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Review Article

A review on thermal analysis of hybrid greenhouse solar dryer (HGSD)

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ABSTRACT

The objective of the paper is to present the modifications done in hybrid greenhouse solar dryers to make them more efficient. As hybrid dryers were developed to overcome the various limitations of other types of solar dryers. Due to modifications in dryers, the effect on various heat transfer parameters like heat transfer coefficient, drying time, drying efficiency, etc. is studied and also encapsulated in the paper. It is found that in most of the hybrid dryers, the maximum temperature of the drying chamber is around 65–80°C. This shows the suitability of a hybrid dryer for drying high moisture crops. Also, the drying time for most of the crops is around 2–3 days, which shows the faster moisture removal rate inside the hybrid dryers. According to the literature studied, the maximum drying efficiency of a hybrid dryer is reported by about 35%. The paper also encapsulates the various relations/equations used by different researchers to carry out the thermal modeling and heat transfer analysis of greenhouse dryers.

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INTRODUCTION

For the existence of human life in earth, the food is one of the basic requirements. The rising population puts pressure on the food production. This rising demand of food can be met either by growing more food or storing the produced food for meeting the future need. The reduction in after harvest loss can also help in meeting the need of food products. The development of solar dryers helps in reducing the after harvest loss of various agro and non-agro products. Most of the agro based products gets spoiled due to presence of high moisture content in them.

The drying is considered as the best way to make the product suitable for long time storage [1–4]. In solar dryers the produce is dried to safe moisture level. The minimum quantity of moisture at which the product is safe for long time storage is considered as safe moisture level [5]. The drying of product gives long life to the product and prevents it from microbial attack [6,7]. Apart from solar dryers, artificial dryers were also used for drying at faster rate [8] but these are operated using non-renewable energy sources and also affects the quality of dried product [9].

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The solar drying is an efficient technique of utilizing solar radiation for space heating and drying products [10–12] as solar energy is inexhaustible and eco-friendly energy source [13,14]. From very ancient period, the open sun drying is practiced for drying various agro and non-agro products [15,16] but it has lot of limitations like dried product gets affected by birds, pest, rain, microbes etc. [17–19]. Hence the solar dryers were developed to counter the limitations of open sun drying [20] and these are also sustainable and eco-friendly [21,22]. The solar dryers are basically of three types namely direct, indirect and mixed-mode dryers [23].

Greenhouse dryers are generally the direct type dryers, which are considered as the best mean to harness solar energy for space heating and drying [24]. It works on the principle of greenhouse effect that implies that the cover of greenhouse dryer allows the short wavelength solar radiation through it while the long wavelength radiation coming from inside remains trapped inside the dryer. This rises the inside temperature of dryer which is required for drying purpose [25,26]. The greenhouse dryers have various applications like drying, aquaculture, soil solarisation, crop cultivation, space heating, etc. [27,28]. The greenhouse is not limited to drying of agro products but also used for drying non-agro products like cotton, sludge, paper, rubber etc. [29–32]. The greenhouse operates usually in either active or passive modes. Figure 1 shows the detailed classification of greenhouse dryers.

In an active greenhouses, the air is forced or induced by some external means like fans blowers, etc. [34]. Thus requiring extra energy for the operation of external devices [35], while the passive greenhouses do not require any such devices. The density difference arising due to temperature change establishes the air circulation in passive dryers [36,37]. In terms of cost, passive dryers are preferred while for faster drying active dryers are preferred [38,39].

Greenhouse dryers operating in active or passive mode give better results in terms of quality, color, drying time, etc. as compared to drying under the open sun [21,40]. Various researches had taken place to improve the efficiency of greenhouse dryers like insulating north wall [29,30,41–43], using mirrors for reflecting infrared radiations [44], using thermal storage material in floor [10,29,32,45,46], etc. The hybrid dryers are also a step towards the use of solar energy in a more effective manner and improving the productivity of greenhouses. Simply a word hybrid means a combination

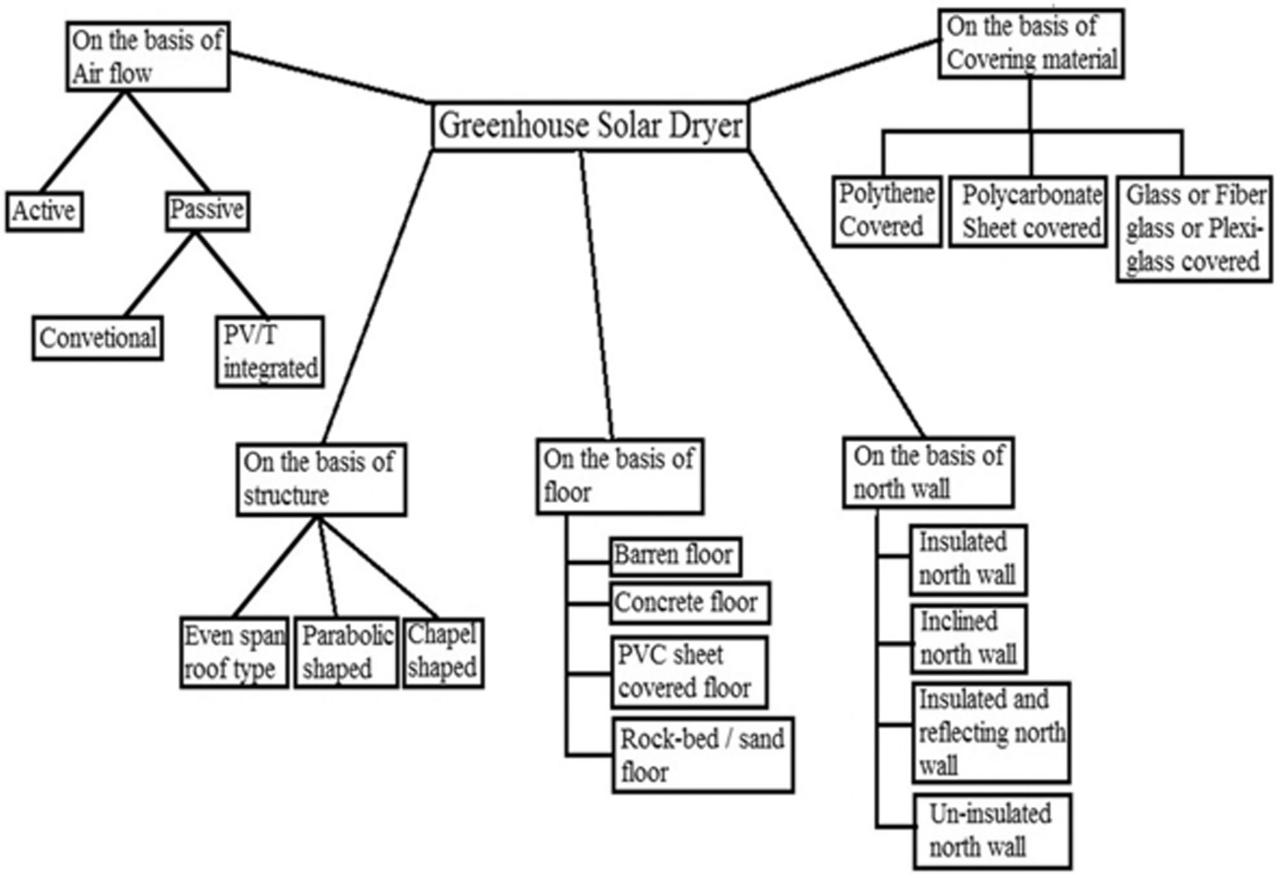

Figure 1. Classification of the greenhouse on the various basis [24].

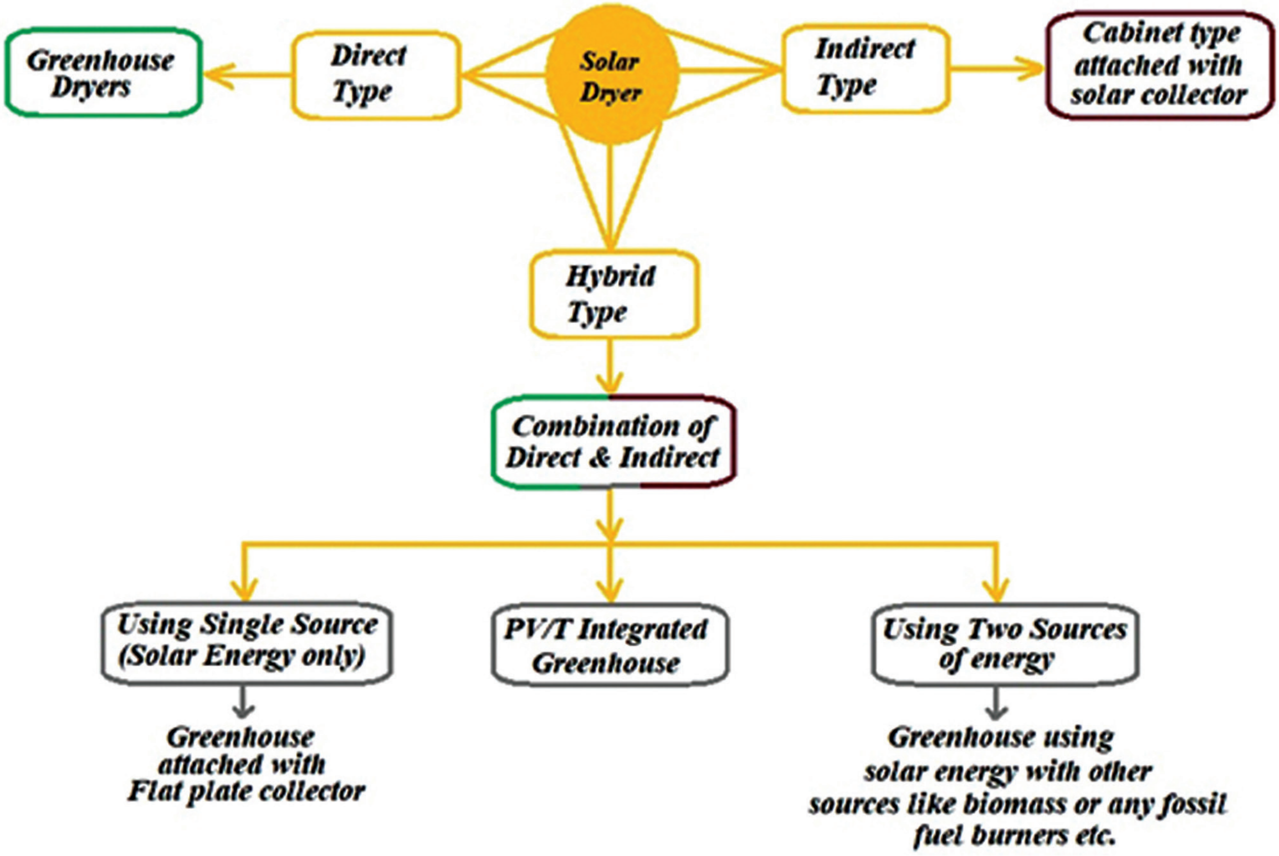

Figure 2. Methods used for making greenhouse hybrid.

