# Recent advances in solar tunnel dryer for performance improvement in food drying process: a review

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**Abstract:** The unexpected increase in demand and persistent shortage of fossil fuels continues the search for an alternative source of power. Solar energy is one of the sustainable and renewable sources of power that encouraged various researchers from all over the world. The production of food and its immediate consumption is the biggest problem to reduce the wastages of food. To overcome the wastage, drying is an excellent method to preserve the food grains, fruits and vegetables. For drying, conventional drying system is sun drying which is free and a renewable source of energy. But, there are various limitations e.g. rain, dust, animals, wind and insects. The use of solar dryers can eliminate these limitations significantly and enhance the productivity of farmers towards better revenue earned. This review attempts to provide in brief the recent developments to increase the temperature of drying chamber and applications of drying technology for different foods and agricultural produce, with particular emphasis on the modifications in the dryer and process conditions. This review paper will be helpful to know about the recent trends and different useful aspects of solar tunnel dryer to the new researchers.

**Keywords:** solar energy; dryer; greenhouse; thermal performance; tunnel dryer.

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## 1 Introduction

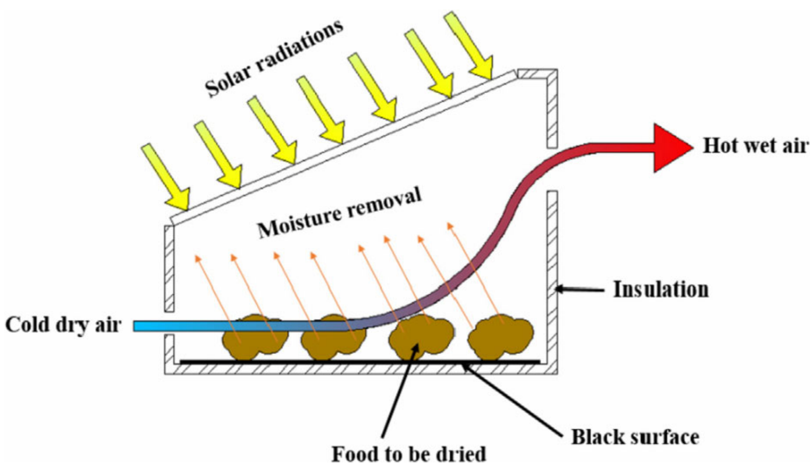
Conventional energy sources, that is, oil, coal reserves and natural gas are finite and hidden. Each resource is limited and buried deep underground. The more it is harvested, the more difficult and more expensive it becomes to find new sources, and becomes challenging to exploiting them. Renewable energy is reliable and plentiful and once technology and infrastructure is improved, it will become much cheaper (Lingayat et al., 2020a; Verma et al., 2020). Small levels of carbon emissions produces from renewable energy helps in tackling climate change using fossil fuel. It is far cleaner than fossil fuels. For human being, food is a basic need after air and water. It is biggest hurdle to manage the balance between food production and its immediate consumption (Tiwari et al., 2016). In developing countries, 30–40% loss of fruits and vegetables occurred after harvesting (El-Sebaii and Shalaby, 2012). To overcome this barrier, drying is an excellent way in which food such as grains, vegetables and fruits are preserved for some time

(Bennamoun, 2011). Drying is a method in which moisture is removed from a product to a stated value because of heat energy (El-Sebaii and Shalaby, 2012).

Since many years, it was a common practice to dry food and agriculture produces in open sun. Due to rain, dust, animals, wind and insects, the quality of materials degraded in open sun drying along with it has no control on drying parameters, e.g., air flow rate, temperature and moisture content (Yadav and Chandramohan, 2020; Vengsungnle et al., 2020). The quality of these products is very low and cheapest as per international standard (Bala, 2000). Thus, to provide a higher quality of dried product, efforts have been developed from sun drying to solar drying.

Solar dryer is a device which increases the vapour pressure of moisture presented inside the drying material by heating the circulating air and material resulting escaping of moisture from material to surrounding (Chauhan et al., 2015). As the air heated, its moisture carrying capacity increases by reducing its relative humidity (Sangamithra et al., 2014). In solar dryer, temperature of air increases due to greenhouse effect and it captures the moisture from the product (Shringi et al., 2014). Figure 1 explains the working of solar dryer.

**Figure 1** Principle of solar dryer (see online version for colours)




*Source:* Elhage et al. (2018)

