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Performance Assessment and Modeling Techniques for Domestic Solar Dryers

Shimpy[1] · **Mahesh Kumar**[1] · **Anil Kumar**[2,3]

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Abstract

Solar dryers have always been criticized for their lower performances. There are numerous ways to define the performance of a solar drying system such as thermal performance, drying kinetics, environmental aspects, economic evaluations, and quality of the dried product. Different modeling techniques have also been developed to design and analyze solar dryers and drying processes. This article presents a systematic, comprehensive, and state-of-the-art overview of various performance indicators and modeling techniques used for the evaluation and analysis of solar dryers, especially domestic and low cost solar dryers. Environmental analysis has severe global implications, and product quality is one of the biggest concerns of consumers. But the environmental impact and product quality assessments for domestic solar dryers are observed to be rarely reported in the literature. The use of modeling techniques in solar drying has changed the way of analyzing any thermal system. Here, an attempt is made to establish an overall assessment criterion for domestic solar dryers and to give a one-stop solution for researchers and users around the world.

Keywords Domestic solar dryers · Performance assessment · Modeling techniques · Environmental analysis · Dried product quality

Introduction

Drying is one of the most attractive techniques used traditionally throughout the globe to preserve food items. It does not just maintain the nutrition of the food but also helps in easy and long storage and transportation due to reduced weight [1]. The ever-increasing prices and shortage of fossil fuels and climate change resulting from the emission of greenhouse gases (GHGs) have forced researchers to explore alternatives to conventional energy demands as drying in itself is an energy-intensive process and contributes to 30% of the total processing cost of fresh produce [2–4].

It is estimated that 8–10% of total emissions of GHGs are related to the food that is produced but not consumed which is about 17% of the food available at retail, food service, and consumer level. It has also been estimated by the Food and Agriculture Organization (FAO) of the United Nations that 690 million people were hungry in 2019 and this number would be increased by an additional 3 billion after the pandemic of COVID-19 [5].

Solar drying has emerged as one of the most attractive alternatives to replace conventionally powered dryers. Solar dryers not only reduce food loss or wastage but also remain unaffected by the problems of price rise and shortage of fuels. The environmentally friendly nature of solar dryers is one of the major reasons for their popularity among researchers [6–8]. Solar dryers are generally categorized on the basis of modes of flow of the drying fluid inside the dryer and heat transfer to the drying commodity. A new class of solar dryers called "Hybrid solar dryers" has also emerged in the last two decades and got much popularity among researchers [9, 10]. Figure 1 shows the categorization of solar dryers.

The energy required to operate a solar dryer comes from the ultimate source of energy i.e., "Sun". This solar energy can be used in three ways to raise the temperature of the food item. The first is the direct way when the solar radiation

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✉ Mahesh Kumar
mkshandilya1@gmail.com

Shimpy
shimpymehra@gmail.com

Anil Kumar
anilkumar76@dtu.ac.in

[1] Department of Mechanical Engineering, Guru Jambheshwar University of Science & Technology, Hisar, India

[2] Department of Mechanical Engineering, Delhi Technological University, Delhi, India

[3] Centre for Energy and Environment, Delhi Technological University, Delhi, India

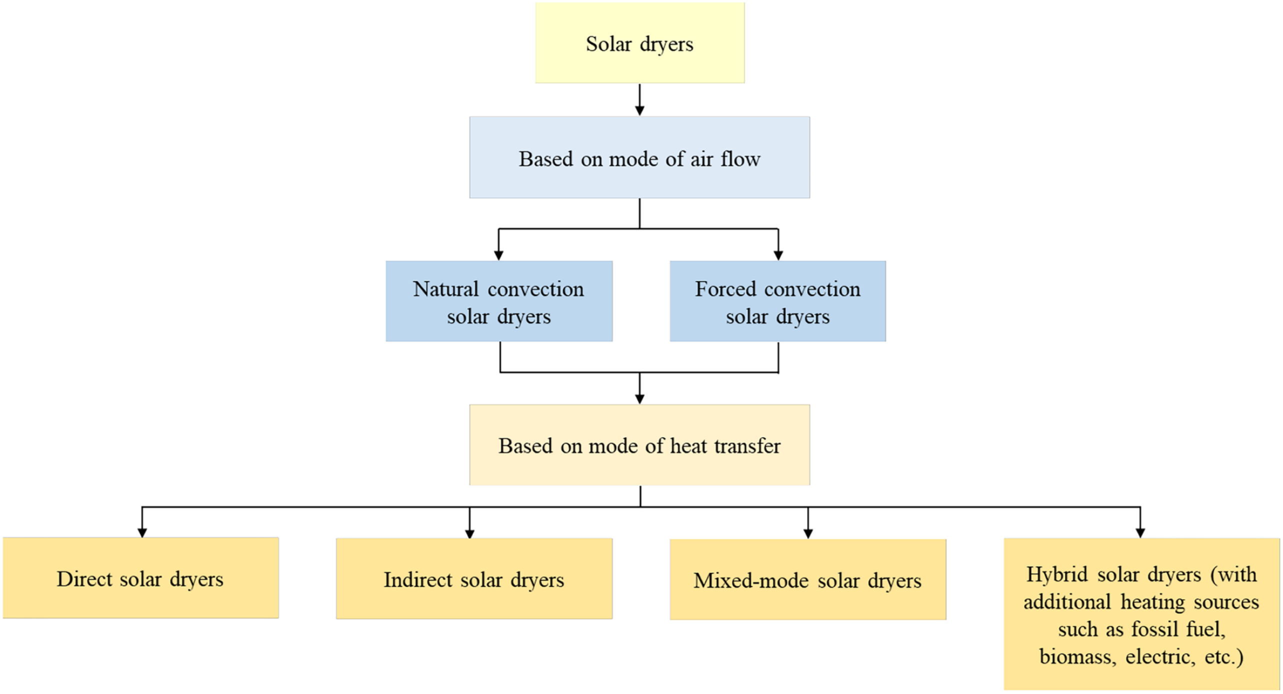


Fig. 1 Categorization of solar dryers [11, 12]

strikes the product directly and gets absorbed, resulting in temperature rise and moisture evaporation. The second way is using solar radiation to raise the temperature of a drying fluid separately and then using that heated fluid to evaporate moisture from the commodity placed in a well-insulated drying chamber. The third way combines both the direct and indirect ways of heat transfer and is called the mixed-mode type of solar drying [13–15]. The evaporated moisture from the drying commodity has to be removed from the drying system, and it can be done either by natural air currents due to the buoyancy effect known as "natural convection" or by some external source of air circulation such as a fan and blower known as "forced convection" [16, 17].

Many researchers have developed various solar dryers since 1976 when Everitt and Collins first introduced the idea of solar dryers. Each dryer has some modifications in terms of design and operation to improve the performance of the dryer and/or the quality of the dried commodity. The performance of a solar dryer was estimated in many investigations and has been shown in terms of various indicators such as thermal efficiency, drying rate, drying time, and energy consumption [18, 19]. For better understanding, control, and higher outputs, solar dryer is being analyzed by using various modeling techniques such as numerical and simulation, and the drying processes are also being modeled and studied by using various mathematical models for highest quality products [20, 21].

