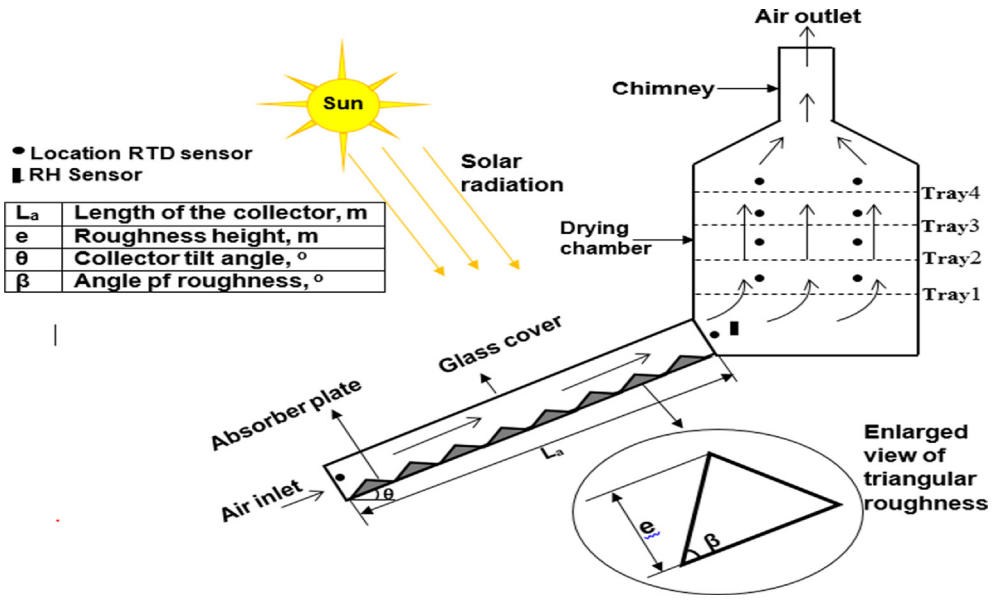

Fig. 8. ITSD with V- shape corrugated absorber surface for SAC.

Table 7
Performance of ITSD having flat collector with roughened, corrugated absorber reported by literature.

Author	Corrugation type	Material used	Coating
Pangavhane et al. [13]	U-shaped with fin	Aluminium absorber Aluminium fin	painted matte black
Kadam and Samuel [36]	V-grooved	Galvanized iron sheet	Black coated
Al-Juamily et al. [37]	V-groove	Galvanized steel	Black paint with 5% dark chromium powder
Vijayan et al. [92]	V-shaped	Galvanized Iron	Black coated
Sarsavadia [67]	U-corrugated with Triangular fin	Aluminum absorber Aluminium fin	Dull black color
Esakkimuthu et al. [102]	V- corrugated	Aluminum absorber	Black paint
Abhay et al. [117]	Square shaped	Aluminum absorber	Black paint

4.4. ITSD using collector with corrugated absorber surface

The collector with a roughened surface absorber or corrugated absorber as shown in Fig. 8 helps to improve heat transfer rate by creating turbulence in the path of air flow. This provision is used to enhance the heat transfer coefficient between air and the absorber plate. Also, in recent years, the performance of drying system has improved because of artificial corrugation over SAC [115–117]. Table 7 shows the details of the ITSD with a flat plate SAC and corrugations over absorber plate.

Several studies have been conducted on the duct of SAC with corrugations of different shapes as mentioned in Table 7. SAC is the most important component of ITSD, as the performance of dryer totally depends on SAC. There were a number of corrugation patterns used by researchers such as U-shape [13], V-groove [36,37,92,102] and square-shaped [117] for the analysis. Some studies identified superior performance when SAC was made with corrugations and fins [13,67]. Some studies were designed with experimental setups having corrugations [36,37,67,102], but what factors were considered while fixing the dimensions of corrugations is not mentioned. These data are essential while designing such type of dryers. The optimized height, length and angle involved in the corrugations need to be identified so that the system can give the maximum efficiency. This may be one of the thrust areas for future researchers.

The materials used for absorber plate and corrugations are aluminium [13,67,102,117], galvanised iron [36,92] and steel [37]. In usual case, these corrugations rusted after six months, therefore increasing the chance of degrading the performance of the system. For longer use, galvanised iron and steel metal can be used to avoid rust formation on the corrugation surface [36]. This topic also needs to be studied elaborately so that one can design the system for longer life of the dryer.