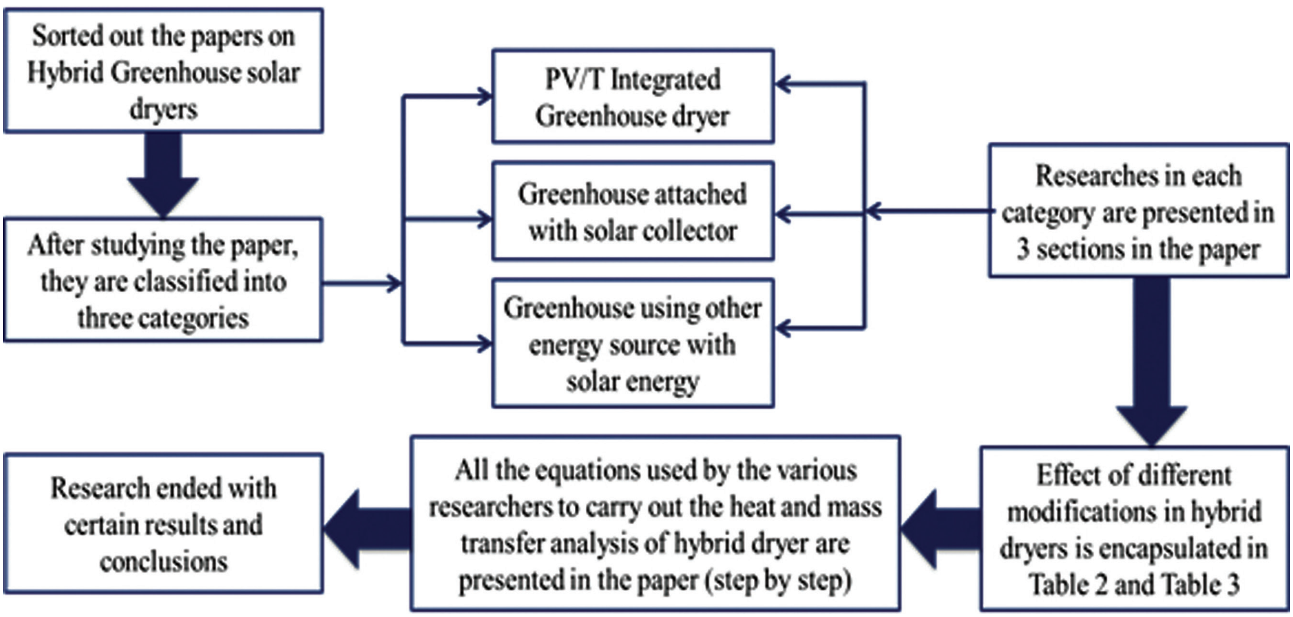

Figure 3. The methodology adopted to carry out this review.

of two or more than two. So hybrid greenhouses are those which utilize two sources of energy or utilize single source (solar energy) in different ways. As per our literature review, the methods by which the greenhouses are converted into a hybrid greenhouse are shown in Figure 2. It depicts that the greenhouses are converted into hybrid ones by three methods given below:

i) PV/T integrated greenhouse solar dryers [47–52]
ii) Greenhouse attached to solar collectors [43,53–57]
iii) Greenhouse attached with other air heating devices like biomass or any other fossil fuel burners [58–65]

The main objective of this paper is to present the advances that took place in the area of hybrid greenhouse solar dryers. The paper also encapsulates the steps that are adopted by different authors to carry out the heat transfer analysis of hybrid dryer. This helps the researchers in understanding the concept of heat transfer in the dryer so they implement some new ideas to make more efficient dryers. The methodology adopted to make this review paper is shown in Figure 3.

RESEARCHES IN HYBRID GREENHOUSE DRYER

The produces are mainly dried to safe moisture levels so that it can be preserved for a long time. The safe moisture level (SML) of some of the crops is shown in Table 1. As solar drying is the best process of crop conservation and hybrid dryer are further making the drying process more efficient. Different modifications are employed by researchers in past to improve the dryer efficiency and the hybrid dryer is one of the development. To make the dryer hybrid, the different methods employed are shown below along with the effect of those methods on various heat transfer parameters is given in Table 2 and Table 3.

PV/T integrated HGSD

The dryers are usually made hybrid by attaching the PV/T modules for generating electric energy to operate the fan and other auxiliary devices. PV/T panels are those which not only produce electricity from solar energy but also use the incident solar radiation for heating the air inside the dryer. One of the ways used to attach PV/T in HGSD is illustrated in Figure 4. Barnwal and Tiwari (2008) developed the PV/T integrated HGSD at IIT, New Delhi, India. The dryer was even spanned roof type having 6.5 m^2 floor area and enclosed with polyethylene sheet. DC fans operated by PV modules were used to force air inside the dryer. Matured (GR-II) and pre-matured (GR-I) grapes were dried under the open sun and also inside the dryer and the observations of both were compared. The heat

Table 1. SML of some of the crops

Type of Crop	SML (%)	References	Type of Crop	SML (%)	References
Fruits			**Vegetables**		
Carrot	12.7	[66]	Peas	6.2	[66]
Sweet Potato	5.9	[66]	Irish Potato	6.2	[66]
Mango chip	8.74-11.43	[67]	Cabbage	21.6	[66]
Mango seed	9.147	[68,69]	Turnip	16.6	[66]
Banana	9.95	[70]	Spinach	4.7	[66]
Melon	7.48-9.26	[71]	Corn	9.1	[66]
Guava	6.94	[72]	Dried Tomato	18.28	[66]
Carrot	9	[73]	Ripen chilli	7-10	[10,74]
Grapes	15-20	[75]	Bitter gourd	5	[76]
Apricot	18	[77]	Pulses	9-10	[78]
Grains			**Cash crops**		
Maize	13	[79]	Cocoa	0.8-2.51	[80]
Wheat	13	[79]	Groundnut	5.5-7	[81]
Oats	12	[82,83]	Rubber	29.7	[84]
Millet	12	[79]	Tea	6.8	[85]
Soyabean	11	[83]	Coffee	12	[86]
Sunflower (30-50% oil)	8	[83]	Alligator Pepper	14.53	[87]
Rice	13	[88]	Mushroom	10	[89]

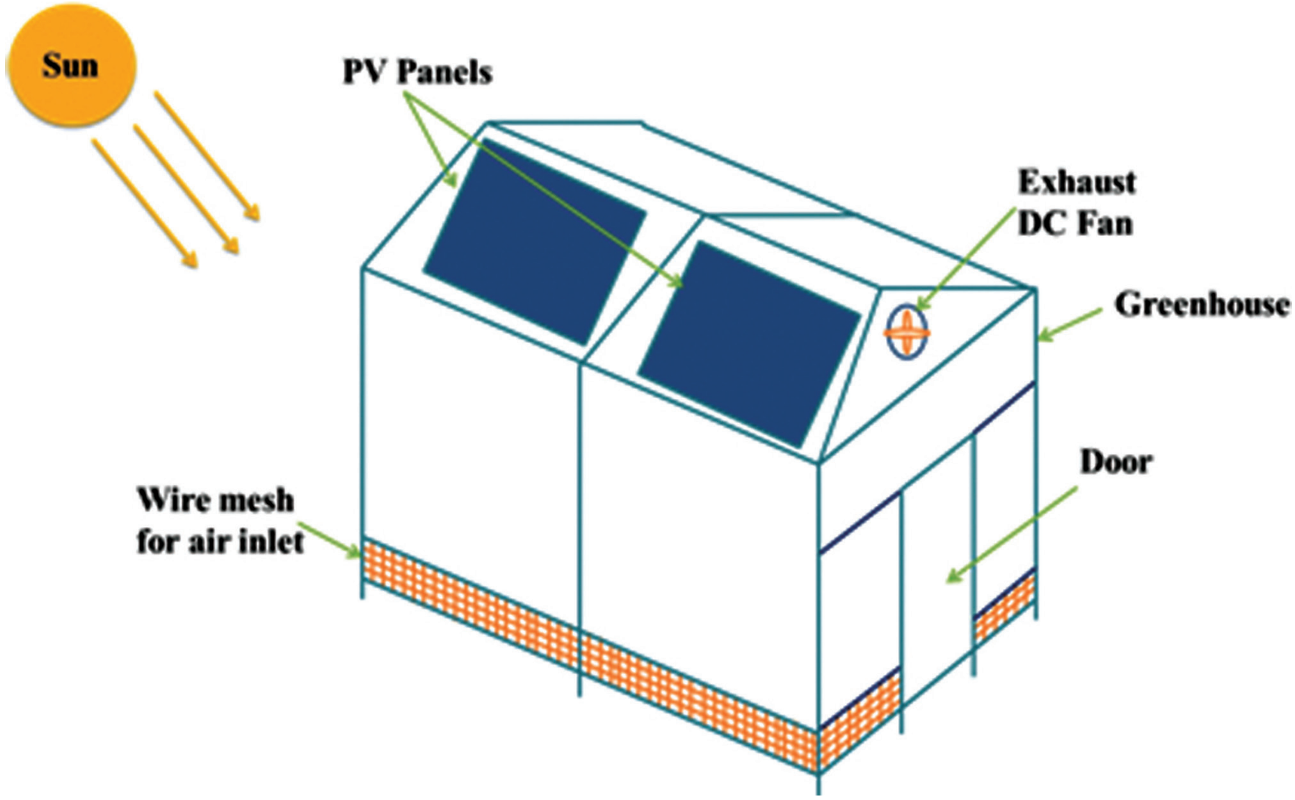

Figure 4. PVT integrated HGSD [47].

transfer coefficient for the GR-II type was found greater than GR-I type [47].