Earlier, Shimpy et al. [11] have reviewed various developments in the designs of domestic solar dryers including their performance and economic feasibility. The literature indicates that a range of domestic solar dryers has been developed and tested by researchers for different commodities. The performance evaluation methods and various modeling techniques have been used in different studies to analyze and compare the dryers, drying processes. and dried products. The present article is mainly focused on the present status of domestic solar dryers in terms of performance assessment parameters and modeling techniques employed to understand their potential for the drying of various household commodities.

Methodology

The literature on solar drying is very vast and diversified. In the present study, keywords such as domestic, household, and small-scale solar dryers were searched from the literature in search engines, namely, Web of Science (WOS), Google Scholar (GS), and Dimensions (D). The details of search results have been given in Table 1. Many studies were available on all the search engines. So, the total results for consideration were comparatively lower, and among them, the most relevant studies were scrutinized on the basis of keywords and the relevancy of the content to the present study. A flow chart for the methodology of present study has been shown in Fig. 2.

Table 1 Publications on domestic solar drying

Solar dryer	Search results		
	Web of Science (WOS)	Google Scholar (GS)	Dimensions (D)
Domestic	72	191	135
Household	39	37	29
Small scale	1	131	8

Performance Parameters and Analysis

"How good a solar dryer performs the drying operation" shows its performance. This goodness can be seen from different perspectives such as thermal, drying kinetics, environmental, economic, and quality of the dried products. This section presents an overview of the performance of domestic solar dryers from different perspectives.

Thermal Performance Parameters and Analysis of Domestic Solar Dryers

Pickup Efficiency

It is the ratio of actual moisture evaporated during the drying process to the total moisture removal capacity of the drying air. It is also called the effectiveness of a solar dryer [22].

$$\eta_{pickup} = \frac{m_{ev}}{m_a \times t\left(h_{sat} - h_{in}\right)} \quad (1)$$

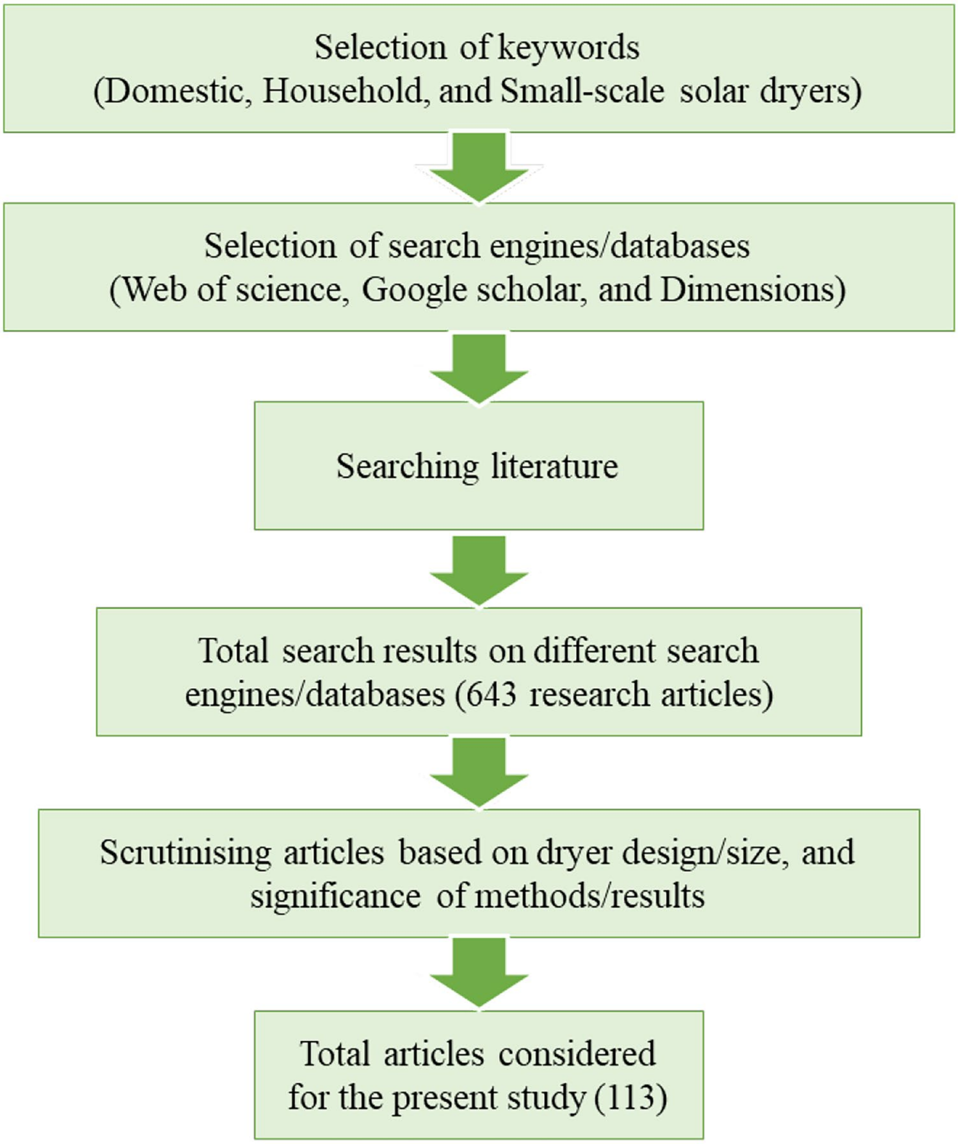


Fig. 2 Flow chart for the methodology of present study

where m_a = Mass flow rate of drying air (kg/s), t = time (s), h_{sat} = adiabatic saturation humidity of the air entering the dryer (kg water/kg dry air), and h_{in} = absolute humidity of the air entering the dryer (kg water/kg dry air).

Thermal Efficiency

Thermal efficiency is one of the most used performance indicators for any solar dryer. It can be calculated as the ratio of energy used in the evaporation of moisture content from the drying commodity (E_{ev}) to the total energy incident on the absorbing surface of the dryer (E_{in}). It is also known as system efficiency or drying efficiency [23, 24].

$$\eta_{th} = \frac{E_{ev}}{E_{in}} \tag{2}$$

Energy Efficiency

Energy efficiency is an indicator of the wellness of energy utilization of a system or in other words of any unaccounted energy losses. It is the ratio of the total energy output (E_{out}) to the total energy input (E_{in}) [25, 26]:

$$\eta_{en} = \frac{E_{out}}{E_{in}} \tag{3}$$

Exergy Efficiency

Exergy is the maximum amount of work that can be produced by a system before attaining equilibrium. The exergy efficiency of a solar dryer can be calculated as the ratio of exergy output (Ex_{out}) to the exergy input (Ex_{in}) [23, 27]:

$$\eta_{ex} = \frac{Ex_{out}}{Ex_{in}} \tag{4}$$

The exergetic performance of a solar dryer can also be described by using different indicators such as exergy loss (E_{loss}), waste exergy ratio (WER), improvement potential (IP), and sustainability index (SI) [28, 29]:

$$E_{loss} = Ex_{in} - Ex_{out} \tag{5}$$

$$\text{WER} = \frac{E_{loss}}{Ex_{in}} \tag{6}$$

$$\text{IP} = \left(1 - \eta_{ex}\right) \times E_{loss} \tag{7}$$

$$\text{SI} = \frac{1}{1 - \eta_{ex}} \tag{8}$$

Specific Energy Consumption

Specific energy consumption (SEC) is an indicator of the amount of energy required by a solar dryer to evaporate a unit mass of moisture content from a drying commodity. It is the ratio of the total energy input to a dryer to the amount of moisture evaporated from the drying commodity [30, 31]:

$$\text{SEC} = \frac{E_{in} \times t}{m_{ev}} \tag{9}$$

Specific Moisture Extraction Rate

The reciprocal of specific energy consumption is considered as the specific moisture extraction rate ($SMER$). It shows the amount of moisture evaporated per unit of energy supplied [22, 32]:

$$\text{SMER} = \frac{m_{ev}}{E_{in} \times t} \tag{10}$$

Heat Utilization Factor

Heat utilization factor (HUF) is the ratio of heat utilized during the drying process to the total heat generated inside the dryer during the operation [33–35]:

$$\text{HUF} = \frac{T_f - T_{air}}{T_f - T_{amb}} \tag{11}$$

where T_f = temperature of the floor of the drying chamber, T_{air} = temperature of the air insider drying chamber, and T_{amb} = temperature of ambient air.

Coefficient of Performance

Coefficient of performance (COP) is the ratio of available useful heat to the total heat generated inside the solar dryer [34, 36].

$$\text{COP} = \frac{T_{air} - T_{amb}}{T_f - T_{amb}} \tag{12}$$

It can also be given as

$$\text{COP} = 1 - \text{HUF} \tag{13}$$

Convective Heat Transfer Coefficient

Newton's law of cooling states that the rate of convective heat transfer ($\dot{Q}$) is directly proportional to the temperature difference (ΔT) between the body and the surrounding air.

The constant used for the elimination of proportionality sign is known as the convective heat transfer constant (h_c). The value of h_c depends on different variables such as thermophysical properties of drying fluid, type of fluid flow, geometry, and surface roughness of the solid surface [37].

$$\dot{Q} \propto \Delta T \tag{14}$$

$$\dot{Q} = h_c \times \Delta T \tag{15}$$

In the case of solar drying, the value h_c is generally calculated by using the Nusselt number (Nu). It is a nondimensional number that shows the ratio of the rate of heat transfer between a solid and fluid by convection to conduction.

For natural convection mode [38]:

$$Nu = \frac{h_c\, L_c}{K_v} = C(Gr\ Pr)^n \tag{16}$$

$$h_c = \frac{K_v}{L_c}\ C(Gr\ Pr)^n \tag{17}$$

For forced convection mode [39]:

$$Nu = \frac{h_c L_c}{K_v} = C(Re\ Pr)^n \tag{18}$$

$$h_c = \frac{K_v}{L_c} C(Re\ Pr)^n \tag{19}$$

where L_c = characteristic length, K_v = thermal conductivity of the fluid, Gr = Grashof number, Pr = Prandtl number, and C and n = experimental constants.

The rate of heat required to evaporate the moisture from the drying commodity (Q_e) is one of the important parameters that can be given as follows [38, 40]:

$$Q_e = 0.016\ h_c \left[P\left(T_v\right) - \gamma P(T_e)\right] \tag{20}$$

where $P(T)$ = partial pressure at the temperature (T), γ = relative humidity, T_v = temperature of the drying commodity, and T_e = temperature of surrounding air of the commodity.

Evaporative Heat Transfer Coefficient

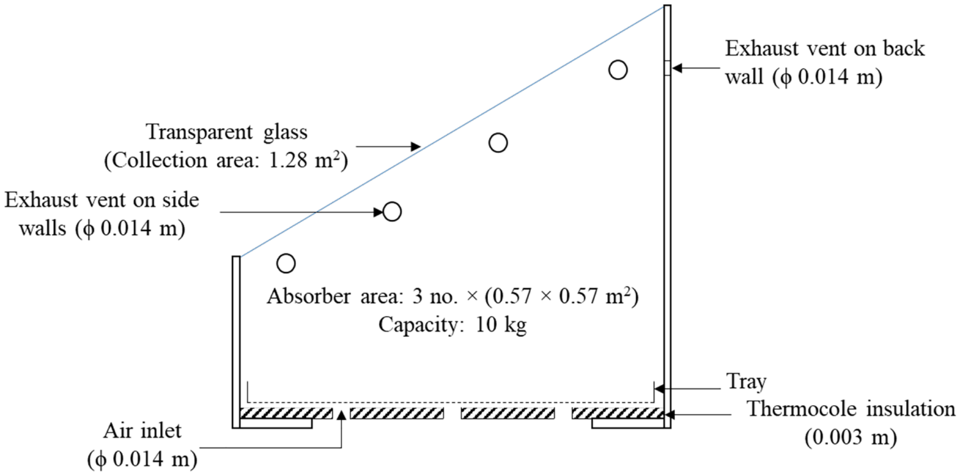
The rate of heat transfer from a drying commodity to the surroundings due to the evaporated moisture is the evaporative heat loss that is majorly governed by a parameter called evaporative heat transfer coefficient (h_e) that can be calculated by the following expression [25, 27, 41]:

$$h_e = 0.016\ h_c \left[\frac{\mathrm{P}\left(T_v\right) - \gamma P\left(T_e\right)}{T_v - T_e}\right] \tag{21}$$

In literature, the thermal performance of domestic solar dryers has been reported in many investigations. Sharma et al. [42] evaluated the energy and area required for the moisture evaporation from peas, grapes, and potatoes using a cabinet type natural convection direct solar dryer (NCDSD) as 5.15, 5.48, and 2.56 kWh/kg and 0.91, 0.96, and 0.45 m^2, respectively. Figure 3 shows the schematics of the cabinet type natural convection solar dryer.

Singh et al. [43] calculated the values of solar energy required/kg of moisture for fenugreek leaves and reported that the energy requirement increased with the drying time, i.e., 2.47, 3.30, and 13.44 kWh/kg for the first, second, and third day of drying. Saleh and Badran [44] tested a domestic type NCDSD for the drying of Jew's mallow and reported that the values of average specific energy consumption (SEC) under fixed and solar tracking modes were 17.78 and 9.17 kWh/kg, respectively. It was observed that the values of SEC increased with the drying time. Haque et al. [45] evaluated the value of exergy efficiency and improvement

Fig. 3 Cabinet type natural convection direct solar dryer [42]



potential of a portable domestic type NCDSD in the range of 17–44% and 0.25–184 W, respectively. Jain et al. [35] studied a domestic type NCDSD and observed that the convective heat transfer coefficient (h_c), heat utilization factor (HUF), and coefficient of performance (COP) ranges between 2.44 and 2.81 W/m^2 ℃, 0.54 and 0.69, and 0.31 and 0.46, respectively. Nabnean and Nimnuan [46] calculated the value of SEC of a domestic type forced convection direct solar dryer (FCDSD) for the drying of banana slices as 5.88 kWh/kg. Tiwari [47] developed an FCDSD with a semi-transparent photovoltaic module as the glazing for drying bitter gourd flakes. The values of h_c varied between 0.69 and 14.45 W/m^2 K with an overall thermal gain of 5.41 kWh/m^2. Moghimi et al. [48] reported that the SEC for tomato drying under forced convection indirect solar dryer (FCISD) (Fig. 4) was 4.24 kWh/kg of which electricity consumption was only 10% (0.424 kWh/kg).