4.5. Comparison of advantages and disadvantages of various ITSDs

The advantages and disadvantages of various ITSDs are mentioned in Table 8. There is a similarity in all ITSDs in that the products are protected from direct ultra-violet radiation compared to OSD drying.

4.6. Effect of chemical pre-treatment before drying

Pre-treatment of the product to be dried is one of the important methods to increase drying rate and hence reduce time required for drying. Chemical pre-treatment is used to enhance the mass transfer from the outer surface of the product as it reduces moisture resistance of the surface. In some cases, it helps to maintain the chemical composition of the dried product.

Dhalsamant et al. [118] analyzed the effect of pre-treatment in a mixed type solar dryer. The sample object taken was potato with different dimensions (length = 50 mm and various diameters of 8, 10 and 13 mm). Surface structures of the dried potato were analyzed by X-ray diffraction analysis, atomic force microscopy and scanning electron microscopy. The structural investigation showed that the pre-treated samples were more porous and had firmer structure. It was found that the porosity of pre-treated potato slices was 18.8%, 17.5% 16.7% more than that of the normal slices of 8, 10 and 13 mm diameters, respectively. It was concluded that sodium metabisulfite pre-treatment was an effective method for maintaining the good quality of dried products with low shrinkage and high porosity. Table 9 shows the influence of

Table 8
Different types of ITSDs with their advantages and disadvantages.

Type	Sub-type	Advantages	Disadvantages
Natural Convection ITSD		• Simple in design and easy to fabricate. • No commercial energy required. • Fabrication, operational and maintenance costs are low. • It is used for the materials with low temperature requirement.	• Low efficiency compared to other types of ITSD. • There is no control over the temperature and velocity of flowing air; hence difficult to control the drying rate. • Not useful for material which requires high drying temperature.
Forced convection setup ITSD	Forced convection ITSD with single pass SAC	• Simple in design and easy to fabricate. • Fabrication and maintenances costs are less. • Control over the drying is possible by controlling the flow rate of air with the help of fan or blower. • Drying is possible with and without fan.	• Low efficiency and low temperature compared to multi pass ITSD. • Needs electric power for fan or blower.
	Forced convection ITSD with multi-pass SAC	• Fabrication and maintenance costs are more compared to natural ITSD. • Controlling the drying rate is possible	• Complex in design and structure. • It cannot work without fan or blower, so needs continuous electric power.
ITSD with heat energy storage	ITSD with sensible heat (SH) storage materials	• This concept can be incorporated in all types of ITSD. • It helps to continue the drying process during off sunshine hour. • Useful for products with high initial MC and products which take much drying time.	• Fabrication and maintenance costs are more compared to ITSD without TES system. • It requires special design to exchange heat between TES and flowing air.
	ITSD with latent heat (LH) storage material	• *Constant temperature of drying air can be achieved.* • It helps to continue the drying process during off sunshine hour. • Useful for products with high initial MC and the products which takes more drying time.	• Fabrication and maintenance costs are more compared to ITSD without TES system. • Lower heat transfer rate between PCM and the air during discharging. • It requires special design to exchange heat between TES and flowing air.
ITSD using collector with corrugated absorber surface	It may be natural type of force type with and without thermal energy storage system	• It helps to enhance the heat transfer rate between the absorber surface and flowing air. • Overall performance of SAC is better than flat plate absorber. • Useful for the products with high temperature requirement.	• Corrugated surfaces create more frictional losses which increases pumping power requirement. • More design calculations needed to other ITSD types.

Table 9
Effect of pre-treatment on drying reported by some authors.