Barnwal and Tiwari (2008) carried out the test on the greenhouse dryer using the thermal loss efficiency factor. The dryer was operated in no-load under active as well as in passive mode. The thermal loss efficiency was observed higher in forced mode [48]. Tiwari et al. (2016) developed the PV/T integrated mixed-mode hybrid dryer having ground area of 1.066 m^2 and was enclosed with 3mm glass. Two DC fans operated by PV panels were provided for forced circulation of air. MATLAB 2013a was used for numerical computation of thermal models developed considering parameters like the temperature of the crop, greenhouse, PV module, etc. [90].

Eltawil M. A. et al. (2018) developed the tunnel type dryer attached with flat-plate collector and PV panels. The dryer had a ground area of 2 m^2 and was enclosed with 2mm thick plexiglass. The dryer was tested with and without load and also with and without a thermal curtain. The potato was dried inside the dryer and the drying rate was observed at a different air flow rate. The drying efficiency reaches a maximum value of 34.29% when air flows at the rate of 0.0786 kg/s with a thermal curtain above the potato slices [91].

Nayak et al. (2011) evaluated the dryer performance by drying various samples of mint. In 21 hours, the mint was dried from 80% (wb) to 11% (wb) moisture content. The dryer had an efficiency of about 34.20%. The CO_2 mitigation and carbon credit earned by the dryer in its lifetime was also evaluated [51].

Greenhouse attached with solar collectors

Solar collectors were also used by different researchers to preheat the air externally in the collectors and then supplying it to the greenhouse drying chamber. The schematic representation of the HGSD attached to the solar collector is shown in Figure 5**.**

Zaineb Azaizia et al. (2017) developed the hybrid greenhouse having a ground area of 14.8 m^2 and a center height of 3 m. The plexiglass enclosed dryer was attached with a solar collector having area 2 m^2. The mathematical model for the proposed system was established using the TRNSYS program. The effect of air flow rate, collector, and drying area on the humidity and temperature inside the dryer was investigated. The result shows that the optimum collector area was 2 m^2 with an optimum airflow rate of 250 kg/h and an optimum drying area of 40 m^2 [53].

Table 2. Effect on different heat transfer parameters observed by different researchers in hybrid dryers

Authors	Type	Concluding Remarks
Barnwal and Tiwari [47]	PV/T integrated greenhouse solar dryer	• Moisture evaporation in natural convection was found better than in forced convection. • Ripen fruits have a higher heat transfer coefficient thus faster moisture removal rate.
Barnwal and Tiwari [48]	PV integrated hybrid Greenhouse dryer	The dryer thermal loss efficiency factor was almost equivalent to the solar air flat plate collector which is about 80%.
Tiwari s. et al. [90]	Mixed-mode type greenhouse dryer	For faster drying and better dryer efficiency, room and crop surface temperature needs to be higher.
Eltawil M.A. et al. [91]	PV operated Mixed-mode solar tunnel dryer	• Pretreatment (Blanching) reduces the drying time of the product as compared to the untreated product. • For the better collector and tunnel dryer efficiency, an optimum airflow needs to be maintained as a higher airflow rate decreases the efficiency and vice versa.
Nayak S. et al. [51]	PVT integrated greenhouse dryer	The storage life of the product is higher at the lower value of moisture content.
Azaizia Z. et al. [53]	Flat plate solar air collector attached greenhouse solar dryer	The drying rate is strongly influenced by the area of the crop surface. It decreases with an increase in area as more moisture is to be evaporated.
Eltawil MA et al. [54]	Flat plate solar collector integrated tunnel dryer	Dehumidification of supply air can increase the moisture evaporation rate from the crop surface.
ELkhadraoui A. et al. [55]	Greenhouse attached with solar collector	• The drying capacity of air inside the greenhouse increases with a decrease in its relative humidity and an increase in its flow rate. • Forced convection gives a better result than natural convection.
Mehta P. et al. [56]	Flat plate solar collector integrated greenhouse dryer	• Dryer efficiency and moisture evaporation rate is affected by collector efficiency, so the collector should be designed and fabricated with great care. • Suggested to recirculate the air going out of the dryer to utilize available energy in a better way and improve dryer performance.
Chauhan and Kumar [43,57]	Greenhouse integrated with a solar collector at the ground	• Solar collector inside the dryer increases the convective heat transfer coefficient which signifies a higher conversion rate of solar energy into useful heat energy. • The heat utilization factor is directly related to the heat generation inside the dryer.
Deeto S. et al. [58]	Greenhouse solar dryer attached with hot water storage system	During day time, water is heated by circulating it inside the dryer and then storing it in the storage tank. That hot water was used to continue the drying operation during night time. Thus water is used as the thermal energy storage medium.
Hamdani et al. [59]	Solar-biomass hybrid dryer	Due to improper circulation of air, the moisture evaporated from the product makes the room air saturated and thus reduces the drying rate. So proper ventilation is to be provided.
Kıyan M. et al. [60]	Greenhouse attached with evacuated tube collector and auxiliary heater	The developed simulation model was used to optimize the size of the solar collector and thermal storage system. Width of air flowing channel and thickness of packed bed affects the crop temperature.
Dilip Jain [61]	Greenhouse attached with crop dryer having packed bed thermal storage	Thermal energy storage reduces the temperature fluctuations during night time and thus drying at night becomes more consistent.
Fudholi A. et al. [62]	Greenhouse having drying chamber with diesel burner	Carried out the energy and exergy analysis of the proposed hybrid setup.
Aritesty and Wulandani [63]	Rack type greenhouse dryer with a biomass burner	The dryer efficiency can be increased by reducing heat losses through the wall, chimney, and heat absorbed in its metallic components.
Serm Janjai [64]	Greenhouse attached with LPG gas burner	For high moisture content crops like tomato, the drying rate needs to be faster, which is possible in the solar dryer rather than in the open sun.

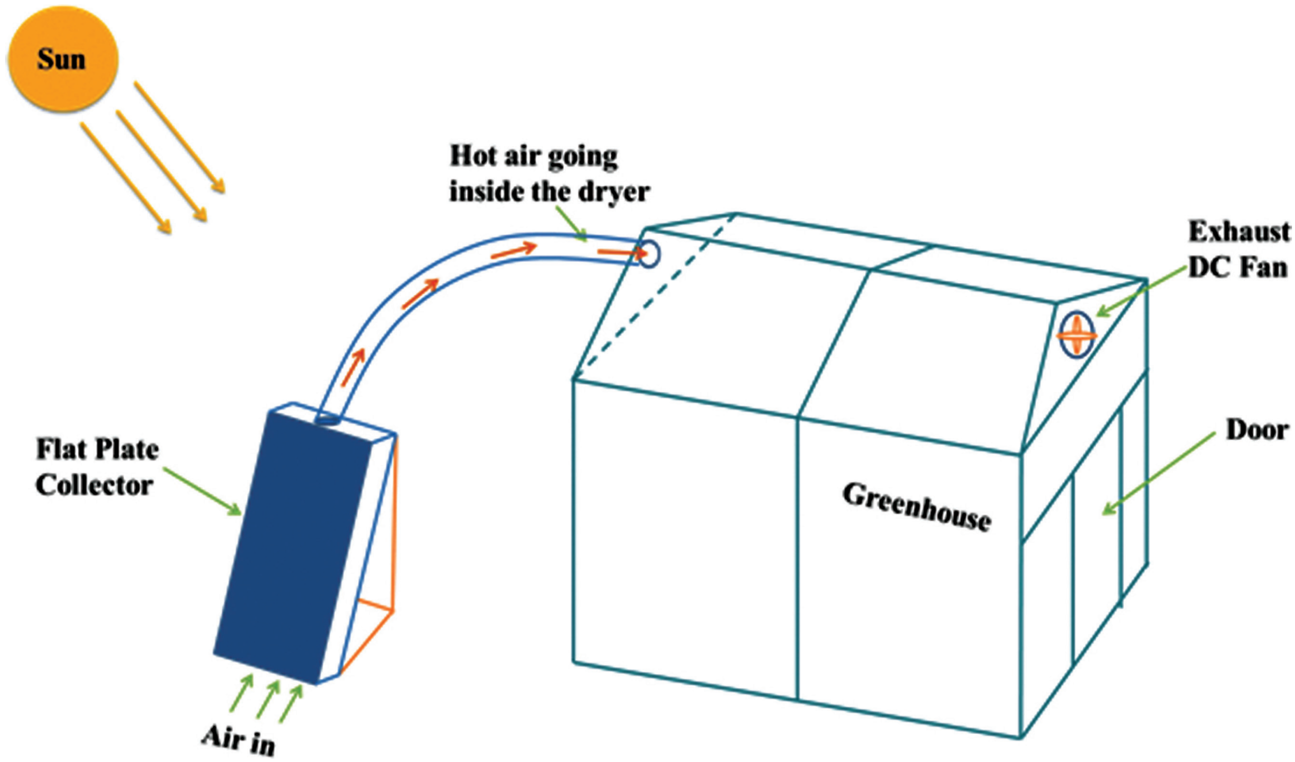

Figure 5. Greenhouse dryer integrated with a flat plate collector.

Eltawil M.A. et al. (2018) developed the tunnel type dryer coupled with flat-plate collector and PV panels at King Faisal University, Saudi Arabia. The peppermint is dried inside the dryer in one, two, and three layers for evaluating dryer performance. The maximum drying time was 360 min inside the dryer while 420 min in the open sun. The use of a thermal curtain gives better quality mint as compared to drying under the open sun. The dryer had an efficiency of 30.71% and an energy payback time of 2.06 years [54]. ELkhadraoui A. et al. (2015) carried out the economic analysis and performance evaluation of the dryer. The dryer operated in forced convection mode and used for drying red peppers and grapes. The dryer payback duration was 1.6 years. The result shows that the drying time for grapes and red pepper was 50 hours and 17 hours respectively inside the dryer while it was 67 hours and 24 hours respectively in the open sun [55].