Sharma et al. [49] tested an FCISD for the drying of tomato slices and evaluated the values of exergy efficiency, improvement potential, waste exergy ratio, and sustainability index in the range of 32.86–58.26%, 0.006966–0.065984, 0.41–0.67, and 1.55–2.39, respectively. The average exergy loss was estimated to be 56.56 W. The efficiency of domestic solar dryers used to dry various products is given in Table 2.

Drying Kinetics and Analysis of Domestic Solar Dryers

Moisture Content

The amount of moisture present in a commodity can be expressed in two ways, i.e., wet basis (wb) or dry basis (db) as given below [34]:

$$MC\ (wb) = \frac{m_i - m_f}{m_i} \times 100 \tag{22}$$

$$MC\ (db) = \frac{m_i - m_f}{m_f} \times 100 \tag{23}$$

where m_i = initial mass and m_f = final mass.

Moisture Ratio

Moisture ratio (MR) is one of the most significant parameters used to understand the drying characteristics of a drying commodity. The values of moisture ratio can be calculated as follows [66]:

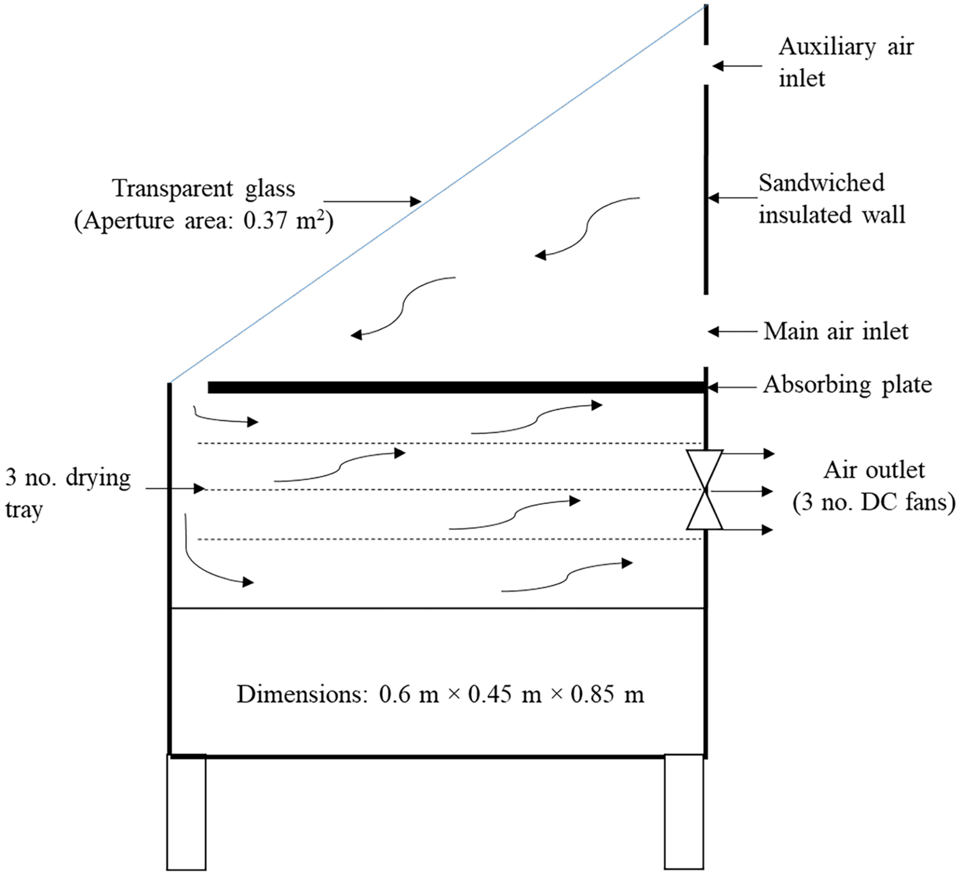


Fig. 4 Forced convection indirect solar dryer [48]

Table 2 Thermal efficiency of domestic solar dryers for different commodities

Researcher/s	Dryer	Commodity	Thermal efficiency (%)
Singh et al. [43]	NCDSD	Fenugreek leaves	Batch mode: 28.05 Semi-continuous mode: 25.6
Saleh and Badran [44]	NCDSD	Jew's mallow	Fixed mode: 3.74 Tracking mode: 7.08
Haque et al. [45]	NCDSD	Bitter gourd, Okra, Hindra Raw mango	10.73
Tiwari [47]	FCDSD	Bitter gourd flakes	49–70
Moghimi et al. [48]	FCISD	Tomato slices	16.4
Sharma et al. [49]	FCISD	Tomato slices	4.04–68.78
Hallak et al. [50]	Natural convection indirect solar dryer (NCISD)	Mango slices	26–65
Thanvi and Pande [51]	NCDSD	Chilies	37.9
Bolaji [52]	NCISD	No-load	60.5
Ezekoye and Enebe [53]	NCDSD	Pepper and Groundnuts	22
Eke [54]	NCDSD	Tomato, carrot, and okra	Tomato: 21.8 Carrot: 19.96 Okra: 24.95
Eke [55]	NCDSD with different collector materials	Tomato	Wood: 19.56 Cement: 20.25 Mud: 20.91 Metal: 27.24
Navale et al. [56]	NCDSD	Fenugreek leaves	34.5
Borah et al. [57]	NCDSD	Turmeric	Whole: 55.36 Sliced: 55.6
Subedi and Bhattarai [58]	NCDSD	Ginger	*Slice thickness* 3–5 mm: 64.36 6–8 mm: 58.86 9–11 mm: 50.97 Whole: 32.84
Chaudhari and Bhavsar [59]	NCDSD cum cooker with and without electrical heating	Green chilies	With electrical heating: 19.50 Without electrical heating: 19.12
Modi et al. [60]	FCDSD	Tomato slices	34.87
Chaudhari et al. [61]	NCDSD	Ginger	19.71
Poonia et al. [62]	FCDSD	Ber (*Zizyphus mauritiana*)	16.7
Poonia et al. [63]	NCDSD and FCDSD	Ber (*Zizyphus mauritiana*)	NCDSD: 15.6 FCDSD: 16.7
Nimnuan and Nabnean [64]	FCDSD	Alpinia galangal	32
Safri et al. [65]	FCISD	No-load	66.34

$$MR = \frac{MC_t - MC_e}{MC_i - MC_e} \tag{24}$$

where MC_t = moisture content at time t, MC_e = equilibrium moisture content, and MC_i = initial moisture content.

The values of MC_e are generally very small as compared to the initial moisture content of food items and hence can be neglected, and the value of moisture ratio can be given as the ratio of moisture content in a commodity at a particular time to the initial moisture content. This parameter is of very high significance as it is widely used for establishing mathematical models to describe the drying behavior of various commodities [67, 68].

$$MR = \frac{MC_t}{MC_i} \tag{25}$$

Drying Rate

The amount of moisture removed from a commodity in a unit time is considered as the drying rate (*DR*). It is generally used to specify the drying capacity of a dryer per unit time and may vary depending upon the mode of operation, i.e., natural or forced, temperature of drying air and type, shape, and size of the drying commodity [49]:

$$DR = \frac{dMC_{t+dt} - MC_t}{dt} \tag{26}$$

where dMC_{t+dt} = moisture content at time t + dt.