Material/literature	Pre-treatment	Effect on drying time	Effect on quality
Strawberry [39]	Different solution such as 1% sodium metabisulphite and 1% citric acid, 1% ascorbic acid and 1% citric acid, 1% citric acid, and 2% sodium metabisulphite.	Reduce the dying time	No effect on the chemical composition of strawberry
Hossain et al. [40]	8 g/L sodium metabisulphite	Improved the color of dried and tomato prevent microbial growth.	Significantly reduced the color, ascorbic acid, lycopene, and total flavonoids of tomato
Cherry tomatoes [81]	blanched in boiled water for 5 min and soaked in 40% of sugar solution for 72 h	Reduced the dying time	Changes in color, no effect on chemical composition
Seedless Grapes, green peas [91]	Whole product deed into boiled water with 0.3% NaOH and 0.4% olive oil for 60 s	Reduced the dying time significantly	—
Apples, onions, figs, tomatoes [91]	Cut pieces deed into boiled water with 0.3% NaOH and 0.4% olive oil for 60 s	No effect on drying	—
Camel meat. [93]	4 kg of Camel meat were sliced with a thickness of 1 cm and pre- treatment with salt	—	Salting before drying acts as an anti- microbial and protects against microbiological degradation meat, which is a good source of protein containing about 20–23%. Which indicated that protein level has been better preserved by the indirect drying
Potato slices [118]	Sodium Metabisulfite	Reduce the dying time	Good quality of dried potato slices with low shrinkage and high porosity

pre-treatment on drying, reported in the literature.

It is proved that pre-treatment of the material before drying helps to preserve the nutritional and protein content in the final dried product, especially in ITSD [90]. Different chemicals were used in the pre-treatment phase: sodium metabisulphite [39,118], citric acid, ascorbic acid [39] and NaOH solution [91]. There were some natural substances such as salt [93], olive oil [91] and sugar solution [81] which were used for the pre-treatment process.

Pre-treatment process is used to reduce drying time. At the same time, the natural flavour and taste of food need to be maintained after drying. For confirming this statement, there was no reliable information available in the literature. The advantages and disadvantages of adding these chemicals with food before drying need to be investigated thoroughly. It is mentioned that the chemical composition of dried strawberries did not change because of adding sodium metabisulphite as a pre-treatment substance [39]. Similarly, the chemical composition of cherry tomatoes also did not change during pre-treatment process [81]. Microbial activity is reduced during the drying of camel meat with the pre-treatment process with salt. Therefore, the degradation of protein content in the meat is avoided [93]. It is also reported that the color of

Table 10
Dryer life, payback period and cost of indirect solar dryer.

Literature	System life	Payback period	Cost of dryer
Boughali et al. [44]	15 years	1.27 years	192319.25 Da (1 US$ = 70 Da)
Sreekumar [47]	20 years	0.54 year	Rs. 550,000* (1US$ = Rs. 45)
Condorí et al. [56]	—	13 months	—
Banout et al. [65]	10 years	3.26 year	2700 US$
Nabnean et al. [81]	15 years	1.37 years	5370 USD
Kareem et al. [89]	—	2.14 years	—
Jain and Tewari [103]	10 years	1.57 years	Rs. 1.00.000/−(1 US$ = Rs. 69)
El-khadraoui et al. [120]	20 years	1.6 years	—
Vijayan et al. [97]	35 years	2.1 years	Rs. 10894/-

the product is degraded in drying with pre-treatment process [42,78]. It is also observed (Table 9) that the drying time of the pre-treated material varied based on the type of materials.

4.7. Payback period and cost analysis

The total cost of the dryer is based on a number of economic parameters which depend on the economic situation in the country.

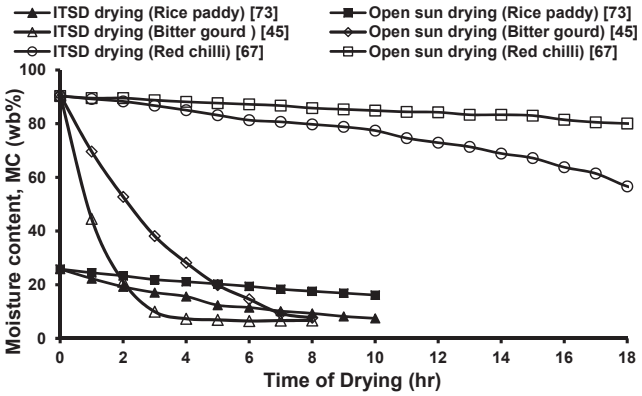

Fig. 9. Effect of ITSD drying over open sun (OS) drying.

Economic parameters considered for payback periods are: capacity of dryer, cost of the dryer, cost of electrical consumption, cost of maintenance, cost of raw material, life of dryer, depreciation and labour cost. The payback period [119] can be estimated by,

$$Payback\ \ period = \frac{Initial\ \ Investment}{Annual\ \ Net\ \ Undiscounted\ \ Benefits} \quad (14)$$

El-khadraoui et al. [120] reported an experimental study for investigating the performance of forced convection mixed type

Table 11
Initial and final moisture contents and permissible temperature limits of food materials.