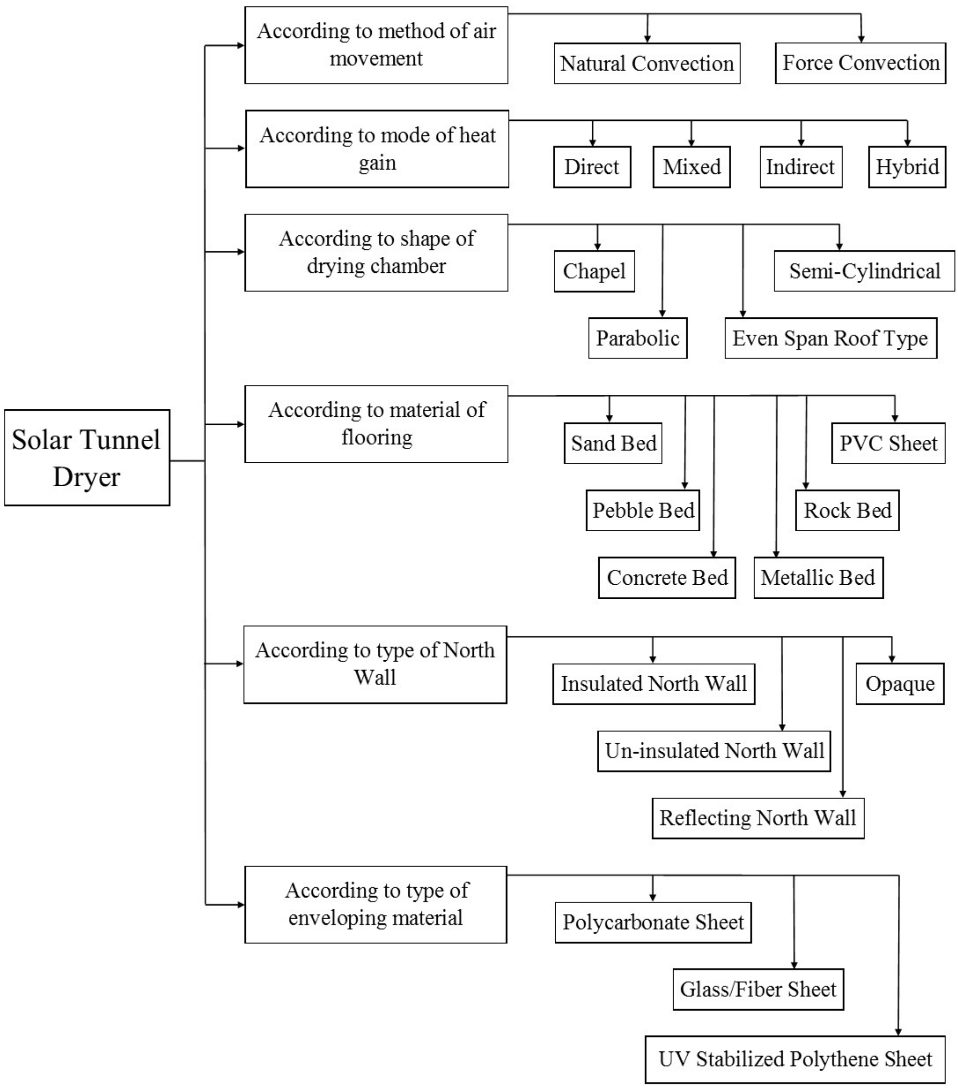
Solar tunnel dryer is a type of dryer in which the agricultural products are dried in the mass quantity. As the name suggest, these dryers are in tunnel shape to receive maximum solar radiations.

The objectives of current study are to present an exhaustive review of recent developments to enhance dryer temperature and performance characteristics of solar tunnel dryer. This study deals with the different techniques and factors influence the dryer temperature. The effecting parameters such as geometrical condition, operating condition, photovoltaic sources, air circulation mode, adding of another power source was reviewed and discussed.

## 2 Classification of solar tunnel dryer

The solar tunnel dryers are broadly classified into different types. Numerous types of solar tunnel dryers have been presented in literature. Few researchers also represented the classification of tunnel dryers (Elhage et al., 2018; Sandali et al., 2019; Tiwari et al., 2016; Singh et al., 2018). Based on literature, classifications have been developed for tunnel dryers. Figure 2 shows the classification of solar tunnel dryer.

**Figure 2** Classification of solar tunnel dryer



Although different researchers have used the different combination of solar drying system according to their convenience and test condition. However, based on the major influencing parameter, important performance related outcomes of previous studies are discussed in the subsequent sections.

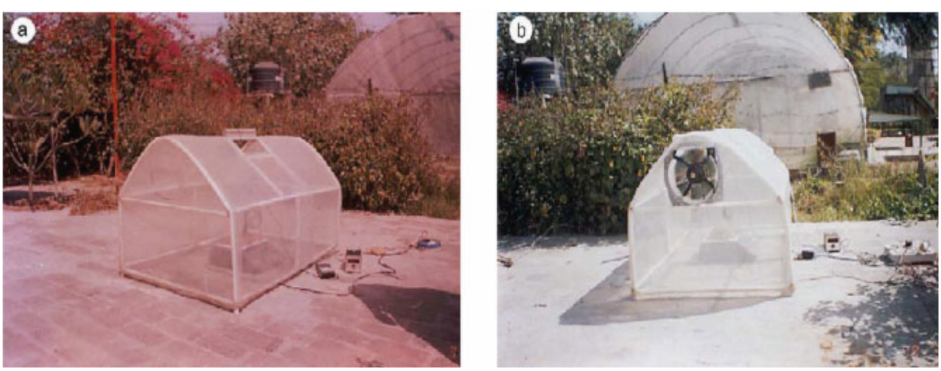
## *2.1 According to method of air flow*

The air flows in the dryer takes the moisture from the produce and escape from dryer. To escape the air from the dryer, a driving force is required to flow the air from the dryer. The driving force to escape the air from the dryer is natural circulation or force circulation. On the basis of these circulations, the dryer can be divided in two categories:

### *2.1.1 Passive mode*

Passive mode dryers are the dryers in which the driving force is pressure difference, buoyancy force or combination of them (Elhage et al., 2018). Since here no mechanical driving force is required, the circulation of air is called natural circulation [Figure 3(a)]. The temperature were maintained in the range of 33–60°C in summer and 26–43°C in winter in solar greenhouse dryer work in passive mode presented by Ayyappan (2018) installed in Pollachi, India. Table 1 represents the past researches that use natural (passive) circulation of air. Many authors studied the behaviour of solar tunnel dryer in natural circulation mode, due to the slow rate of circulation, the moisture contained air escape the tunnel slowly resulting the slow rate of drying of agricultural produce. To increase the drying rate in passive mode solar dryer, it should be required to add other heating source as seen in Table 1.