A semi-cylindrical greenhouse dryer with a flat-plate collector was constructed by Mehta P. et al. in 2018. Fish was dried inside the dryer to test its performance. To predict the collector temperature at its outlet, a mathematical model was established and then solved by the SageMath programming language. The drying time of fish was 18 hours inside the dryer while it takes 38 hours in the open sun [56]. Chauhan and Kumar (2016) constructed the north wall insulated greenhouse at Energy Centre, MANIT, Bhopal, India. The greenhouse was tested with and without a solar collector. The dryer was operated in passive mode and tested in a no-load condition. The dryer performance in terms of heat utilization factor (HUF), coefficient of performance (COP), heat loss factor, etc. were calculated. The result shows that the dryer with a collector has better HUF and COP than the dryer without a collector [43,57].

Other air heating devices attached to greenhouse

The other method applied to the greenhouse dryers is the attachment of auxiliary air heating devices like biomass or LPG burner. These devices supply the hot air during the off sunshine period also. This increases the operating time of dryer so its drying time also gets reduced. The schematic representation of the HGSD attached to solar collectors and water as a thermal heat storage medium is shown in Figure 6. The HGSD with auxiliary heaters and thermal storage materials is presented in Figure 7 (a) and Figure 7 (b) respectively.

Deeto S. et al. (2017) developed a greenhouse attached with a solar collector and heat storage unit. The floor area of the dryer was 0.3 m^2 and mounted on a black PVC sheet. A water storage tank of 180-liter capacity and insulated with polyurethane foam was attached to the dryer for storing

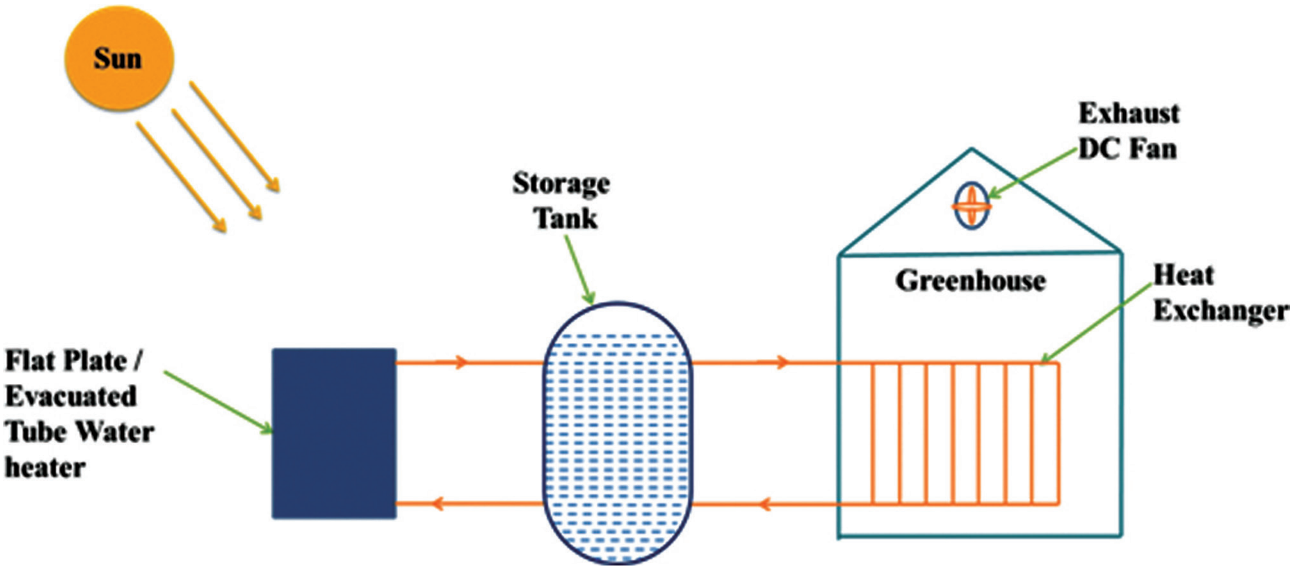

Figure 6. HGSD with solar collector and water as thermal energy storage material.

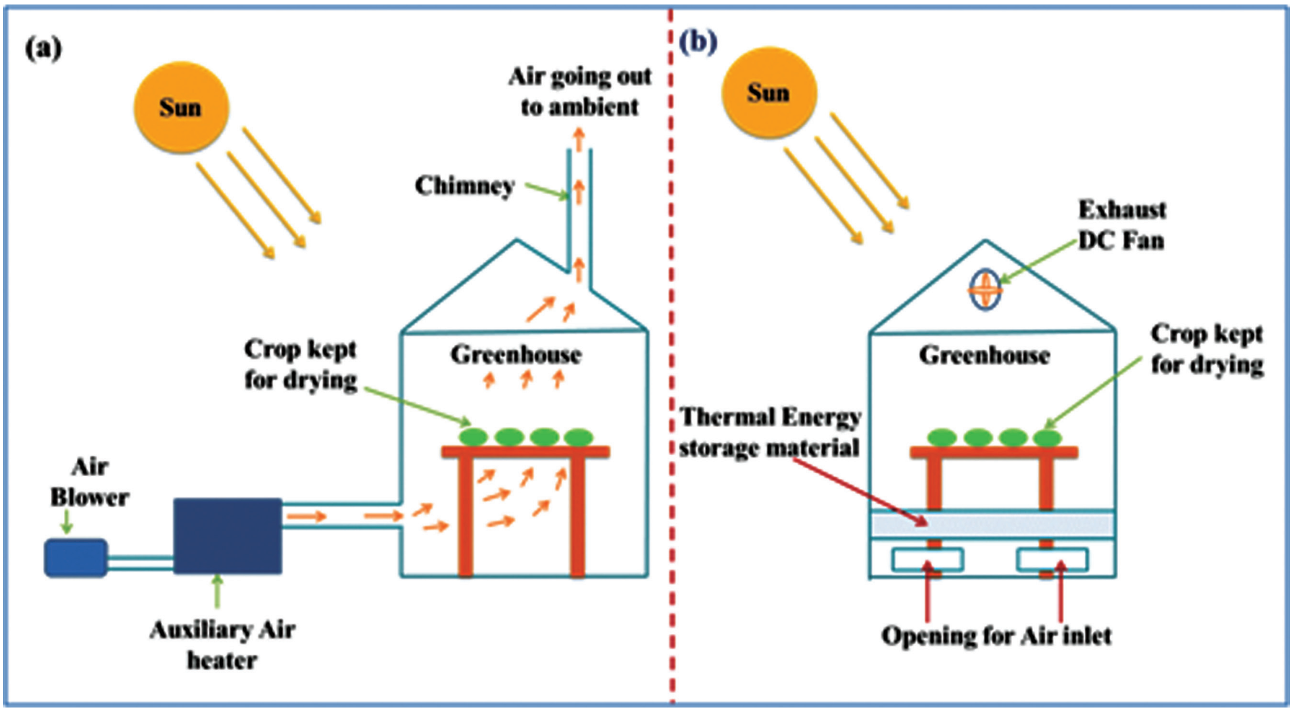

Figure 7. (a) HGSD with auxiliary air heater arrangement **(b)** HGSD with a layer of thermal energy storage material.

hot water. The coffee beans were dehumidified from 55% to 12% (wb) in 12 hours. The model suitable for coffee drying was also determined [58].

Hamdani et al. (2018) manufactured the tunnel type greenhouse dryer attached with biomass burner at Samudra University, Aceh, Indonesia. The drying area was 2.08 m^2 and the dryer was enclosed with a transparent plastic sheet. The Queenfish was dried for evaluating the dryer performance. Wood was used as fuel for supplying hot air during off-sunshine hours. The result shows that in 15 hours only the fish was dried to 12% moisture level [59]. Kıyan M. et al. (2013) proposed a hybrid greenhouse attached with a hot water storage unit and fossil fuel heater. The mathematical model had been developed for the proposed setup.

Table 3. Effect of modifications observed by some of the researchers in their solar dryers

Type of solar dryer	Effect on heat transfer parameters	References
Dryer with a heat exchanger having a reflector and corrugated sheet	• Drying time was decreased by about 30 hours as compared to open sun drying (OSD). • The room air temperature rose to above 50°C during the summer season of Germany.	[92]
Wooden frame dryer with a polythene cover	• The air temperature inside the direct type dryer reached maximum to 55.1°C and 38.4°C for natural and forced mode respectively. • The drying rate was observed higher in the forced mode.	[93]
Dryer attached with air heater in series	• The drying efficiency increases from 3.56 to 11.24% with an increase in loading capacity from 1.08 to 4.33 kg/m^2 respectively. • With an increase in the thickness of the potato chips from 5 to 18 mm, the drying efficiency decreases from 10.61 to 3.11% respectively.	[94]
PV attached greenhouse dryer	• Dryer takes about 2 days less than OSD for drying peeled longan and banana. The room temperature varies between 30-60°C. • The payback time of the developed commercial setup is only 2.3 years.	[95]
Dryer with heat exchanger and water type solar collector	• The air temperature inside the hybrid dryer reaches to the maximum value of 65°C. • The drying time of 100 kg tomatoes is 4 days and the payback time of setup is 1.37 years.	[96]
Dryer with auxiliary heater and double-pass solar collector	• The average exergy efficiency of the prosed setup was 30%. • The air temperature inside the dryer varies between 35–60°C.	[97]
Cabinet dryer with solar collectors	• The use of solar energy for cocoon drying saves the electrical energy by 0.75 kWh/kg. • The dryer was operated in forced mode and the air temperature varies from 50-80°C inside the drying chamber.	[98]
Polycarbonate covered greenhouse dryer with PV modules	The drying time for drying 1000 kg of banana, chili, and coffee was reduced by 2 days in dryers as compared to OSD. The maximum room temperature was 60°C.	[99]
HGSD with insulated North wall and solar collector	• The use of solar collectors increases the convective heat transfer coefficient by about 22 W/m^2°C and room temperature by 10°C. • The maximum energy and exergy efficiency of the modified dryer was 16.8% and 21.4% respectively.	[100]
Dryer with flat plate collector	• The quality of banana chips was found best at the air flow rate of 0.0338 m^3/s. • At bottom flow condition, the maximum collector temperature reaches to 45°C.	[101]

The models were solved by simulation software MATLAB/Simulink. A case study had been done on the greenhouse at Aılım University, Ankara, Turkey to check the feasibility of the developed models [60].