Fruits or Vegetable	Author	Moisture Content (wb%)		T_{max} °C	Required Final MC (wb%) [122–125]	Allowable T_{max}. (°C) [122–125]
		Initial	Final			
Green chilly	Parikh and Agrawal [28]	–	–	47.3	5	48
Potato (S. tuberosum)	Parikh and Agrawal [28]	28.01	12.05	47.3	13	75
	Devahastin and Pitaksuriyarat [105]	–	13.04	60		
Grapes	Pangavhane et al. [13]	77.75	14.53	69.5	15–20	70
	Al-Juamily et al. [37]	80	18	64		
	El-Sebaii et al. [91]	80	18	46.5		
Paddy	Ezeike [71]	25.93	5.31	90	11	50
	Chan et al. [68]	28.4	14.3	50		
	Jain et al. [86]	28	11	61		
Cauliflower (Bras-sica oleracea)	Kadam and Samuel [36]	–	–	–	6	65
Green Beans	Al-Juamily et al. [37]	65	18	48	5	75
Apricot	Al-Juamily et al. [37]	80	13	54	–	–
Strawberry	El-Beltagy et al. [39]	88.3	18.5	46.8	–	–
Silk cocoon (Bombyx Mori)	Singh [42]	60	12	75	–	–
Bitter gourd (Momo-rdica Charantia)	Sundari et al. [43]	91	6.25	131	– –	–
Mulberries (Morus)	Akbulut and Durmus [45]	80	8	45	10	65
Amelie mango	Dissa et al. [49]	–	13.79	70	10–12	–
Mango	Wang et al. [58]	77.38	20	65–67	10–12	–
Red Chilli(Capsicum Annuam)	Banout et al. [65]	90.21	10	64.30	5	48
	Fudholi et al. [66]	80	10	–		
	Potdukhe and Thombre [82]	–	–	65 ± 3	–	–
Copra	Mohanraj and Chandrasekar [80]	51.8	7.8	62	5	
Yam	Ezeike [71]	64.90	10.66	90	10	65
Onion	Condorí et al. [56]	–	–	80–90		
	Sarsavadia [67]	86	7	75	10	55
	El-Sebaii et al. [91]	95	7	–	–	–
Tomato	Nabnean et al. [81],	59–62	15	65	7	60
	El-Sebaii et al. [91]	85	6	55.5		
Green peas	Shanmugam et al. [83]	80	5	60	5	60
	El-Sebaii et al. [91]	80	5	55.5		
Pineapple	Shanmugam et al. [83]	86	27	60	10	65
Coriander	Chauhan et al. [87]	28.2	11.4	50	–	–
Roselle	Kareem et al. [89]	85.6	9.2	57	–	–
Figs	El-Sebaii et al. [91]	70	20	55.5	20	70
Apple	El-Sebaii et al. [91]	82	13.5	55.5	11–14	65–70
Rhizomes	Bhardwaj et al. [107]	89	9	60	–	–
Garlic cloves	Shringi et al. [111]	55.5	6.5	98	–	–
Red pepper	ELkhadraoui et al. [120]	92.36	14.65	54.68	13	–

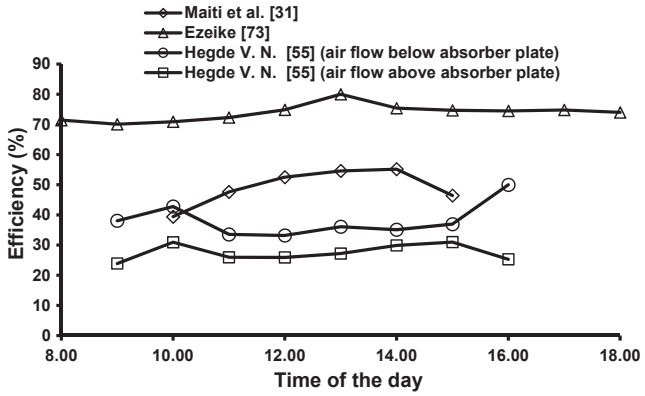

Fig. 10. Efficiency variation of triple pass indirect type solar dryer with respect to time.