**Figure 3** (a) Natural convection solar dryer (b) Force convection solar dryer (see online version for colours)




*Source:* Tiwari et al. (2004)

**Table 1** Past researches that uses natural (passive) circulation of air in the dryer

| *Literature* | *Drying material* | *Obtained temperature in dryer* | *Remarks* |
|---|---|---|---|
| Ayyappan (2018) | Coconut | Summer: 33–60°C<br>Winter: 26–43°C | • With the aid of biomass heater, the temperature maintained in the range of 35–45°C during night. |
| Chauhan and Kumar (2016) | No load condition | 53.8°C | • With the aid of solar collector inside dryer, the temperature was increased by 19.5%. |
| Tham et al. (2017) | Dry Java tea, Sabah snake grass | 45°C | • With the aid of low temperature heat pump, the temperature in the dryer was 47 °C.<br>• The room relative humidity was maintained 65% (max.) with the help of heat pump at night or cloudy day to mitigate the product rehydration issue. |
| Belloulid et al. (2018) | Wastewater sludges | 28–47°C | • In hot season, the drying rate was obtained higher. |
| Puello-Mendez et al. (2017) | Cocoa beans | - | • Solar dryer with plastic roof reduced the moisture content from 58.0% to 7.0% in 4 d whereas 4 d was taken by direct solar dryer. |
| Tiwari and Tiwari (2016b) | No load condition | 25.5°C (with PVT) | • By increasing the packing factor of PV module, 76.39% decreased the thermal energy and 88.73% increased the electrical energy. |
| Moreno et al. (2016) | Wood chips of *Pinus pinaster* | 55.90°C | • Compared to open sun drying, found 20% less relative humidity in the dryer. |
| Chauhan and Kumar (2016) | No load condition | 56.2°C (max.) with north wall insulation | • With aid of solar collector inside dryer, temperature was increased by 4.11%. |

### *2.1.2 Active mode*

For circulation of air in the tunnel dryer, mechanical force is required to fast the rate of drying. Hence, some mechanical devices to force the air like fan, blowers are used to increase the air circulation rate [Figure 3(b)] resulting the moisture contained air escape the dryer rapidly. Many researchers worked on force circulation to investigate the tunnel dryer performance. Drying rate was improved significantly by force circulation as shown in Table 2.

The dryer temperature rise increases with decrease in mass flow rate, because the contact period of air with the absorber surface is long when the velocity of air decreases (Vijayan et al., 2020). With addition of other sources of power and solar collector inside the dryer, the drying rate has been improved.

**Table 2** Past researches that uses force (active) circulation in the dryer

| *Literature* | *Drying material* | *Obtained temperature in dryer* | *Remark* |
|---|---|---|---|
| Seerangurayar et al. (2019) | Dates | 51°C (avg.) | • Drying time were lowered by 37, 38 and 38% for Khalal, Rutab and Tamr stage of dates, respectively in comparison to open sun drying |
| Sreekumar and Rajarajeswari (2018) | Tapioca, apple tomato, pineapple, onion | 37–65°C | • Achieved 32°C max. temperature difference<br>• The drying duration of onion, tomato, tapioca, apple and pineapple samples dried in solar drier was 4, 4, 5, 6, 6 hours respectively. |
| Eltawil et al. (2018) | Potato slices | 46.45°C (without load condition)<br>50.5°C with load condition | • With the aid of solar PV and flat plate collector, performance was enhanced.<br>• Black thermal curtains were applied above potato slices to enhance the quality of dried product. |
| Chauhan et al. (2018) | No load condition | 48°C | • With installation of solar collector at the surface of dryer, 60°C temperature was obtained from 41.3°C ambient temperature. |
| Noh et al. (2018) | Sericite mica | 59°C (max) | • Results of CFD simulation showed that highest temperature is produced by active mode condition. |
| Deeto et al. (2018) | Coffee bean | 37.9°C (average) | • Assisted with solar collector along with producing solar hot water. |
| Condorí et al. (2017) | Vegetables | 80–90°C | • System consisted with bank of solar collector. |
| Morad et al. (2017) | Peppermint plants | 46.41°C | • Compared with periodic fan operating, 22.78% drying rate was increased by continuous operating fan. |
| Rabha et al. (2017) | Ghost chilli pepper, sliced ginger | 57°C | • In the later stages of drying periods, the exegetic efficiencies were found to be high. |
| Metidji (2016) | Apricot waste | 65.3°C | • The temperature gradient inside the dryer is in the range of 35–65.3°C from 9:30–13:30 h |
| Saini et al. (2017) | No load | 45°C | |

**Table 2** Past researches that uses force (active) circulation in the dryer (continued)

| *Literature* | *Drying material* | *Obtained temperature in dryer* | *Remark* |
|---|---|---|---|
| Tiwari and Tiwari (2017) | No load condition | 40°C | • Maximum temperature was achieved with mass flow rate of 0.01 kg/s.<br>• With varying air collector (N-PVT) from 1 to 5, the room temperature of dryer increases from 22.44°C to 87.42°C whereas the ambient temperature was in the range of 8.8°C to 21.6°C. |
| Chavan et al. (2016) | Mackerel | 34.2–57.20°C | • At night, with the aid of biomass stove, temperature of 40.6–55.7°C was maintained in the dryer.<br>• The overall drying efficiency was estimated to be about 5.42% during fish drying. |
| Tiwari and Tiwari (2016b) | No load condition | 25.5°C (with PVT) | • By increasing the packing factor of PV module, 76.39% decreased the thermal energy and 88.73% increased the electrical energy. |
| Tiwari and Tiwari (2016a) | No load condition | 45°C | • 1.23 years and 10 years energy payback time by energy and exergy analysis respectively..<br>• For 25 years life of solar dryer, founded 81.75 tons and $817.50 for reduction in $CO_2$ emission and carbon credit to be earn respectively |

## 2.2 According to mode of heat gain

Solar tunnel dryers are working on the principal of thermal heat. Heat is required to increase the temperature of air and product, so the moisture contained in the product evaporates. A tunnel dryer receives the heat in different modes. Figure 4 depicted the outline of dryers depending upon mode of heat gain. Depending upon the heat gain, the dryer is classified as follows.