Effective Moisture Diffusivity

The entire drying process can be divided in two phases, i.e., the constant and falling rate phases. The drying of most of the agricultural and other food items generally lies under the falling rate period. The period in which the moisture removal is governed by the rate of internal moisture transportation phenomenon called as "moisture diffusivity." This internal moisture diffusion can be a result of different mechanisms viz. capillary action, molecular diffusion, liquid and vapor diffusion through solid and air-filled pores, respectively, vaporization–condensation sequence and hydrodynamic flow; and change in shape, size and texture of the material. The collective action of all the moisture transportation mechanisms is termed as "effective moisture diffusivity" [69].

The solution of Fick's second law in the form of a reduced exponential model was used for the determination of effective moisture diffusivity [70–72].

For sphere:

$$MR = \frac{6}{\pi^2} \times \exp\left(-\frac{\pi^2 D_{ef}}{r^2} t\right) \tag{27a}$$

For cylinder:

$$MR = \frac{4}{b_n^2} \times \exp\left(-\frac{b_n^2 D_{ef}}{r^2} t\right) \tag{27b}$$

For slab:

$$MR = \frac{8}{\pi^2} \times \exp\left(-\frac{\pi^2 D_{ef}}{4L^2} t\right) \tag{27c}$$

where D_{ef} = effective diffusion coefficient (m^2/s), r = half of the thickness of the sample (mm), t = drying time in (s), and b_n^2 = characteristic root of first kind and zero order Bessel functions ($b_1 = 2.4048$).

In the case of longer drying operations, equation can be expressed in logarithmic form as given below:

For sphere:

$$ln(MR) = ln\left(\frac{6}{\pi^2}\right) - \left(\frac{\pi^2 D_{ef}}{r^2} t\right) \tag{28a}$$

For cylinder:

$$ln(MR) = ln\left(\frac{4}{b_n^2}\right) - \left(\frac{b_n^2 D_{ef}}{r^2} t\right) \tag{28b}$$

For slab:

$$ln(MR) = ln\left(\frac{8}{\pi^2}\right) - \left(\frac{\pi^2 D_{ef}}{4L^2} t\right) \tag{28c}$$

The value of D_{ef} can be obtained from the slope of the line obtained from the plot of ln(MR) with respect to the drying time (t).

For sphere:

$$Slope = \frac{\pi^2 D_{ef}}{r^2} \tag{29a}$$

For cylinder:

$$Slope = \frac{b_n^2 D_{ef}}{r^2} \tag{29b}$$

For slab:

$$Slope = \frac{\pi^2 D_{ef}}{4L^2} \tag{29c}$$

Activation Energy

Activation energy is the energy required to initiate the diffusion of the moisture within the drying commodity during the process of drying. It can be a significant criteria to design a solar dryer for a particular product or a class of products. Arrhenius equation correlates the effective moisture diffusivity with the absolute drying air temperature [73, 74]:

$$D_{ef} = D_0 \times exp\left(-\frac{E_A}{\mathrm{RT}}\right) \tag{30}$$

where E_A = activation energy (J/mole), D_0 = pre-exponential factor of the Arrhenius equation (m^2/s), R = ideal gas constant (8.314 J/mole K), and T = drying air temperature in (K).

The natural log of Eq. (30) can be given as

$$ln\left(D_{ef}\right) = ln\left(D_0\right) - \left(\frac{E_A}{\mathrm{RT}}\right) \tag{31}$$

The slope of line obtained from the plot of ln(D_{ef}) against the inverse of absolute temperature of the drying air (1/T).

$$Slope = \frac{E_A}{R} \tag{32}$$

Various researchers have used drying kinetics for domestic solar drying. Ezekoye and Enebe [53] reported the drying rate for groundnuts under NCDSD and open sun drying as 0.198 and 0.1 g/day, respectively. Alonge and Adeboye [75] evaluated the drying rate for pepper, okra, and vegetables under NCDSD as 3.94, 17.65, and 13.33 kg/hour, respectively. Eke [55] reported that an NCDSD with metal, wood, cement, and mud as absorbing materials took 76, 96, 96, and 94 h, respectively, for the drying of tomatoes. Borah et al. [57] evaluated the values of effective moisture diffusivity for whole and sliced turmeric samples under NCDSD as 1.456×10^{-10} and 1.852×10^{-10} m^2/s, respectively. Poonia et al. [62] reported that the moisture diffusivity of ber (*Zizyphus mauritiana*) was 3.34×10^{-7} m^2/s under an FCDSD (Fig. 5). Islam et al. [76] developed an NCDSD having three drying chambers with thin tube chimney, attic, and simple-type ventilation arrangements and tested for pineapple, apple, banana, and guava fruits drying. The simply ventilated chamber showed highest moisture removal rate (58.9%) as compared to the chimney type (44.5%) and attic type (33.3%). A comparison of the drying kinetic performance parameters of different domestic solar dryers has been presented in Table 3.

Environmental Performance Parameters and Analysis of Domestic Solar Dryers

Embodied Energy (EE)

Energy invested in the development of a product is considered as the embodied energy. The coefficient of embodied energy