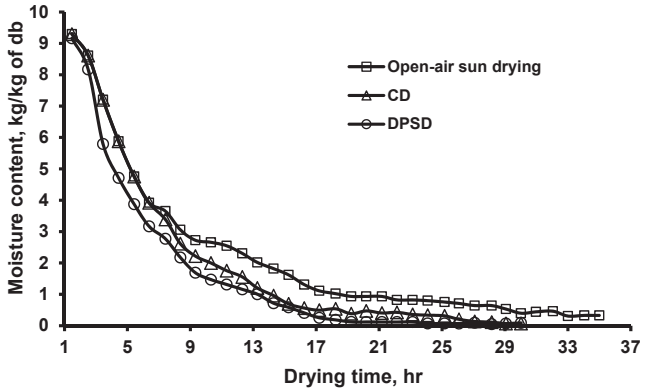

Fig. 11. Change of moisture content of red chilli with drying time [65].

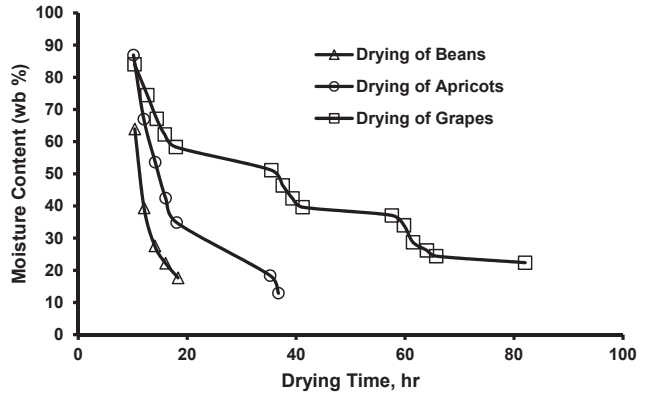

Fig. 12. Relation between moisture content and time for bean, apricots and grapes [37].

greenhouse solar dryer. It consisted of chapel-shaped greenhouse and solar flat plate collector. The analysis was done for sultana grape and red pepper. The payback period was estimated as 1.6 years, which was much lower than the system life of 20 years.

Based on the location and seasons in a particular region, the payback period varies. Table 10 gives data about the dryer life, payback period and cost of ITSD reported in literature.

The payback period varies with the type of material considered for the drying and market value of the dried material. The market value of dried material is low for readily available material. It is found that the payback period is always low compared to the life of dryer which is generally more than 10 years, and so it is useful to dry any type of food product using ITSD. The maximum payback period is noticed in the

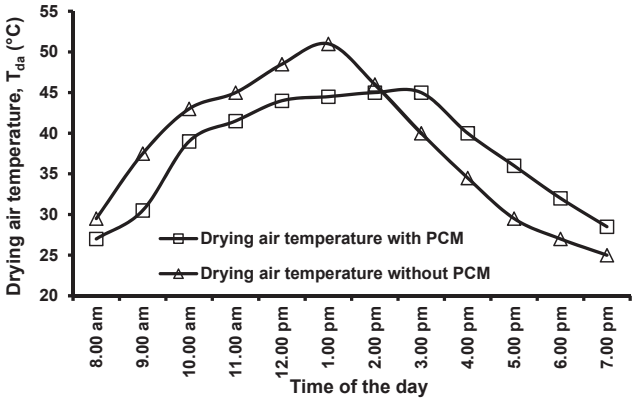

Fig. 13. Comparison between average T_{da} with and without PCM in indirect solar dryer [101].

setup of Banout et al. [65] during the drying of red chillies and the minimum is noticed with 0.54 years during the drying of different fruits and vegetables (Sreekumar [47]). The average payback period of setups is 1.66 years and against the system life (average) of 17.85 years. It is a good sign for food processing industries and farmers, that they can use ITSD dryers very effectively for their use.

5. Important findings and future scopes

The main purpose of solar drying is to reduce MC in agricultural produce to store it for long periods of time. Table 11 gives details of the final MC of some fruits and vegetables that was achieved during their experimentation and the final MC to preserve fruits and vegetable.

In this section, comparison is made between different drying properties. Fig. 9 shows the comparison of results on ITSD over OSD for red chilli [65], bitter gourd [43] and paddy [71]. In all the cases MC decreased when the drying time increased. It is noticed that the time required to dry is more in OSD than drying with ITSD system. In the case of drying bitter-gourd, OSD drying takes 8 h, but ITSD takes only 4 h (approximately). It is also noticed that depending on the type and quantity of crops, the curve of transient moisture content varies.