### 2.2.1 Direct mode

Solar radiations are directly incidents on the cover of solar tunnel dryer. As the transmittance of covering materials is high, radiation enters to the drying chamber and heat air and product directly. The dryer receives the heat directly by solar radiations is called direct mode solar tunnel dryers. Many researchers worked on the direct mode of heat gain (Table 3) to enhance the drying rate. Chauhan and Kumar (2018a) investigated dryer in direct mode in which a solar collector was installed inside the dryer reported that peak temperature of dryer has been achieved by 64.8°C situated in Bhopal, India.

**Table 3** Past researches that uses direct heat gain in the dryer

| *Literature* | *Drying material* | *Obtained temperature in dryer* | *Remark* |
|---|---|---|---|
| Sreekumar and Rajarajeswari (2018) | Tapioca, apple tomato, pineapple, onion | 37–65°C | • Achieved 32°C max. temperature difference<br>• The drying duration of onion, tomato, tapioca, apple and pineapple samples dried in solar drier was 4, 4, 5, 6, 6 hours respectively. |
| Chauhan et al. (2018) | No load condition | 48°C | • With installation of solar collector inside dryer, 60°C temperature was obtained from 41.3°C ambient temperature. |
| Chauhan and Kumar (2016) | No load condition | 53.8°C | • With the aid of solar collector inside the dryer, the temperature was increased by 19.5%. |
| Puello-Mendez et al. (2017) | Cocoa beans | - | • Solar dryer with plastic roof reduced the moisture content from 58.0% to 7.0% in 4 d whereas 4 d was taken by direct solar dryer. |

### *2.2.2 Indirect mode*

These dryers were consisted by drying chamber and solar collector. Solar collector collects the solar radiation by black absorbing material and transfer the heat to ambient air. This heated ambient air than goes to drying chamber by using fan or blower to drying the agricultural products. The dried agricultural products obtained from dryer gets good quality in terms of colouring as the drying chamber did not receive direct solar radiations. In indirect mode solar dryer, the dryer temperature has been increased significantly in various past studies as presented in Table 4.

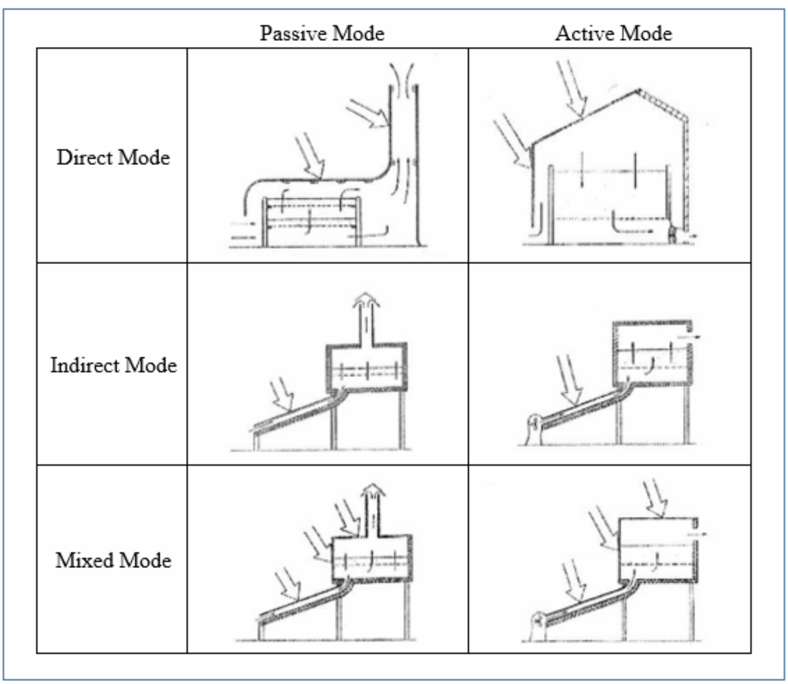
**Table 4** Past researches on indirect type solar greenhouse dryer

| *Literature* | *Drying material* | *Obtained temperature in dryer* | *Remark* |
|---|---|---|---|
| Condorí et al. (2017) | Vegetables | 80–90°C | • System consisted with bank of solar collector. |
| Rabha et al. (2017) | Ghost chilli pepper, sliced ginger | 57°C | • In the later stages of drying periods, the exegetic efficiencies were found to be high. |
| Shrivastava and Kumar (2017) | Fenugreek leaves | - | • Embodied energy was 1,081.83 kWh.<br>• 4.36 years energy payback time and 391.52 kg per year $CO_2$ emission were founded. |
| Goud et al. (2019) | Green chilli and okra | 50.68°C | • - |