Dilip Jain (2005) developed a hybrid solar dryer in which the tray-type dryer including thermal storage material at the bottom was attached to the north wall of the greenhouse. During day time, the heated air from the greenhouse is supplied to the drying cabinet through blower while during off sunshine hours the heat stored in the thermal storage material was used for drying. The greenhouse had a floor area of 24 m^2. The thermal model was developed to determine the effect of size and mass flow rate of air on the crop temperature [61]. Ahmad Fudholi et al. (2016) developed the hybrid dryer incorporating solar collectors, PV panels, and diesel burners. The developed dryer is located at Johor, Malaysia. Silver Jewfish was dried inside the dryer to evaluate its energy and exergy. The result shows that fish was dried from 64% to 10% (wb) in 8 hours. Also, the dryer exergy efficiency lies between 17-44% [62].

Aritesty and Wulandani (2014) developed the greenhouse solar dryer attached with a biomass burner. The dryer consist of 144 trays and 3 blowers. Wild ginger was dried to test the dryer performance. The dryer was tested in no-load and also in two loads condition i.e. 21 kg and 60 kg. The result shows that drying time and drying efficiency increases with increase in load [63]. Serm Janjai (2012) constructed the parabolic shaped greenhouse attached with LPG gas burner at Nakhon Pathom, Thailand. The dryer had a ground area of 160 m^2 and enclosed it with a polycarbonate sheet. PV panel operates the nine DC fans provided to maintain the air circulation. The highest temperature recorded inside the dryer was 65 °C. The tomatoes were dried from 54% to 17% (wb) in 4 days [64].

STEPS TO DO THE HEAT AND MASS TRANSFER ANALYSIS OF DRYER

Energy Balance inside the dryer

Energy balance is the balancing of incident energy coming from different sources with the energy released or stored within the system. For the complete drying system, the energy and moisture balance was proposed by Zaineb et al (2017) as given by Eq. 1 and Eq. 2.

Energy balance Eq. for drying system,

$$C_{tca}\frac{dT_a}{dt} = \dot{Q}_{sa} + \dot{Q}_{if} + \dot{Q}_{vt} + \dot{Q}_{gdc} + \dot{Q}_{cgz} \tag{1}$$

Where T_a is the air temperature, C_{tca} is the thermal capacitance of air, t is the time, $\dot{Q}_{sa}$ is the total heat gain from all surfaces, $\dot{Q}_{if}$ is the heat gain through infiltration, $\dot{Q}_{vt}$ is gain through the ventilation system, $\dot{Q}_{gdc}$ is the convective heat gain through instruments and occupants and $\dot{Q}_{cgz}$ is the convective heat gain due to the coupling of zones.

Moisture balance

$$M_{ef} = \frac{d\omega_g}{dt} = \dot{m}_{if}\left(\omega_o - \omega_g\right) + \dot{m}_{vt}\left(\omega_{vt} - \omega_g\right) + W_{ag} \tag{2}$$

Here, M_{ef} is the effective moisture capacitance, ω_o, ω_g and ω_{vt} is the humidity ratio of outside air, greenhouse air and air passing through vent respectively, $\dot{m}_{if}$ and $\dot{m}_{vt}$ are the infiltration and ventilation mass flow rate respectively.

For the greenhouse chamber, the energy balance is given by Tiwari et al (2016) as follows:

$$\begin{aligned} h_{cp}\left(T_{cp} - T_{rm}\right)A_{cp} &= \dot{m}_a C_a\left(T_{rm} - T_0\right) \\ &+ \left(\sum U_{gr} A_d\right)\left(T_{rm} - T_0\right) \end{aligned} \tag{3}$$

Where, h_{cp} is the convective heat transfer coefficient from crop to drying chamber, T_{cp}, T_{rm}, T_o are the crop surface, room, and ambient temperature respectively, A_{cp} and A_d are crop surface and dryer area respectively, $\dot{m}_a$ is the mass flow rate of air and U_{gr} is the overall heat transfer coefficient from greenhouse room air to ambient through canopy cover.

For the greenhouse type dryer, if the drying cabinet is kept separate from the greenhouse chamber, the energy balance Eq. for the air inside the drying cabinet is given as [61],

$$\begin{aligned} &\left[\left(1-\alpha_g\right)\left[1-F_n\right] + \rho' F_n\right]\sum I_i A_i \tau_i + h_{nr}\left(T\big|_{z=0} - T_r\right)A_n \\ &+ h_{gr}\left(T\big|_{y=0} - T_r\right)A_d = M_a C_a \frac{dT_r}{dt} \\ &+ \sum U_i A_i\left(T_r - T_a\right) + \dot{m}_a C_a\left(T_r - T_a\right) \end{aligned} \tag{4}$$

Energy balance Eq. for separated drying chamber,

$$h_{cz}\left(T_{cz} - T_{ch}\right)A_c = \dot{m}_a C_a\left(T_{ch} - T_a\right) + h_{ch}\left(T_{ch} - T_a\right)A_{ch} \tag{5}$$

Where C_a is the specific heat capacity of air and A_{ch} is the area of drying chamber.

Energy balance for the dryer operating in no-load condition [56],

$$\dot{m}_a C_a\left(T_{do} - T_{di}\right) = A_a h_{pf}\left[\left(T_{pl} - T_{ca}\right) - \frac{h_{fg}}{h_{pf}}\left(T_{ca} - T_{gl}\right)\right] \tag{6}$$

T_{ca}, T_{pl}, T_{gl} is the collector air, plate, and glass temperature respectively, T_{di} and T_{do} is the air temperature at the inlet and outlet of dryer and h_{pf} is the convective heat transfer coefficient from plate to the fluid.

For parabolic shaped hybrid greenhouse with LPG burner for auxiliary heating of air, the energy balance Eq. used for air inside dryer [64],

$$\begin{aligned} &m_a C_{pa}\frac{dT_a}{dt} = A_a h_{c,p-a}\left(T_p - T_a\right) + A_f h_{c,f-a}\left(T_f - T_a\right) \\ &+ D_p A_p C_{pv}\rho_p\left(T_p - T_a\right)\frac{dM_p}{dt} + \left(\rho_a V_{out} C_{pa} T_{out} - \rho_a V_{in} C_{pa} T_{in}\right) \\ &+ U_c A_c\left(T_{am} - T_a\right) + \left[\left(1-F_p\right)\left(1-\alpha_f\right) + \left(1-\alpha_p\right)F_p\right] I_t A_c \tau_c \end{aligned} \tag{7}$$

The Eq. used for mass balance,

$$\begin{aligned} \rho_a\frac{VdH}{dt} &= A_{in}\rho_a H_{in} V_{in} - A_{out}\rho_a H_{out} V_{out} \\ &+ D_p A_p \rho_d\left(T_p - T_a\right)\frac{dM_p}{dt} \end{aligned} \tag{8}$$

Here, ρ_a is air density.

To calculate the convective heat transfer coefficient, Barnwal and Tiwari (2008) proposed the Eq. for active as well as passive mode:

For Active Mode,

$$\ln\left[\frac{m_{evp}}{R}\right] = lnC + nln(Re) + nln(Pr) \tag{9}$$

C, n, and *R* are constants, *Re, Pr* is Reynolds, and Prandtl number respectively. Reynolds number is the ratio of the inertia to viscous force within the fluid while the Prandtl number is the ratio of momentum to thermal diffusivity of fluid.

For Passive Mode,

$$\ln\left[\frac{m_{evp}}{R}\right] = lnC' + n'ln(Gr) + n'ln(Pr) \qquad (10)$$

Mass evaporated from crop per hour (m_{evp}) is usually calculated to know the quantity of moisture evaporating from the crop surface per hour,

$$m_{evp} = \left[\frac{0.016K_h\left[P\left(T_{cp}\right) - Rh\cdot P\left(T_0\right)\right]}{L_{cr}\cdot LHV}\right]\times Nu \qquad (11)$$

K_h is the thermal conductivity of humid air, L_{cr} is characteristic Length, *LHV* is the latent heat of vaporization, *Rh* is Relative humidity of the air, and *P(T)* is partial vapor pressure at temperature T.

Nusselt number *(Nu)* is the dimensionless number that shows the increase in heat transfer due to convection over conduction while the Grashof number *(Gr)* is usually the ratio of buoyancy to viscous force. Nusselt number is usually calculated to compute the value of the convective heat transfer coefficient.

Moisture removed from the dried product was calculated using [54,91];

$$M_C = \frac{m_l\left(m_{in} - m_{fi}\right)}{\left(100 - m_{fi}\right)} \qquad (12)$$

The relation used to determine the moisture content at any time t, moisture removal rate (MR), and the drying rate of the crop is given by Eq. 13 to Eq. 15 [55].

$$M_t = \frac{m_t - m_d}{m_d} \qquad (13)$$

The ratio of moisture removed from the crop at any time '*t*' to the initial weight of crop is termed as moisture removal rate and is calculated as,

$$MR = \frac{M_t}{M_o} \qquad (14)$$

$$DR = \frac{M_{t+\Delta t} - M_t}{\Delta t} \qquad (15)$$

Here, m_d is dry material in the crop, m_{in}, m_{fi}, m_t is the initial mass, final mass, the mass of crop at any time t, M_0 is the initial moisture content in the crop.

The efficiency of the drying system

Instantaneous thermal loss efficiency factor under passive and active mode is given by Eq. 16 and Eq. 17 respectively [48].

$$\eta_{i,nt} = 1 - \frac{\left[U_{gr}\left(\sum A_t - \sum A_{pv}\right) + U_{pv}\sum A_{pv}\right]\left(T_{rm} - T_0\right)}{I(t)A_{fa}} \qquad (16)$$

$$\eta_{i,fr} = \frac{0.33N_aV_g\left(T_{rm} - T_0\right)}{I(t)A_{fa}} \qquad (17)$$

N_a is the number of air exchange, *I(t)* is solar insolation intensity inside the dryer, A_{fa}, A_t, A_{pv} is the floor, tray, and PV area respectively. U_{pv} is the overall heat transfer coefficient from greenhouse room air to surrounding through the PV module, which is calculated as,

$$U_L\sum A_t = U_{gr}\left(\sum A_t - \sum A_{pv}\right) + U_{pv}\sum A_{pv}$$

Where U_L is taken 6 W/m^2°C [48].