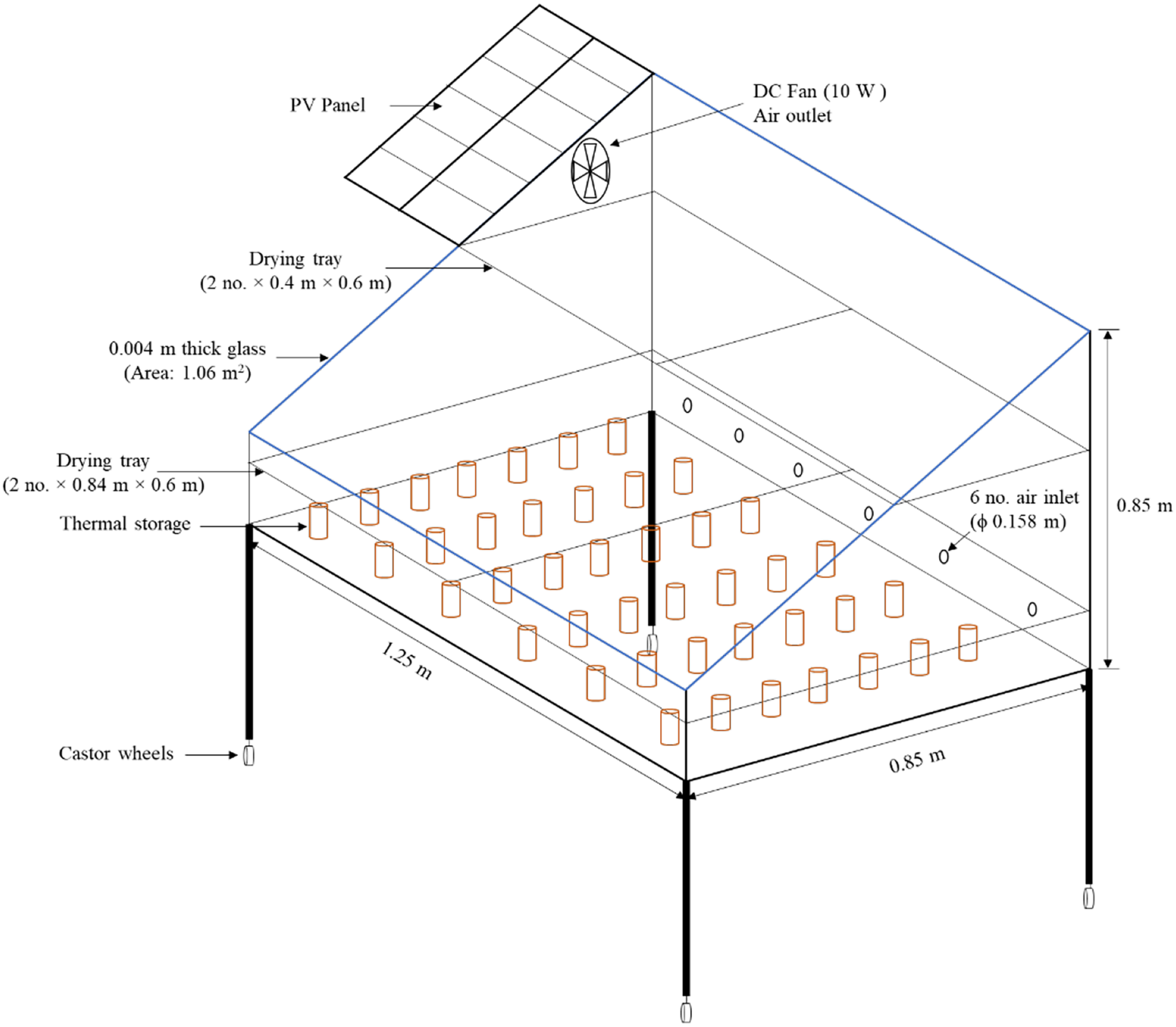


Fig. 5 PVT hybrid solar dryer [62]

Table 3 Drying kinetics parameters of different domestic solar dryers

Researcher (Year)	Dryer	Commodity	Moisture content (% wb)		Drying time (hours)
			Initial	Final	
Sharma et al. [42]	NCDSD	Peas	70	11.2	3 days
		Grapes	75	15	
		Potatoes	40	10.6	
Singh et al. [43]	NCDSD	Chilies	-	-	18.75
		Fenugreek leaves	88.5	7.3	
Haque et al. [45]	NCDSD	Bitter gourd	89	7.6	8
		Okra	88.4	5	9
		Raw mango	88.8	5.7	9
		Hindra	68.6	10	6
Nabnean and Nimnuan [46]	FCDSD	Banana slices	72	28	4 days
Sharma et al. [49]	FCISD	Tomato slices	95	9	10
Thanvi and Pande [51]	NCDSD	Chilies	86.3	4.1	9 days
Eke [54]	NCDSD	Tomato	93	4	34
		Carrot	88	5	35
		Okra	88	4	28
Eke [55]	NCDSD	Tomato	90	4	76–94
Borah et al. [57]	NCDSD	Turmeric	78.65	5.5–6.36	12
Chaudhari and Bhavsar [59]	Hybrid NCDSD	Green chilies	80.58	6.89	9
Modi et al. [60]	FCDSD	Tomato slices	90.48	7.73	5.5
Chaudhari et al. [61]	NCDSD	Ginger	79.31	6.73	9
Poonia et al. [62]	FCDSD	Ber (*Zizyphus mauritiana*)	80	20	240
Nimnuan and Nabnean [64]	FCDSD	Alpinia galangal	89	12	1 day
Alonge and Adeboye [75]	NCDSD	Pepper	78.9	24	33
		Okra	92	20	51
		Vegetables	90	20	30
Sreekumar et al. [77]	FCISD	Bitter gourd	95	5	6
Rawat et al. [78]	NCDSD	Chilies	74.4	4.4	8
Alonge and Omoniwa [79]	NCDSD	Cassava chips	53.7	11	32
Seveda and Jhajharia [80]	FCDSD	Large cardamom	75.6	10.1	24
Daud and Simate [81]	NCDSD	Pineapple slices	85.12	12.23	8
Chavan et al. [82]	NCDSD	Potato slices	80	5	-
Dubey et al. [83]	FCMMSD	Grapes	80	10	1 day

is calculated by considering all the energy inputs during the development of the product. The value of EE can be evaluated by multiplying the coefficient of embodied energy to the weight of the product as follows [28]:

$$\mathrm{EE} = \mathrm{Coefficeint\ of\ embodied\ energy} \times \mathrm{product\ weight} \tag{33}$$

Energy Payback Time (EPBT)

It is the time required by the product to deliver the amount of required work equivalent to the energy spent during the development of that product and can be calculated as follows [35]:

$$EPBT = \frac{EE}{Annual\ energy\ output} \tag{34}$$

where annual energy output is given as follows [24]:

$$Annual\ energy\ output = Daily\ energy\ output \times Operating\ days/year \tag{35}$$

The daily energy output can be calculated as follows [84]:

$$\mathrm{Daily\ energy\ output} = \frac{m_{ev} \times \lambda}{3.6 \times 10^6} \tag{36}$$

where λ = latent heat of vaporization.

CO_2 Emissions

The amount of annual CO_2 emissions by a solar dryer can be given by considering the electricity production from coal. Generally, taken as 0.98 kg/kWh of CO_2 [85]:

$$CO_2 \text{ emission per year} = \frac{EE \times 0.98}{Lifetime} \tag{37a}$$

Considering the losses associated with the electricity such as transmission and distribution losses (L_{td}) and domestic appliance losses (L_{da}), the Eq. (37a) can be given as follows:

$$CO_2 \text{ emission per year} = \frac{EE \times 0.98}{Lifetime} \times \frac{1}{1 - L_{td}} \times \frac{1}{1 - L_{da}} \tag{37b}$$

The values of L_{td} and L_{da} are generally considered as 0.4 and 0.2, respectively. So Eq. (37b) can be written as follows:

$$CO_2 \text{ emission per year} = \frac{EE}{Lifetime} \times 2.042\ kg \tag{37c}$$

CO_2 Mitigation Potential

The CO_2 mitigation potential of the dryer for its entire life can be given as follows [24]:

$$CO_2\ mitigation = (Annual\ energy\ output \times Life - EE) \times 2.042\ kg \tag{38}$$

Carbon Credit Earned (CCE)

For the international trading of energy systems specifically renewable energy systems, carbon credit earned is an important environmental sustainability indicator that can be given as follows [86]:

$$CCE = CO_2 \text{ mitigation} \times Cost\ of\ one\ carbon\ credit \tag{39}$$

where the cost of carbon credit varies from USD 5–20/tones of CO_2 mitigation.

Environmental performance parameters indicate the contribution of the developed solar drying system to the global climate change and environment. Rawat et al. [78] reported that for a working life of 10 years, an NCDSD can save up to 2486.40 kg of fuel wood, 1776 L of light diesel oil, 2072 kg of coal, and 1554 kg of natural gas, respectively. Table 4 presents a quick overview of the environmental performance of different domestic solar dryers.