**Table 4** Past researches on indirect type solar greenhouse dryer (continued)

| *Literature* | *Drying material* | *Obtained temperature in dryer* | *Remark* |
|---|---|---|---|
| Lingayat et al. (2020b) | Apple and watermelon slices | 70°C | • V shaped absorber plate used.<br>• Activation energy for apple and watermelon is 17.34 and 18.71 kJ/mol, respectively. |
| Etim et al. (2020) | Cooking banana | - | • The shapes of air inlet area namely square, rectangular, circular and triangular were considered.<br>• It was observed that performance of dryer was enhanced with increase in air inlet area and vice versa. |
| Vijayan et al. (2020) | Bitter gourd | 58°C | • It was observed that the temperature rise of dryer was increased when the mass flow rate of air increases. |

**Figure 4** Classification of dryer according to mode of heat gain (see online version for colours)




*Source:* Prakash and Kumar (2013)

Rabha et al. (2017) experimented indirect type solar dryer with two double pass solar heater and a blower. The results reported that moisture content was reduced from 89.6% to 12% in 123 hours in the dryer and 193 hours in open sun drying of chilli. Daghigh et al. (2020) reported that solar dryer with the aid of evacuated tube solar collector have better performance compared with the aid of solar PVT collector, because evacuated tube collected have higher outlet temperature and humidity than solar PVT collector. Güler et al. (2020) analysed the dryer experimentally and with CFD tool and results reported that double pass indirect solar dryer with mesh absorber modification had better efficiency and gave the best results in compared with double pass indirect solar dryer.

### *2.2.3 Mixed mode*

This is a modified version of indirect type of dryers in which drying chamber is also receiving direct solar radiation along with solar collector. This will enhance the drying rate. Eltawil et al. (2018) reported that solar dryer with the aid of solar PV and flat plate collector, enhanced the dryer temperature from 24°C to 46.45°C in without load condition and from 37°C to 50.5°C with load condition. Black thermal curtains were also applied above potato slices to enhance the quality of dried product. Noh et al. (2018) simulated a solar dryer having the size of $1.25 * 1.7 * 17\ m^3$ and drying material Sericite mica and found that dryer temperature were increased 59°C from 50°C ambient temperature. The simulated results also showed that highest temperature is produced by active mode condition. Tiwari and Tiwari (2017) reported that maximum temperature was achieved with mass flow rate of 0.01 kg/s. With varying air collector (N-PVT) from 1 to 5, the room temperature of dryer increases from 22.44°C to 87.42°C whereas the ambient temperature was in the range of 8.8°C to 21.6°C.

### *2.2.4 Hybrid mode*

The solar dryer connected with another source of power to heat the air in night or cloudy day (without solar radiation), is called hybrid type solar dryer. In night or cloudy day, another source of power, e.g., biomass, electric heater, etc. heat the air, then it goes to drying chamber for drying the products. Ayyappan (2018) investigated the dryer in hybrid mode using biomass heater that maintained the temperature in the range of 35–45°C during night inside the dryer.

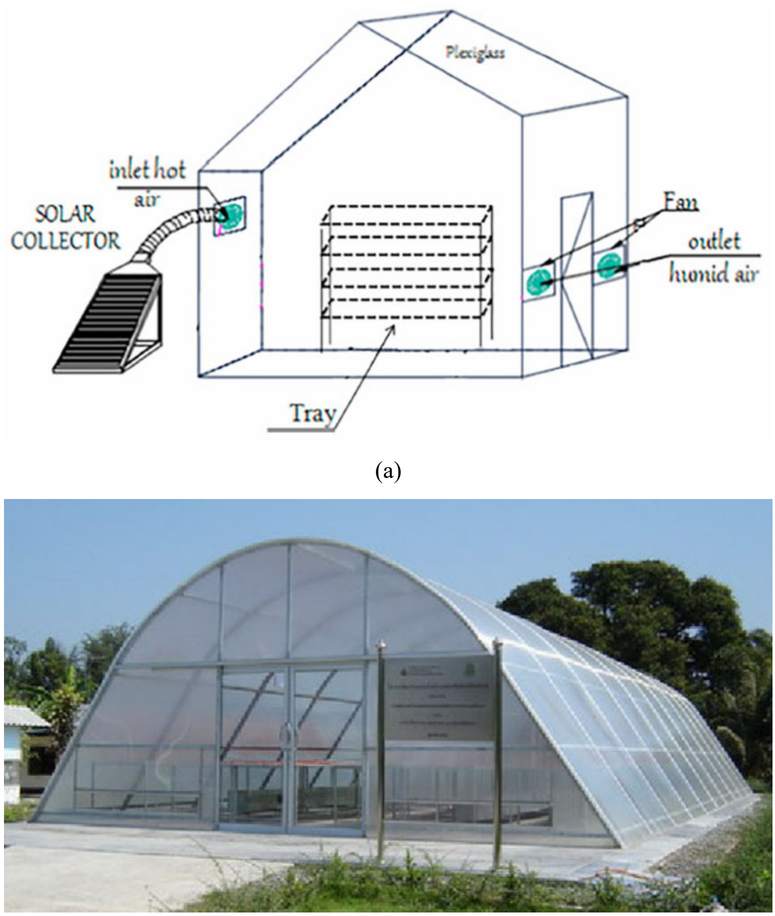
Chavan et al. (2016) reported that in solar biomass hybrid tunnel dryer, temperature were maintained from 34.2–57.2°C whereas in open sun drying, it were 31–40°C. During night, biomass stove was used that maintain the temperature of 40.6–55.7°C in the dryer. A greenhouse solar dryer with the aid of fans and electric heater were studied by Vengsungnle et al. (2020). The difference of relative humidity between inside and outside air adjusted by humidity transmitter sensor connected to the fan. To control the relevant parameters inside the dryer, automatic closed loop system was used.