Electrical efficiency of PV Panel attached to a dryer for supplying the electrical power to fan is given as [48],

$$\eta_{el} = \left(\frac{0.8V_{ocv}I_{scc}}{A_{pv}I_{pv}}\right)\times 100 \qquad (18)$$

V_{ocv} is the open-circuit voltage, I_{scc} is the short circuit current and I_{pv} is the solar radiation intensity normal to PV panel.

Daily drying efficiency was calculated by Nayak et al. using the relation given by Eq. 19 as [51],

$$\eta_d = \frac{M_{evp}\times LHV}{I(t)\times A_d}\times 100 \qquad (19)$$

The efficiency of the dryer, when attached with fan or pump [62],

$$\eta_{dr} = \frac{m_e\times LHV}{Q_{fn} + Q_{pm}} \qquad (20)$$

Q_{fn} and Q_{pm} are the thermal energy of the fan and pump respectively.

Overall efficiency or system efficiency or energy efficiency indicates the performance of the entire drying system comprising of solar collectors, drying chamber, and other energy sources. The overall efficiency of the hybrid dryer (η_{dr}) attached with auxiliary air heating devices is given as [58,102],

$$\eta_{dr} = \frac{m_c \times LHV}{A_{ct} I(t) + P_{fn} + E_{as}} \tag{21}$$

m_c is the mass of crop for drying, A_{ct} is the area of collector and E_{as} is the energy supplied from additional energy sources.

Exergy efficiency is an important parameter to indicate the performance of solar dryers. It is the ratio of exergy available at the output (Ex_{out}) to the exergy input to the hybrid dryer (Ex_{in}) [103,104]. It is given by,

$$\eta_{Exe} = \frac{Ex_{out}}{Ex_{in}} = \frac{Ex_{evp} + Ex_{work}}{Ex_{in}} \tag{22}$$

Exergy input to the hybrid dryer is the summation of exergy by the sun, the exergy of PV module, exergy of solar collector, and exergy of any other auxiliary devices. The exergy at the output is the summation of exergy consumed in evaporating the moisture from crop surface (Ex_{evp}) and exergy of work (Ex_{work}).

Exergy efficiency presents a more realistic situation as compared to energy efficiency. As energy efficiency tells that how much work is obtained from the available energy while exergy efficiency tells that how much real work is obtained from the maximum possible available work (ideal condition). Exergy analysis calculates the losses more accurately than energy analysis.

Aritesty and Wulandani (2014) proposed the different relation to calculate the Dryer efficiency [63],

$$\eta_{dr} = \frac{m_c \times LHV + m_c C_c \Delta T_g}{Q_{bio} + Q_{so} + Q_{el}} \tag{23}$$

Q_{bio}, Q_{so}, and Q_{el} are bio, solar and electrical energy respectively.

Other heat transfer parameters

Total energy and exergy gain by the PV/T coupled dryer is given by Eq. 24 and Eq. 25 [90].

$$\dot{Q}_{t,en} = \dot{m}_a C_a \left(T_{rm} - T_0\right) + \frac{\eta_{pv} A_{pv} I(t)}{0.38} \tag{24}$$

$$\dot{Q}_{t,ex} = \dot{Q}_{u,th,ex} + \eta_{pv} A_{pv} I(t) \tag{25}$$

$\dot{Q}_{u,th,ex}$ is the thermal exergy gain.

Solar energy going inside the dryer is given [91] as,

$$E_{i,d} = A_d \int_o^t I_n(t)\,dt \tag{26}$$

Energy going outside the dryer and flat plate collector attached to the dryer is given as [91],

$$E_{o,d} = M_C \times LHV \tag{27}$$

$$E_{o,coll} = \int_o^t \dot{m}_t \times C_a \left(T_{oc} - T_{ic}\right) dt \tag{28}$$

$\dot{m}_t$ is the mass flow rate at time t, $T_{oc,}$ and T_{ic} are outlet and inlet temperature of solar collector respectively.

The daily thermal output of the dryer can be determined as [51],

$$\dot{Q}_{th} = M_c \times \textit{Latent heat of evaporation} \tag{29}$$

The heat required to evaporate the moisture content in the drying product [56],

$$Q = M_c \times LHV \times \frac{\eta_{dr}}{\eta_{cl}} \tag{30}$$

η_{dr} and η_{cl} are dryer and collector efficiency.

Amount of useful energy inside the drying cabinet [58],

$$Q_u = \dot{m}_a C_a \left(T_{oc} - T_{ic}\right) \tag{31}$$

Energy taken by hot air to the ambient can be calculated using the relation [59],

$$Q_h = \dot{m}_a \left(h_h - h_0\right) \tag{32}$$

h_h and h_0 are enthalpies of hot and ambient air respectively.

Chan et al. (2015) proposed the Eq. governing the crop drying as given by Eq. 33 [65],

$$\frac{\partial M}{dt} - D_v \left[\frac{\partial^2 M}{\partial r^2} + \frac{2}{r} \times \frac{\partial M}{\partial r}\right] \tag{33}$$

Where D_v is the thermal diffusivity, M is the moisture removal rate and r is the radial distance.

The convective heat transfer coefficient of air is calculated to determine the heat transfer occurring inside the dryer by using Eq. 34 [43,57].

$$h_{ca} = 0.884 \times \left[\begin{array}{l} \left(T_{grd} - T_{rm}\right) \\ + \dfrac{\left[P\left(T_{grd}\right) - Rh \cdot P\left(T_{rm}\right)\right]\left(T_{rm} + 273\right)}{268900 - P\left(T_{grd}\right)} \end{array}\right]^{1/3} \tag{34}$$

T_{grd} is the ground temperature.

Table 3. Value of heat transfer coefficient for different solar dryer

Crop Dried	Type of Dryer	h (W/m²°C)	Reference
Pear Drying	Air heated solar collector	12.4 – 20.8	[105]
Fenugreek	Indirect Dryer	6.73 (Inside Dryer)	[106]
		2.90 (Open Sun)	
No-load	Modified Greenhouse dryer	3 – 43.2 (With Collector)	[100]
		2.6 – 21.6 (Without Collector)	
Fish	Greenhouse Solar dryer	1.23 – 9.2 (Natural Mode)	[107]
		1.5 – 21 (Forced Mode)	
No Load	North Wall Insulated greenhouse dryer	3.85 – 46.62 (With collector)	[57]
		2.64 – 7.5 (Without Collector)	
Grapes	Greenhouse Solar dryer	0.26 – 1.21 (Forced mode)	[47]
No Load	North Wall Insulated greenhouse dryer	4.20 – 50.02 (With collector)	[43]
	(Natural mode)	2.51 – 19.23 (Without Collector)	
Fish	Greenhouse dryer	1.5 – 19.2 (Forced Mode)	[107]
		1.23 – 9.2 (Natural Mode)	
Onion Flakes	Greenhouse dryer	1.29 – 2.28 (Natural Mode)	[13]
		1.09 – 3.07 (Forced Mode)	
Jaggery	Greenhouse dryer	0.55 – 1.80 (Natural Mode)	[108]
		0.33 – 7.07 (Forced Mode)	

The value of the convective heat transfer coefficient (h) plays a significant role in the drying rate. As higher is the value of h, more is the heat transfer through convection and faster is the drying. It reduces with a reduction in the moisture of the crop and depends strongly on the mass and thickness of the layer. The value of h calculated for different types of the solar dryer is shown in Table 4 and it is found that h is greater in the forced mode as compared to natural mode.

Heat Utilization Factor of the dryer is calculated by Chauhan and Kumar (2016) to indicate the performance of dryer [43,57],

$$HUF = \frac{T_{grd} - T_{rm}}{T_{grd} - T_0} \tag{35}$$

CONCLUSIONS

Hybrid dryers are the future of drying systems, as it not only eliminates the various drawbacks of conventional direct and indirect dryers but also improves the drying rate and drying efficiency. The application of thermal energy storage material in hybrid dryers increases the operating time in a day. This same thing can be achieved by using auxiliary heaters with dryers. The increased operating time, faster drying rate, and higher room temperature make the hybrid dryer suitable for drying high moisture crops. The convective heat transfer coefficient is the most important heat transfer parameter that affects the drying rate as well as drying time. In hybrid dryers, the value of h is about 2-5 times higher than other conventional dryers. The airflow rate is another important parameter that needs to be optimized as it affects the evaporation rate from crop surface to room air. Although the capital cost of hybrid dryers is high that can be compensated by less payback time. As the payback time of commercial hybrid dryers is about 2-3 years only. The use of dehumidifiers can be one modification in hybrid dryers for further boosting up their efficiency. The application of nanoparticle in the dryer can be also one major field for research that might make the drying process faster.

AUTHORSHIP CONTRIBUTIONS

Authors equally contributed to this work.

DATA AVAILABILITY STATEMENT

The authors confirm that the data that supports the findings of this study are available within the article. Raw data that support the finding of this study are available from the corresponding author, upon reasonable request.

CONFLICT OF INTEREST

The author declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

ETHICS

There are no ethical issues with the publication of this manuscript.

REFERENCES

[1] Koyuncu T, Tosun I, Pinar Y. Drying characteristics and heat energy requirement of cornelian cherry fruits (Cornus mas L.). J Food Eng 2007;78:735–739. [CrossRef]

[2] Singh P, Shrivastava V, Kumar A. Recent developments in greenhouse solar drying: A review. Renew Sustain Energy Rev 2018;82:3250–3262. [CrossRef]

[3] Stegou-Sagia A, Fragkou D V. Thin layer drying modeling of apples and apricots in a solar-assisted drying system. J Therm Eng 2018;4:1680–1691. [CrossRef]

[4] Stegou-Sagia A, Fragkou D V. Influence of drying conditions and mathematical models on the drying curves and the moisture diffusivity of mushrooms. J Therm Eng 2015;1:236–244. [CrossRef]

[5] Afolabi IS. Moisture migration and bulk nutrients interaction in a drying food Systems: A review. Food Nutr Sci 2014;5:692–714. [CrossRef]

[6] Vijayan S, Arjunan T V., Kumar A. Exergo-environmental analysis of an indirect forced convection solar dryer for drying bitter gourd slices. Renew Energy 2020;146:2210–2223. [CrossRef]

[7] Tiwari S, Agrawal S, Tiwari GN. PVT air collector integrated greenhouse dryers. Renew Sust Energy Rev 2018;90:142–159. [CrossRef]

[8] Banout J, Ehl P, Havlik J, Lojka B, Polesny Z, Verner V. Design and performance evaluation of a Double-pass solar drier for drying of red chilli (Capsicum annum L.). Sol Energy 2011;85:506–515. [CrossRef]

[9] Mewa EA, Okoth MW, Kunyanga CN, Rugiri MN. Experimental evaluation of beef drying kinetics in a solar tunnel dryer. Renew Energy 2019;139:235–241. [CrossRef]

[10] Janjai S, Khamvongsa V, Bala BK. Development, design, and performance of a PV-ventilated greenhouse dryer. int energy j 2007;8:249–258.