Economic Performance Parameters and Analysis of Domestic Solar Dryers

Life Cycle Cost

Life cycle cost (LCC) is the total cost involved during the entire life of the dryer and is given as follows [62]:

$$LCC = C_{ic} + C_{lom} - \text{SV} \tag{40}$$

where C_{ic} = initial cost; C_{lom} = cost of labor, operation, and maintenance; and SV = salvage value of the dryer at the end of its life.

Life Cycle Benefit (LCB)

It is the total benefit that can be achieved during the entire life of the solar dryer [62]:

$$LCB = R \times \frac{X(1 - X^j)}{(1 - X^j)} \tag{41}$$

where R = annual benefit, X = $\frac{1\ +\ annual\ escalation}{1\ +\ interst\ rate}$, and j = Lifetime.

Payback Period (PBP)

The payback period (PBP) is the time period required by the developed system to recover the amount equivalent to that is spent for its fabrication. Following expression can be used for the evaluation of PBP for any drying system [47, 88]:

$$PBP = \frac{\ln\left[1 - \frac{C_{cc}}{S_1}(i - d)\right]}{\ln\left(\frac{1+d}{1+i}\right)} \tag{42}$$

Table 4 Environmental performance of various domestic solar dryers

Study	Drying method	Product	EE (kWh)	EPBT (years)	Annual CO_2 emission (kg)	CO_2 mitigation (kg)	CCE ($)
Jain et al. [35]	NCDSD	-	339.015	7.57	16.62	1553.73	30.34
Rawat et al. [78]	NCDSD	Chillies	762.4	1–2	-	-	-
Rawat et al. [87]	NCDSD	Amla (*Phyllanthus emblica* L.)	762.4	3–5	-	8812.4–34,368.3	-

where C_{cc} = capital cost, S_1 = savings after 1 year, i = interest rate, and d = inflation rate.

The various parameters required for calculating PBP has been given in Appendix A.

Economics is one of the most important considerations for domestic and small-scale users. Many researchers have focused on the economic assessment of domestic solar dryers. Singh et al. [43] reported the present cumulative worth of a domestic type NCDSD for fenugreek leaves as \$236.26. Sreekumar et al. [77] calculated the annualized cost and net present worth of a cabinet type FCISD for the drying of bitter gourd as \$11.86 and \$408.23, respectively. Mustapha et al. [89] used plastic, mosquito net, glass, aluminum, and glass with black pebbles in five different solar dryers for the drying of fish. The value of cost to benefit ratio varied from 2.5:1 to 4.5:1 for different dryers. Modi et al. [60] obtained a net profit of \$4.7/kg by using a low cost cabinet type FCDSD for the drying of tomatoes. Chaudhari et al. [61] evaluated the values of net present worth and benefit to cost ratio for the drying of ginger under NCDSD as \$266.92/year and 2.3, respectively. Haque et al. [45] calculated the values of annualized cost and cumulative present worth for a portable domestic type NCDSD (Fig. 6) as \$12.12 and \$1216.55, respectively.

Poonia et al. [62] reported that the life cycle cost and benefit of a PV/T enabled hybrid FCDSD were \$556.44 and \$1033.77, respectively. The values of benefit to cost ratio, net present worth, annuity, and internal rate of return were evaluated as 1.86, \$477.33, \$64.33, and 54.5%, respectively, for the drying of ber. Sandali et al. [90] appraise the life cycle cost and benefit of NCDSD with various heat supplying techniques as \$28,843.37 and \$37,017.44, respectively. A quick overview of the initial cost and the payback period of different solar dryers for different products has been presented in Table 5.

Product Quality Parameters and Analysis of Domestic Solar Dryers

Sensory Evaluation

Sensory evaluation is one of the most widely used quality assessment methods used for solar dried food products. It involves the assessment of change in color, texture, taste, and flavor of the food products after drying [20, 46].

Color Deviation

Color deviation (C_{dev}) is the variation in the color of the solar dried samples with reference to the color of the fresh samples. The two most commonly used methods to analyze the color deviation of food items are $L^* a^* b^*$ and $L^* C^* h^*$ methods. The value of C_{dev} can be calculated as follows [45]:

$$C_{dev} = \sqrt{\left(\left(L^* - L_r^*\right)^2 + \left(a^* - a_r^*\right)^2 + \left(b^* - b_r^*\right)^2\right)} \quad (43)$$

where L^* = lightness, a^* = red/green coordinate, b^* = yellow/blue coordinate, C^* = chroma, h^* = hue, and subscript (r) shows the respective reference values.

The values of C^* and h^* can be calculated as given below [46]:

$$C^* = \sqrt{a^{*2} + b^{*2}}$$

$$h^* = \tan^{-1}\left(\frac{b^*}{a^*}\right) \; if \; a^* > 0$$

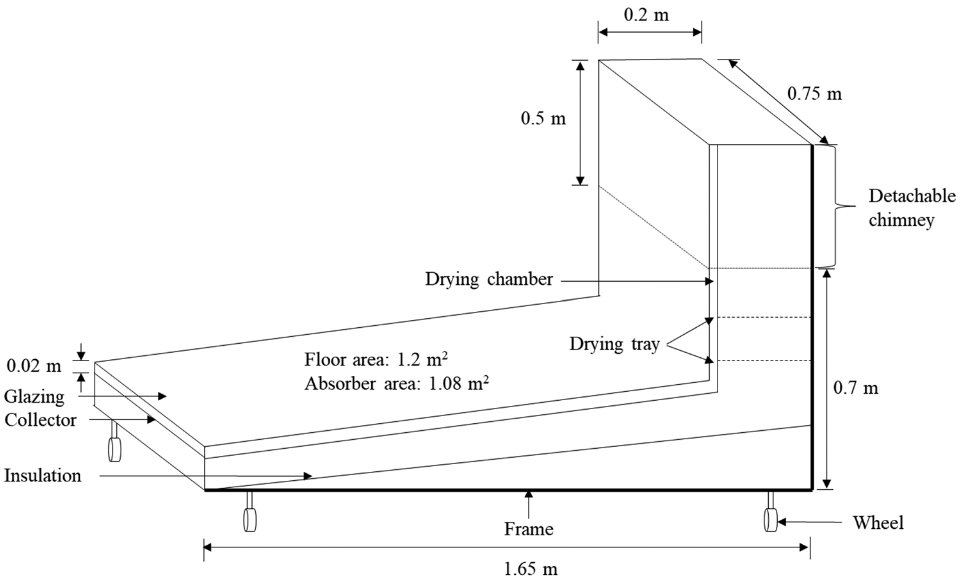


Fig. 6 Schematics of a portable domestic solar dryer [45]