Lamrani and Draoui (2020) numerically studied the hybrid solar electrical dryer of wood having thermal energy storage system with commercial PCM RT55. The results reported that in the night, the dryer temperature was achieved 4–20°C higher from the ambient temperature. Singh et al. (2020) recommended solar-infrared-assisted heat pump dryer for the food chips drying as it take lowest time to dry and highest exergy destruction.

## *2.3 According to shape of drying chamber*

In the literature, there were many shapes of solar tunnel dryer to collect the maximum solar radiations. These shapes are chapel shape, parabolic shape, even span roof type shape, semi cylindrical shape (Figure 5), etc. The shape and size of the dryer largely depends upon the mass of the product to be dried. It has seen form Table 5 that in the even span roof dryer and semi cylindrical shape dryer, the average temperature rise of the dryer is significantly high.

**Figure 5** Pictorial view of solar tunnel dryer (see online version for colours)




(a)

(b)

*Source:* Cerino and Garcia (2018)

**Table 5** Past studies that uses different shapes of the dryer

| *Literature* | *Shape of drying chamber* | *Drying material* | *Obtained temperature in dryer* | *Remark* |
|---|---|---|---|---|
| Chauhan and Kumar (2016) | Chapel shape | No load condition | 56.2°C (max.) with north wall insulation | • With the aid of solar collector inside dryer, the temperature was increased by 4.11%. |
| Nimrotham et al. (2017) | Parabolic | Red Chili | 29.86°C to 63.16 °C | - |

**Table 5** Past studies that uses different shapes of the dryer (continued)

| *Literature* | *Shape of drying chamber* | *Drying material* | *Obtained temperature in dryer* | *Remark* |
|---|---|---|---|---|
| Seerangurayar et al. (2019) | Semi cylindrical | Dates | 51°C (avg.) | • Drying time were lowered by 37, 38 and 38 percent for khalal, rutab and tamr stage of dates, respectively in comparison to open sun drying |
| Morad et al. (2017) | Semi cylindrical | Peppermint plants | 46.41°C | • Compared with periodic fan operating, 22.78% drying rate was increased by continuous operating fan. |
| Natarajan et al. (2017) | Semi cylindrical | Vitis vinifera, Momordica charantia | 67 °C for Vitis vinefera and 57 °C for Momordica charantia | • Sand, rock bed and aluminium used as a thermal heat storage system |
| Moreno et al. (2016) | Semi cylindrical | Wood chips of Pinus pinaster | 55.90°C | • Compared to open sun drying, found 20% less relative humidity in the dryer. |
| Eltawil et al. (2018) | Even span shape | Potato slices | 46.45°C (without load condition)<br>50.5°C with load condition | • With the aid of Solar PV and flat plate collector, performance was enhanced.<br>• Black thermal curtains were applied above potato slices to enhance the quality of dried product. |
| Chauhan and Kumar (2016) | Even span shape | No load condition | 53.8°C | • With the aid of solar collector inside the dryer, the temperature was increased by 19.5%. |
| Deeto et al. (2018) | Gabble structure | Coffee bean | 37.9°C (average) | • Assisted with solar collector along with producing solar hot water. |
| Condorí et al. (2017) | Gabble roof | Vegetables | 80–90 °C | • System consisted with bank of solar collector. |
| Metidji (2016) | Square shape | Apricot waste | 65.3°C | • The temperature gradient inside the dryer is in the range of 35–65.3°C from 9:30–13:30 h |

**Table 5** Past studies that uses different shapes of the dryer (continued)

| *Literature* | *Shape of drying chamber* | *Drying material* | *Obtained temperature in dryer* | *Remark* |
|---|---|---|---|---|
| Saini et al. (2017) | Cabinet shape | No load | 45°C | - |
| Shrivastava and Kumar (2017) | Cabinet shape | Fenugreek leaves | - | • Embodied energy was 1,081.83 kWh.<br>• 4.36 years energy payback time and 391.52 kg per year $CO_2$ emission were founded. |
| Subahana and Natarajan (2016) | Hemispherical shape | Sugarcane trash, rice straw leaf, switch grass | 60.30°C for sugarcane trash, 63.30°C for rice straw leaf and 61.90°C for switch grass | • Highest drying rate was achieved in yellow coloured soil compared with black, red, grey coloured soils spread in compartments |

## 2.4 According to material of flooring

The material of the flooring has a very important role in the solar tunnel dryer. It absorbs the heat in the day time and releases it when there are no solar radiations. For absorbing more heat, many researches have been used different heat storage materials such as pebble bed, sand bed, concrete bed, PVC sheet, metallic bed, rock bed etc. to enhance the performance of solar tunnel dryer as shown in Table 6. The drying rate has been increased from the material due to maintaining higher temperature in night time also. Some studies were based on placing heat storage material in the dryer and other studies were based on placing the heat storage material on the floor of the dryer. There was also a saving of the space in the dryer when heat storage materials were placed at floor.