[11] Singh Chauhan P, Kumar A, Tekasakul P. Applications of software in solar drying systems: A review. Renew Sust Energy Rev 2015;51:1326–1337. [CrossRef]

[12] Selvanayaki S, Sampathkumar K. Techno-economic analysis of solar dryers. In: Prakash O, Kumar A, editors. Green Energy Technol. Springer Verlag; 2017, p. 463–493. [CrossRef]

[13] Kumar A, Tiwari GN. Effect of mass on convective mass transfer coefficient during open sun and greenhouse drying of onion flakes. J Food Eng 2007;79:1337–1350. [CrossRef]

[14] Bhardwaj AK, Kumar R, Chauhan R. Experimental investigation of the performance of a novel solar dryer for drying medicinal plants in Western Himalayan region. Sol Energy 2019;177:395–407. [CrossRef]

[15] Vijayavenkataraman S, Iniyan S, Goic R. A review of solar drying technologies. Renew Sustain Energy Rev 2012;16:2652–2670. [CrossRef]

[16] Cerci KN, Akpinar EK. Experimental determination of convective heat transfer coefficient during open sun and greenhouse drying of apple slices. J Therm Eng 2016;2:741–747. [CrossRef]

[17] ELkhadraoui A, Kooli S, Farhat A. Study on effectiveness of mixed mode solar greenhouse dryer for drying of red pepper. Int J Sci Res Eng Technol 2015;3:143–146.

[18] Ramos IN, Brandão TRS, Silva CLM. Simulation of solar drying of grapes using an integrated heat and mass transfer model. Renew Energy 2015;81:896–902. [CrossRef]

[19] Lamidi RO, Jiang L, Pathare PB, Wang YD, Roskilly AP. Recent advances in sustainable drying of agricultural produce: A review. Appl Energy 2019;233–234:367–385. [CrossRef]

[20] Fudholi A, Mat S, Basri DF, Ruslan MH, Sopian K. Performances analysis of greenhouse solar dryer with heat exchanger. Contemp Eng Sci 2016;9:135–144. [CrossRef]

[21] Semple L, Carriveau R, Ting DSK. A techno-economic analysis of seasonal thermal energy storage for greenhouse applications. Energy Build 2017;154:175–187. [CrossRef]

[22] Singh P, Gaur MK. A Review on Role of Solar Drying Technology in Sustainable Development. In: Pandit M, Shrivastava L, Rao RV, Bansal JC, editors. Proc Adapt Learn Optim Intell Comput Appl Sustain Real-World Syst, Springer Nature Switzerland, ICSISCET 2019, PALO 13; 2020, p. 18–27. [CrossRef]

[23] Prakash O, Kumar A. Solar greenhouse drying: A review. Renew Sust Energy Rev 2014;29:905–910. [CrossRef]

[24] Singh P, Shrivastava V, Kumar A. Recent developments in greenhouse solar drying: A review. Renew Sust Energy Rev 2018;82:3250–3262. [CrossRef]

[25] Morad MM, El-Shazly MA, Wasfy KI, El-Maghawry HAM. Thermal analysis and performance evaluation of a solar tunnel greenhouse dryer for drying peppermint plants. Renew Energy 2017;101:992–1004. [CrossRef]

[26] Mohammadi B, Ranjbar SF, Ajabshirchi Y. Application of dynamic model to predict some inside environment variables in a semi-solar greenhouse. Inf Process Agric 2018;5:279–288. [CrossRef]

[27] Chauhan PS, Kumar A, Gupta B. A review on thermal models for greenhouse dryers. Renew Sustain Energy Rev 2017;75:548–558. [CrossRef]

[28] Prakash O, Kumar A. Thermal performance evaluation of modified active greenhouse dryer. J Build Phys 2014;37:395–402. [CrossRef]

[29] Sevda MS, Rathore NS. Performance evaluation of the semicylindrical solar tunnel dryer for drying handmade paper. J Renew Sustain Energy 2010;2:1–19. [CrossRef]

[30] Panwar NL, Kaushik SC, Kothari S. Thermal modeling and experimental validation of solar tunnel dryer: A clean energy option for drying surgical cotton. Int J Low-Carbon Technol 2014;11:16–28. [CrossRef]

[31] Jitjack K, Thepa S, Sudaprasert K, Namprakai P. Improvement of a rubber drying greenhouse with a parabolic cover and enhanced panels. Energy Build 2016;124:178–193. [CrossRef]

[32] Belloulid MO, Hamdi H, Mandi L, Ouazzani N. Solar greenhouse drying of wastewater sludges under arid climate. Waste Biomass Valorization 2016;8:193–202. [CrossRef]

[33] Hamdi I, EL khadraoui A, Kooli S, Abdelhamid F, Guizani A. Drying of red pepper slices in a solar greenhouse dryer and under open sun: Experimental and mathematical investigations. Innov Food Sci Emerg Technol 2019;52:262–270. [CrossRef]

[34] Belessiotis V, Delyannis E. Solar drying. Sol Energy 2011;85:1665–1691. [CrossRef]

[35] Kesavan S, Arjunan T V, Vijayan S. Thermodynamic analysis of a triple-pass solar dryer for drying potato slices. J Therm Anal Calorim 2019;136:159–171. [CrossRef]

[36] Patil R, Gawande R. A review on solar tunnel greenhouse drying system. Renew Sustain Energy Rev 2016;56:196–214. [CrossRef]

[37] Jairaj KS, Singh SP, Srikant K. A review of solar dryers developed for grape drying. Sol Energy 2009;83:1698–1712. [CrossRef]

[38] Hossain MA, Bala BK. Drying of hot chilli using solar tunnel drier. Sol Energy 2007;81:85–92. [CrossRef]

[39] Reddy VS. Portable solar drying system with inbuilt PV module for standalone forced convection operation. J Therm Eng 2020;6:92–98. [CrossRef]

[40] Nayak S, Kumar A, Singh AK, Tiwari GN. Energy matrices analysis of hybrid PVT greenhouse dryer by considering various silicon and non-silicon PV modules. Int J Sust Energy 2014;33:336–348. [CrossRef]

[41] Rathore NS, Panwar NL. Experimental studies on hemi cylindrical walk-in type solar tunnel dryer for grape drying. Appl Energy 2010;87:2764–2767. [CrossRef]

[42] Prakash O, Kumar A. Performance evaluation of greenhouse dryer with opaque north wall. Heat Mass Transf 2014;50:493–500. [CrossRef]

[43] Chauhan PS, Kumar A. Heat transfer analysis of north wall insulated greenhouse dryer under natural convection mode. Energy 2016;118:1264–1274. [CrossRef]

[44] Sethi VP, Arora S. Improvement in greenhouse solar drying using inclined north wall reflection. Sol Energy 2009;83:1472–1484. [CrossRef]

[45] Prakash O, Kumar A, Laguri V. Performance of modified greenhouse dryer with thermal energy storage. Energy Reports 2016;2:155–162. [CrossRef]

[46] Ayyappan S, Mayilsamy K, Sreenarayanan VV. Performance improvement studies in a solar greenhouse drier using sensible heat storage materials. Heat Mass Transf 2015;52:459–467. [CrossRef]

[47] Barnwal P, Tiwari GN. Grape drying by using hybrid photovoltaic-thermal (PV/T) greenhouse dryer: An experimental study. Sol Energy 2008;82:1131–1144. [CrossRef]

[48] Barnwal P, Tiwari A. Design, construction and testing of hybrid photovoltaic integrated greenhouse dryer. Int J Agric Res 2008;3:110–120. [CrossRef]

[49] Tiwari S, Tiwari GN, Al-Helal IM. Performance analysis of photovoltaic–thermal (PVT) mixed mode greenhouse solar dryer. Sol Energy 2016;133:421–428. [CrossRef]

[50] Eltawil MA, Azam MM, Alghannam AO. Solar PV powered mixed-mode tunnel dryer for drying potato chips. Renew Energy 2018;116:594–605. [CrossRef]

[51] Nayak S, Kumar A, Mishra J, Tiwari GN. Drying and testing of mint (mentha piperita) by a hybrid photovoltaic-thermal (PVT) -based greenhouse dryer drying and testing of mint (mentha piperita) by a hybrid photovoltaic-thermal (PVT) -based gre. Dry Technol An Int J 2011;29:1002–1009. [CrossRef]

[52] Gupta A, Diwania S, Agrawal S, Siddiqui AS, Pal Y. A bibliographical view on research and developments of photovoltaic and thermal technologies as a combined system: PV/T system. Lect. Notes Electr. Eng., vol. 607, Springer; 2020, p. 713–722. [CrossRef]

[53] Azaizia Z, Kooli S, Elkhadraoui A, Hamdi I, Guizani AA. Investigation of a new solar greenhouse drying system for peppers. Int J Hydrogen Energy 2017;42:8818–8826. [CrossRef]

[54] Eltawil MA, Azam MM, Alghannam AO. Energy analysis of hybrid solar tunnel dryer with PV system and solar collector for drying mint (MenthaViridis). J Clean Prod 2018;181:352–364. [CrossRef]

[55] ELkhadraoui A, Kooli S, Hamdi I, Farhat A. Experimental investigation and economic evaluation of a new mixed-mode solar greenhouse dryer for drying of red pepper and grape. Renew Energy 2015;77:1–8. [CrossRef]

[56] Mehta P, Samaddar S, Patel P, Markam B, Maiti S. Design and performance analysis of a mixed mode tent-type solar dryer for fish-drying in coastal areas. Sol Energy 2018;170:671–681. [CrossRef]