Fig. 10 shows the efficiency variation of triple pass ITSD with other single pass setups. It is seen from Fig. 10 that the triple pass collector used by Ezeike [71] has the highest thermal efficiency (81%) compared to single pass solar collector used by Maiti et al. [29] (58.5%) and Hegde et al. [53] (50% for the setup of air flow below absorber and 31% for air flow above absorber). Average efficiencies were in the range of 70–81%, 40–58.5%, 33–50% and 24–31% and 27.5% for the collector developed by Ezeike [71], Maiti et al. [29], Hegde et al. [53] (air flow below the collector).

Fig. 11 shows the change in moisture content with respect to time for DPSD and the cabinet dryer (In Fig. 11, it is mentioned as CD) and traditional OSD [65]. It is observed that the highest drying rate was noticed for DPSD compared to cabinet and OSD drying. Therefore double pass solar dryer is more efficient as it saves time and energy during drying. Hence, it is suggested that all ITSD single pass collector should be upgraded with double or triple pass solar dryer, so that drying time and hence energy consumption can be reduced. System performance is also increased from the use of double/triple pass solar dryer. An efficient setup can be made, if the existing systems were altered with double or triple pass setup.

Drying kinetic variations of different food materials (beans, apricot and grapes) are shown in Fig. 12. It is observed that the drying kinetics varied with the product; for example, for grapes, the drying time was almost 82 h to reach the final MC whereas beans took only 20 h (approximately) (Fig. 12). Though MC of apricot is higher than that of grapes, because of the physical structure and chemical properties, drying rate was quicker in the case of apricot. Drying period for grapes

Table 12
Important findings from literature.

Literature	*Important Findings*
Parikh and Agrawal [28], Maiti et al. [29]	• Mass flow rate of drying air in natural convection type collector depends on incident solar radiation, atmospheric air temperature, collector design and wind conditions
Boughali et al. [44], Condorí et al. [56], Banout et al. [65], Nabnean [81], Kareem et al. [89], Jain and Tewari [103], ELkhadraoui et al. [120]	• The life of the dryer is more compared to the payback period so dried product obtained from the dryer is free of cost after its payback period.
Kadam and Samuel [36], Boughali et al. [44], Chan et al. [68], Komilov et al. [70], Mohanraj and Chandrasekar [80]	• Drying rate and overall efficiency increased with the increased drying time.
El-Beltagy et al. [39], Sundari et al. [43], Midilli [46]	• The indirect solar dryer has faster drying rate, less spoilage than the traditional sun-drying method. • Quality of the food material is superior as the food materials dried with ITSD are free from dust, sand, metal pieces and any other form of contamination.
El-Beltagy et al. [39], Nabnean [81], El-Sebaii et al. [91], Dhalsamant et al. [118]	• Chemical pre-treatment for small size food product increased the drying rate, food quality and dryer efficiency.
Banout et al. [65]	• Increased in the surface area of chamber increased the rate of moisture evaporation and consequently decreased drying time.
Sarsavadia [67], Chan et al. [68]	• The solar energy storage and recirculation enhanced the productivity and efficiency of the system.
Mohanraj and Chandrasekar [80]	• The products in the bottom tray get higher moisture removal rate than the top tray under same drying time.
Mohanraj and Chandrasekar [80], Nabnean [81], Potdukhe and Thombre [82], Jain [88], Kareem et al. [89], Aboul-Enein et al. [90], Shalaby and Bek [101]	• Use of SH and LH storage material results in decreasing the drying time by supplying drying air temperature more than ambient temperature after sunset
Performance of the system can be increased by,	
Maiti et al. [29]	• Using solar collector provided with reflectors.
Pangavhane et al. [13], Kadam and Samuel [36], Sarsavadia [67], Esakkimuthu et al. [102]	• Providing corrugated plates along the length and across the length of the solar collector.
Kadam and Samuel [36]	• Optimized the gap between collector cover and absorber plate
Hegde et al. [53]	• Providing bottom air flow configurations (air flow between the absorber and the bottom insulation layer).
Slimani et al. [77]	• Used Photovoltaic-thermal SAC which provided hot air as well as power supply for fan or blower.
Fudholi et al. [64], Banout et al. [65], Fudholi et al. [66], Ezeike [71]	• Using double pass or triple pass solar air collector for ITSD.

is longer than that for apricot and beans. Similar results were obtained although grapes were dried with air temperature higher than the temperature under which beans and apricot were dried. So the selection of drying method for a product is important. For grapes, multi pass setup is preferred for reducing the drying time. It is an added advantage, if the system is provided with re-circulated working fluid and with TES device to extend the drying time beyond sunset.