**Table 6** Different floorings used by researchers

| *Literature* | *Type of flooring* | *Drying Material* | *Obtained temperature in dryer* | *Remark* |
|---|---|---|---|---|
| Natarajan et al. (2017) | Sand bed, rock bed and aluminium filing | Vitis vinifera, Momordica charantia | 67°C for Vitis vinefera and 57°C for Momordica charantia | • Sand, rock bed and aluminium used as a thermal heat storage system |
| Bukke et al. (2016) | Pebble bed | Orange peel | - | • With use of black coated pebbles, it took 8 h and 14 h time to dry with pebbles and without pebbles respectively. |
| Belloulid et al. (2018) | Cement slab | Wastewater Sludges | 28–47°C | • In hot season, the drying rate was obtained higher. |

**Table 6** Different floorings used by researchers (continued)

| *Literature* | *Type of flooring* | *Drying Material* | *Obtained temperature in dryer* | *Remark* |
|---|---|---|---|---|
| Chauhan and Kumar (2016) | Black PVC sheet | No load condition | 53.8°C | • With the aid of solar collector inside the dryer, the temperature was increased by 19.5%. |
| Deeto et al. (2018) | Black PVC sheet | Coffee bean | 37.9°C (average) | • Assisted with solar collector along with producing solar hot water. |
| Condorí et al. (2017) | Polystyrene expended thermal insulated plate | Vegetables | 80–90°C | • System consisted with bank of solar collector. |
| Morad et al. (2017) | Black plastic wire net | Peppermint plants | 46.41°C | • Compared with periodic fan operating, 22.78% drying rate was increased by continuous operating fan. |
| Chauhan and Kumar (2017) | Black PVC sheet | No load condition | 50°C | • With the use of solar collector at the surface of dryer, 65°C was achieved from 41°C ambient temperature. |
| Puello-Mendez et al. (2017) | Polyethylene film | Cocoa Beans | - | • Solar dryer with plastic roof reduced the moisture content from 58.0% to 7.0% in 4 d whereas 4 d was taken by direct solar dryer. |
| Chauhan and Kumar (2016) | Black PVC sheet | No load condition | 56.2°C (max.) with north wall insulation | • With the aid of solar collector inside dryer, the temperature was increased by 4.11%. |
| Seerangurayar et al. (2019) | Metallic plate | Dates | 51°C (avg.) | • Drying time were lowered by 37, 38 and 38 percent for khalal, rutab and tamr stage of dates, respectively in comparison to open sun drying |
| Sreekumar and Rajarajeswari (2018) | Selective coated aluminium sheet | Tapioca, apple tomato, pineapple, onion | 37–65°C | • Achieved 32°C max. temperature difference<br>• The drying duration of onion, tomato, tapioca, apple and pineapple samples dried in solar drier was 4, 4, 5, 6, 6 hours respectively. |

**Table 6** Different floorings used by researchers (continued)

| *Literature* | *Type of flooring* | *Drying Material* | *Obtained temperature in dryer* | *Remark* |
|---|---|---|---|---|
| Chauhan et al. (2018) | Black painted copper sheet | No load condition | 48°C | • With installation of solar collector at the surface of dryer, 60°C temperature was obtained from 41.3°C ambient temperature. |

## 2.5 According to type of north wall

In the northern hemisphere, the solar radiations are absence in north side. Due to this, there is a loss of heat from the north wall of the dryer. Some arrangements have been carried out, e.g., apply insulation on north wall, applying reflecting surfaces on north wall, opaque north wall, to reduce the heat losses from the dryer. Chauhan and Kumar (2016) tested the solar dryer with insulating north wall having the dimensions of $1.35 * 0.85$ m$^2$ in no load condition, the room temperature of dryer was increased to 53.8°C from 40.3°C ambient temperature and with the aid of solar collector inside the dryer, the temperature was increased by 19.5%. Chauhan and Kumar (2017) tested the dryer having the north wall made by insulated nickel polished aluminium sheet. The results reported that the temperature of dryer was achieved 50°C from 40°C ambient temperature and with use of solar collector inside dryer, 65°C temperature was achieved. Chauhan et al. (2018) also reported that with the use of stainless steel reflection sheet on north wall, the temperature of dryer was increased 48°C from 40.1°C ambient temperature.

## 2.6 According to the type of enveloping material

The covering material of solar dryer have important role in transmitting the solar radiations inside the dryer and making greenhouse effect. Many researchers used polycarbonate sheet, UV stabilised polythene sheet or glass/fibre sheet to enhance the performance of the dryer as shown in Table 7. A material, which has high transmittance, should be used for transmitting maximum solar radiation inside the dryer. The transmittance of polycarbonate sheet is in between 80 to 90% range. UV coating and colour have also be applied on polycarbonate sheet to enhance even distribution of radiation inside the dryer (Polycarbonate-and-light-transmission, n.d.). In low and medium tunnels and greenhouse covering, plastic film (polyethelene sheet) are widely used. The indoor air temperature is higher and more comparable with old plastic sheet and produces more thermal effect (Balocco et al., 2018).