[57] Chauhan PS, Kumar A. Performance analysis of greenhouse dryer by using insulated north-wall under natural convection mode. Energy Reports 2016;2:107–116. [CrossRef]
[58] Deeto S, Thepa S, Monyakul V, Songprakorp R. The experimental new hybrid solar dryer and hot water storage system of thin layer coffee bean dehumidification. Renew Energy 2017;115:954–968. [CrossRef]
[59] Hamdani, Rizal TA, Muhammad Z. Fabrication and testing of hybrid solar-biomass dryer for drying fish. Case Stud Therm Eng 2018;12:489–496. [CrossRef]
[60] Kıyan M, Bingöl E, Melikog M, Albostan A. Modelling and simulation of a hybrid solar heating system for greenhouse applications using Matlab / Simulink. Energy Convers Manag 2013;72:147–155. [CrossRef]
[61] Jain D. Modeling the performance of the reversed absorber with packed bed thermal storage natural convection solar crop dryer. J Food Eng 2007;78:637–647. [CrossRef]
[62] Fudholi A, Yendra R, Basri DF, Ruslan MH, Sopian K. Energy and exergy analysis of hybrid solar drying system. Contemp Eng Sci 2016;9:215–223. [CrossRef]
[63] Aritesty E, Wulandani D. Performance of the rack type-greenhouse effect solar dryer for wild ginger (curcuma xanthorizza roxb.) drying. Energy Procedia, vol. 47, Elsevier Ltd; 2014, p. 94–100. [CrossRef]
[64] Janjai S. A greenhouse type solar dryer for small-scale dried food industries: Development and dissemination. Int J Energy Environ 2012;3:383–398.
[65] Chan Y, Dyah N, Abdullah K. Performance of a recirculation type integrated collector drying chamber (ICDC) solar dryer. Energy Procedia 2015;68:53–59. [CrossRef]
[66] Williams RD, Wick L, Bierman HR, Olmsted WH. Carbohydrate Values of Fruits and Vegetables. J Nutr 1940;19:593–604. [CrossRef]
[67] Appiah F, Kumah P, Idun I. Effect of ripening stage on composition, sensory qualities and acceptability of keitt mango (*mangifera indica* L.) chips. African J Food Agric Nutr Dev 2011;11:5096–5109. [CrossRef]
[68] Fowomola MA. Some nutrients and antinutrients contents of mango (Magnifera indica) seed. African J Food Sci 2010;4:472–476.
[69] Afolabi IS. Chemical qualities of oils from some fresh and market vegetable crops within Kwara State of Nigeria. Biokemistri 2008;20:71–75.
[70] Unuigbe OM, Ozekhome MC. Comparative Quality Assessment of Flour from Sun-Dried and Heated Air-Dried Green Banana (Musa sapientum) and Plantain (Musa paradisiaca). Niger Food J 2009;27:114–118. [CrossRef]
[71] Bankole SA, Osho A, Joda AO, Enikuomehin OA. Effect of drying method on the quality and storability of "egusi" melon seeds (Colocynthis citrullus L.). African J Biotechnol 2005;4:799–803.
[72] Prasad, K.N., Azlan A, Yusof BNM. Neutraceutical Properties of Dried Tropical Fruits: Guavas and Papayas. In: Alasalvar C, Shahidi F, editors. Dried Fruits (Phytochemicals Heal. Eff., U.K.: John Wiley & Sons, Inc.; 2013, p. 444–453. [CrossRef]
[73] Seshachalam K, Thottipalayam Velliangiri A, Selvaraj V. Drying of carrot slices in a triple pass solar dryer. Therm Sci 2017;21:389–398. [CrossRef]
[74] Mishra MK, Shrestha KR, Sagar V, Amatya RK. Performance of hybrid solar-biomass dryer. Nepal J Environ Sci 2019;5:61–69. [CrossRef]
[75] Kant K, Shukla A, Sharma A, Kumar A, Jain A. Thermal energy storage based solar drying systems: A review. Innov Food Sci Emerg Technol 2016;34:86–99. [CrossRef]
[76] Sreekumar A, Manikantan PE, Vijayakumar KP. Performance of indirect solar cabinet dryer. Energy Convers Manag 2008;49:1388–1395. [CrossRef]
[77] Tiwari S, Tiwari GN. Energy and exergy analysis of a mixed-mode greenhouse-type solar dryer, integrated with partially covered N-PVT air collector. Energy 2017;128:183–195. [CrossRef]
[78] Agrawal A, Sarviya RM. A review of research and development work on solar dryers with heat storage. Int J Sustain Energy 2016;35:583–605. [CrossRef]
[79] FAO. Sorghum and Millets in Human Nutrition. Agricultur. Rome: Food and Agricultural Organisation of the United Nations; 1995.
[80] Jayeola CO, Oluwadun AO. Mycoflora and nutritional components of cocoa powder samples in South West Nigeria. African J Agric Res 2010;5:2694–2698.
[81] Ingale S, Shrivastava SK. Nutritional study of new variety of groundnut (Arachis hypogaea L .) JL-24 seeds. African J Food Sci 2011;5:490–498.
[82] Grausgruber H, Scheiblauer J, Schönlechner R, Ruckenbauer P, Berghofer E. Variability in chemical composition and biologically active constituents of cereals. In: Vollmann J, Grausgruber H, Ruckenbauer P, editors. Genet. Var. plant breeding, Proc. 17th EUCARPIA Gen. Congr. (electronic Ed. 8 - 11 Sept. 2004, Tulln, Austria., Vienna Austria: BOKU – University of Natural Resources and Applied Life Sciences; 2004, p. 23–26.
[83] Hellevang KJ. Grain moisture content effects and management. NDSU Ext Serv 1995:1–8.
[84] Iyayi AF, Akpaka PO, Ukpeoyibo U. Rubber seed processing for value-added latex production in Nigeria. African J Agric Res 2008;3:505–509.
[85] Mohammed M, Sulaiman M. Proximate, caffeine and tannin analyses in some brands of tea consumed in Kano Metropolis, Nigeria. Bayero J Pure Appl Sci 2011;2:19–21. [CrossRef]

[86] Ghosh P, Venkatachalapathy N. Processing and Drying of Coffee - A review. Int J Eng Res Technol 2014;3:784–794.

[87] Odebunmi EO, Oluwaniyi OO, Awolola GV, Adediji OD. Proximate and nutritional composition of kola nut (Cola nitida), bitter cola (Garcinia cola) and alligator pepper (Afromomum melegueta). African J Biotechnol 2009;8:308–310.

[88] FAO. Grain crop drying , handling and storage. Rural Struct. Trop. Des. Dev., Food and Agriculture Organization. p. 363–86.

[89] Reyes A, Mahn A, Cubillos F, Huenulaf P. Mushroom dehydration in a hybrid-solar dryer. Energy Convers Manag 2013;70:31–39. [CrossRef]

[90] Tiwari S, Tiwari GN, Al-Helal IM. Performance analysis of photovoltaic–thermal (PVT) mixed mode greenhouse solar dryer. Sol Energy 2016;133:421–428. [CrossRef]

[91] Eltawil MA, Azam MM, Alghannam AO. Solar PV powered mixed-mode tunnel dryer for drying potato chips. Renew Energy 2018;116:594–605. [CrossRef]

[92] Amer BMA, Gottschalk K, Hossain MA. Integrated hybrid solar drying system and its drying kinetics of chamomile. Renew Energy 2018;121:539–547. [CrossRef]

[93] Sallam YI, Aly MH, Nassar AF, Mohamed EA. Solar drying of whole mint plant under natural and forced convection. J Adv Res 2015;6:171–178. [CrossRef]

[94] Singh S, Kumar S. Solar drying for different test conditions: Proposed framework for estimation of specific energy consumption and CO2 emissions mitigation. Energy 2013;51:27–36. [CrossRef]

[95] Janjai S, Lamlert N, Intawee P, Mahayothee B, Bala BK, Nagle M, et al. Experimental and simulated performance of a PV-ventilated solar greenhouse dryer for drying of peeled longan and banana. Sol Energy 2009;83:1550–1565. [CrossRef]

[96] Nabnean S, Janjai S, Thepa S, Sudaprasert K, Songprakorp R, Bala BK. Experimental performance of a new design of solar dryer for drying osmotically dehydrated cherry tomatoes. Renew Energy 2016;94:147–156. [CrossRef]

[97] Fudholi A, Sopian K, Othman MY, Ruslan MH. Energy and exergy analyses of solar drying system of red seaweed. Energy Build 2013;68:121–129. [CrossRef]

[98] Singh PL. Silk cocoon drying in forced convection type solar dryer. Appl Energy 2011;88:1720–1726. [CrossRef]

[99] Janjai S, Intawee P, Kaewkiew J, Sritus C, Khamvongsa V. A large-scale solar greenhouse dryer using polycarbonate cover: Modeling and testing in a tropical environment of Lao People's Democratic Republic. Renew Energy 2011;36:1053–1062. [CrossRef]

[100] Chauhan PS, Kumar A, Nuntadusit C. Heat transfer analysis of PV integrated modified greenhouse dryer. Renew Energy 2018;121:53–65. [CrossRef]

[101] Hegde VN, Hosur VS, Rathod SK, Harsoor PA, Narayana KB. Design, fabrication and performance evaluation of solar dryer for banana. Energy Sustain Soc 2015;5:23. [CrossRef]

[102] Bennamoun L. An Overview on Application of Exergy and Energy for Determination of Solar Drying Efficiency. Int J Energy Eng 2012;2:184–194. [CrossRef]

[103] Lingayat A, Chandramohan VP, Raju VRK. Energy and Exergy Analysis on Drying of Banana Using Indirect Type Natural Convection Solar Dryer. Heat Transf Eng 2019;41:551–561. [CrossRef]

[104] Tiwari GN., Barnwal P. Fundamentals of Solar Dryers. New Delhi: Anamaya Publishers; 2008.

[105] Das M, Akpinar EK. Investigation of pear drying performance by different methods and regression of convective heat transfer coefficient with support vector machine. Appl Sci 2018;8:215. [CrossRef]

[106] Shrivastava V, Kumar A. Experimental investigation on the comparison of fenugreek drying in an indirect solar dryer and under open sun. Heat Mass Transf 2015;52:1963–1972. [CrossRef]

[107] Tiwari GN, Das T, Chen CR, Barnwal P. Energy and exergy analyses of greenhouse fish drying. Int J Exergy 2009;6:620. [CrossRef]

[108] Tiwari GN, Kumar S, Prakash O. Evaluation of convective mass transfer coefficient during drying of jaggery. J Food Eng 2004;63:219–227. [CrossRef]