Using TES system with PCM, the temperature inside the drying cabinet can be maintained above atmospheric temperature after sunset, which reduces the total processing time of the product, as may be observed from Fig. 13. The minimum temperature of 25 °C was observed at 7.00 pm for the setup without TES device while at the same time, it was 28.5 °C for the setup with TES device, which is 3.5 °C more than that of atmospheric air temperature. Therefore, a system with TES device increases the performance of the system, so that overall efficiency of the system increases.

Several investigators have suggested methods and techniques for improving the drying performance of systems. Some of the important findings from the work carried out by the writers of the manuscript are summarized and mentioned in Table 12.

The drying air temperature, mass flow rate, RH of air are most influential parameters to control the drying performance. Increase of airflow rate reduces the drying time and moisture ratio. RH of air is decreased abruptly when the air is heated with solar energy. With low RH, the heated air has more moisture absorbing capability. The rate of drying is high during the initial stage (high MC region). In later stages, the rate of moisture removal becomes slow. Few suggestions are given (multi-pass SAC, an optimized gap for airflow in SAC, corrugated absorber plate, desiccant material for moisture absorption) in order to maintain required air temperature, mass flow rate, relative humidity which ultimately increases the drying rate and reduces drying time.

6. Recommendations proposed for better performance of system

ITSD is an important facility to avoid post harvesting losses of agricultural food produce especially in the rural area of the developing countries. A well-designed ITSD is necessary for the effective drying process, better performance with minimum operating and maintenance cost. Also, it is better, if the system can operate after sunshine hour, so that the food can be dried continuously and therefore the wastage can be reduced.

Among the various types of dryer, forced convection ITSD with double-pass roughened SAC with TES system has been recommended to get the final product with superior quality and higher drying rate. A dryer with forced convection provision always encourages drying rate. SAC is the most important component of ITSD which can lead to better performance of the system. The double and triple pass SACs are more effective compared to single pass as it can transfer more heat. V-corrugated and roughened SAC are preferable because of higher heat transfer coefficient and turbulence effect.

The new concept of photovoltaic-thermal (PV/T) operated fan is preferable for forced convection ITSD as the power needed for the fan is generated by the PV panel. It saves electric energy. Also, PV/T provision with SAC improves the drying efficiency of ITSD. SH or LH storage system within ITSD accelerates and continues the drying process during the off-sunshine periods. It also excludes the dependency of auxiliary heat sources. LH storage system has the ability to supply constant heat during the drying hence, it is more preferable than SH storage.

It is recommended that numerical analysis should be carried out before developing ITSD for large scale and industrial applications. The dimensions of the system and other design parameters can be optimised by solving numerical problems. Numerical analysis helps to analyse short and long term performances of ITSD.

7. Conclusions and future scope

This work provided a review of indirect type solar dryers (ITSD) by presenting different designs, the construction details and performance evaluation of the models. Dryer selection depends on a number of parameters such as solar insolation, ambient temperature, drying air

velocity, humidity, type of product, moisture content in the product, mass of the product, etc. Drying time varied with different types of product as the drying curves were different for different products. Temperature and velocity of drying air affected the quality of the product. Two categories of ITSDs were identified; natural convection or passive solar dryers and forced convection or active solar dryers. Passive solar dryers were easy to fabricate and required lower cost than active solar dryers. Passive solar dryers were self-operated dryers but had no control over drying rate, unlike active solar dryers. Forced convection in ITSD offered excellent control over drying rate. From the various types of solar dryers, forced convection ITSD with double pass or triple pass provision and collector with reflector promised better performance and hence overall efficiency and drying quality of the product improved. Use of TES units and SH and LH storage material enhanced the continuous use of ITSDs, enabling solar dryers to function even after sunset. Use of TES helped to reduce the required time for drying. Use of photovoltaic panel helped to fulfil the requirement of electric power needed for the fan or blower to make the dryer as forced convection ITSD. Pre-treatment of the crops before drying was good for enhancement of drying rate and it also helped to maintain the quality of product. Solar energy is a clean and freely available energy system therefore, initial investment can be returned as early as possible (pay-back) through effective utilization of the dryer system.

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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