**Table 7** Past studies that uses different covering material for the dryer

| *Literature* | *Type of covering material* | *Drying material* | *Obtained temperature in dryer* | *Remark* |
|---|---|---|---|---|
| Belloulid et al. (2018) | Polycarbonate sheet | Wastewater sludges | 28–47°C | • In hot season, the drying rate was obtained higher. |
| Chauhan et al. (2018) | Polycarbonate sheet | No load condition | 48°C | • With the aid of solar collector at the surface of dryer, the temperature was obtained 60°C from 41.3°C ambient temperature. |
| Noh et al. (2018) | Polycarbonate sheet | Sericite mica | 59°C (max) | • Results of CFD simulation showed that highest temperature is produced by active mode condition. |
| Metidji (2016) | Polycarbonate sheet | Apricot waste | 65.3°C | • The temperature gradient inside the dryer is in the range of 35–65.3 °C from 9:30–13:30 h |
| Chauhan and Kumar (2017) | Polycarbonate sheet | No load condition | 50°C | • With aid of solar collector at surface of dryer, 65°C was achieved from 41°C ambient temperature. |
| Nimrotham et al. (2017) | Polypropylene sheet | Red chili | 29.86°C to 63.16°C | - |
| Moreno et al. (2016) | Plastic film | Wood chips of Pinus pinaster | 55.90°C | • Compared to open sun drying, found 20% less relative humidity in the dryer. |
| Chauhan and Kumar (2016) | Polycarbonate sheet | No load condition | 53.8°C | • With the aid of solar collector inside the dryer, the temperature was increased by 19.5%. |
| Sreekumar and Rajarajeswari (2018) | Toughened glass | Tapioca, apple tomato, pineapple, onion | 37–65°C | • Achieved 32°C max. temperature difference<br>• The drying duration of onion, tomato, tapioca, apple and pineapple samples dried in solar drier was 4, 4, 5, 6, 6 hours respectively. |
| Eltawil et al. (2018) | Plexiglas sheet | Potato slices | 46.45°C (without load condition)<br>50.5°C with load condition | • With the aid of Solar PV and flat plate collector, performance was enhanced.<br>• Black thermal curtains were applied above potato slices to enhance the quality of dried product. |

**Table 7** Past studies that uses different covering material for the dryer (continued)

| *Literature* | *Type of covering material* | *Drying material* | *Obtained temperature in dryer* | *Remark* |
|---|---|---|---|---|
| Deeto et al. (2018) | Plastic sheet | Coffee bean | 37.9°C (average) | • Assisted with solar collector along with producing solar hot water. |
| Condorí et al. (2017) | Insulated corrugated galvanised sheet | Vegetables | 80–90°C | • System consisted with bank of solar collector. |
| Shrivastava and Kumar (2017) | Insulated metallic sheet | Fenugreek leaves | - | • Embodied energy was 1,081.83 kWh.<br>• 4.36 years energy payback time and 391.52 kg per year $CO_2$ emission were founded. |
| Tiwari and Tiwari (2016b) | Glass sheet | No load condition | 25.5°C (with PVT) | • By increasing the packing factor of PV module, 76.39% decreased the thermal energy and 88.73% increased the electrical energy. |
| Ayyappan (2018) | UV treated polyethylene sheet | Coconut | Summer: 33–60°C<br>Winter: 26–43°C | • With the aid of biomass heater, the temperature maintained in the range of 35–45°C during night. |
| Morad et al. (2017) | Plastic film | Peppermint plants | 46.41°C | • Compared with periodic fan operating, 22.78% drying rate was increased by continuous operating fan. |
| Natarajan et al. (2017) | Polyethylene transparent film | Vitis vinifera, Momordica charantia | 67°C for Vitis vinefera and 57°C for Momordica charantia | • Sand, rock bed and aluminium used as a thermal heat storage system |
| Tham et al. (2017) | Polyethylene film | Dry Java tea, Sabah snake grass | 45°C | • With the aid of low temperature heat pump, the temperature in the dryer was 47 °C.<br>• The room relative humidity was maintained 65% (max.) with the help of heat pump at night or cloudy day to mitigate the product rehydration issue. |

**Table 7** Past studies that uses different covering material for the dryer (continued)

| *Literature* | *Type of covering material* | *Drying material* | *Obtained temperature in dryer* | *Remark* |
|---|---|---|---|---|
| Puello-Mendez et al. (2017) | Plastic sheet | Cocoa Beans | - | • Solar dryer with plastic roof reduced the moisture content from 58.0% to 7.0% in 4 d whereas 4 d was taken by direct solar dryer. |
| Subahana and Natarajan (2016) | UV stabilised polythene sheet | Sugarcane trash, rice straw leaf, switch grass | 60.30°C for sugarcane trash, 63.30°C for rice straw leaf and 61.90°C for switch grass | • Highest drying rate was achieved in yellow coloured soil compared with black, red, grey coloured soils spread in compartments. |
| Chavan et al. (2016) | UV stabilised polyethylene sheet | Mackerel | 34.2–57.20°C | • At night, with the aid of biomass stove, temperature of 40.6–55.7°C was maintained in the dryer.<br>• The overall drying efficiency was estimated to be about 5.42% during fish drying. |

## 3 Conclusions

This review work presents the analysis of different types of solar tunnel dryers and discusses their effects on temperature of the dryer and role of material selection for improving the drying temperature. Some other parameters have also studied that increase the temperature of the dryer significantly. Based on the study, following remarks have been drawn:

- Solar tunnel dryer accommodate large quantity of drying material and enhances drying rate due to maintaining higher temperature. It increases the temperature about 20–50% and 20–30% with and without any external sources respectively as compared to ambient temperature. Weather conditions may also affect the temperature range.
- With the aid of other heat source and heat storage materials like pebble bed, sand bed with force circulation of the air, the drying rate and duration enhances. Among various types of covering material, polycarbonate sheet and polyethylene sheet have high transmittance. UV treated polyethylene sheet distribute the radiation evenly in dryer.
- The shape and orientation of the dryer affects the amount of energy captures from solar radiation. When the applying insulation on north side wall found also effective to prevent heat losses from the dryer.

There is a lot of scope to utilise 50% to 60% wasted energy to increase the productivity of solar dryer. The material handling trays may be rearranged according to flow pattern of drying air. Phase change material may also effective for energy storage in shining and utilise this energy in absence of sun light.

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