Table 5 Initial cost and payback period of various domestic solar dryers

Study	Dryer	Product	Initial cost ($)	Payback period (years)
Singh et al. [43]	NCDSD	Fenugreek leaves	35.55	1.36
		Chilies		0.57
Haque et al. [45]	NCDSD	Bitter gourd, okra, hirda, and raw mango	77.38	0.56
Nabnean and Nimnuan [46]	FCDSD	Banana slices	390	1.1
Moghimi et al. [48]	FCISD	Tomato	306.6	-
Thanvi and Pande [51]	NCDSD	Chilies	3.61	-
Eke [55]	NCDSD	Tomato slices	12.05–36.14	-
Sreekumar et al. [77]	FCISD	Bitter gourd	83.81	3.26
Alonge and Omoniwa [79]	NCDSD	Cassava chips	500	-
Mustapha et al. [89]	NCDSD	Fish	4.34–8.19	0.25
Sandali et al. [90]	NCDSD	No-load	-	0.8–5.4
Tefera et al. [91]	NCDSD	Potato slices	For box type: 39.92 For pyramid type: 10.94	-
Poonia et al. [92]	NCDSD	Ber (*Ziziphus*)	10.32	-
Chaudhari et al. [61]	NCDSD	Ginger	116.05	0.5
Poonia et al. [62]	FCDSD	Ber (*Ziziphus mauritiana*)	180.52	2.26
Nimnuan and Nabnean [64]	FCDSD	Galangal	375	0.9

$$h^* = 180 + \tan^{-1}\left(\frac{b^*}{a^*}\right)\ if\ a^* < 0$$

Ash Content

It is calculated in terms of percentage as the ratio of the total weight of ash content remained after complete combustion of the sample at or above 500 ℃ to the initial weight of the sample [83].

$$Ash\ content\ (\%) = \frac{Weight\ of\ ash}{Initial\ weight\ of\ sample} \times 100 \tag{44}$$

Rehydration Ratio

A measure to estimate the loss of tissues during the drying process is the rehydration ratio which can be given as the ratio of the weight of the sample after rehydration and the weight of the dried sample. It is also known as the rehydration capacity or hydration coefficient [93].

$$Rehydration\ ratio = \frac{Weight\ of\ rehydrated\ sample}{Weight\ of\ the\ dried\ sample} \tag{45}$$

Shrinkage

The percentage of change in dimension after solar drying to the initial dimension of a product is called as the shrinkage [94, 95]:

$$Shrinkage\ (\%) = \frac{D_i - D_f}{D_i} \times 100 \tag{46}$$

where D_i = initial dimension and D_f = final dimension.

Nutritional Analysis

As the drying process can affect various nutritive properties of products, the evaluation of various nutrients (such as carbohydrates, fat, sugar, and vitamins) and minerals (calcium, iron, potassium, magnesium, etc.) can also be considered

Fig. 7 Fresh (**A**), solar dried (**B**), and open sun dried (**C**) bitter gourd samples (with permission from [96])

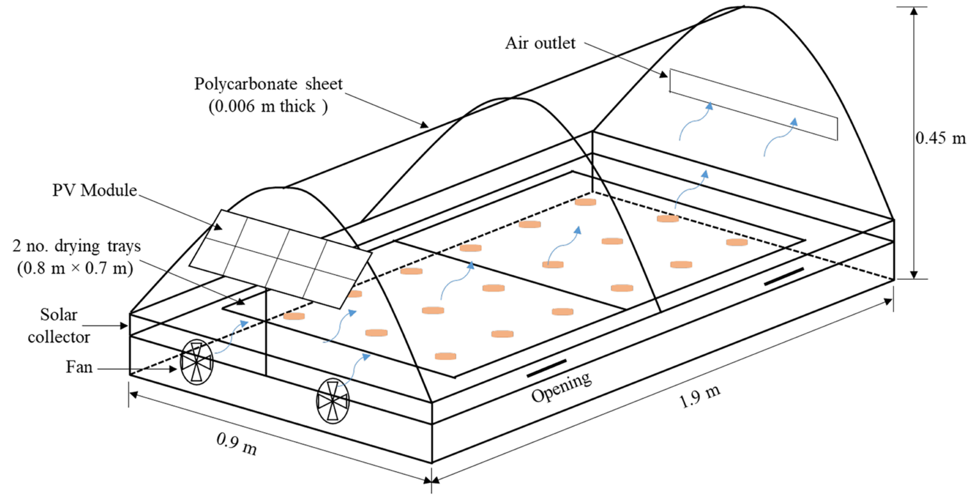


Fig. 8 Parabolic-shaped FCDSD [46]

one of the significant criteria for the solar dried product quality assessment. Various chemical tests can be conducted to evaluate the values of solar dried products so that the best solar drying system can be designed as per the product requirements [20, 83].

Quality of the dried product has also been analyzed and reported in some investigations on domestic solar dryers. Haque et al. [45] recommended the solar dried products over open sun dried products on the basis of color testing parameters. The value of C_{dev} for solar dried bitter gourd and okra were found to be 9.71 and 14.17, respectively. Vijayan et al. [96] presented the effect of solar drying on the quality of the bitter gourd. Higher color retention was observed in solar dried sample as compared to open sun dried sample (Fig. 7). Nabnean and Nimnuan [46] analyzed the quality of banana slices dried in a parabolic-shaped FCDSD (Fig. 8) on the basis of appearance, color, texture, flavor, taste, and overall acceptance. Solar dried samples were found superior in comparison to open sun dried bananas. Table 6 shows the nutrition facts of solar dried banana samples.

Gyawali et al. [97] used biochemical analysis and suggested that the retention of essential oil in solar dried ginger and turmeric samples was comparatively higher than that of under open sun drying. Oleoresin content was reported to be almost similar under both the drying conditions. Sharma et al. [49] observed that the quality of solar dried tomatoes was superior with an overall acceptability score of 4.2 as compared or open sun dried samples on the basis of five quality attributes, namely, color, flavor, mouthfeel, taste, and appearance. Dubey et al. [83] developed a domestic type forced convection mixed mode solar dryer (FCMMSD) and compared the effect of solar and open sun drying on the nutritional properties of grapes such as total sugars, proteins, and lipids. The percentage ash content of solar and open sun dried grapes was observed to be 2.71 and 1.95%, respectively. Solar dried samples were having higher percentages of macronutrients such as calcium, potassium, magnesium, and sodium and micronutrients iron, molybdenum, and zinc (Table 7). A brief summary of various product quality indicators used for solar dried products is presented in Table 8.

Table 6 Nutrition facts of solar dried banana samples [46]

Parameter	Value (per 100 g)
Vitamin B1	30 µg
Calories	286.26 kcal
Carbohydrate	69.29 g
Ash content	1.95 g
Protein	1.69 g
Fat	0.26 g

Modeling Techniques Used for Domestic Solar Dryers

The testing of solar drying systems can be challenging in both physical and financial ways. The development of any system needs money and testing requires labor. Modeling

Table 7 Nutrients retention in solar and open sun dried raisins [83]

Nutrients	Solar drying	Open sun drying
Ca (%)	0.065	0.056
K (%)	0.647	0.477
Mg (%)	0.380	0.030
Na (%)	0.996	0.494
Fe (ppm)	130	90
Mo (ppm)	20	10
Zn (ppm)	40	30

Table 8 Product quality analysis for domestic solar dryers

Study	Drying method	Product	Parameters studied	Remarks
Nabnean and Nimnuan [46]	FCDSD	Banana	• Color deviation • Sensory	The values of color deviation for solar and open sun dried samples were 30.06 and 44.15.
Nimnuan and Nabnean [64]	FCDSD	Galangal	• Color deviation	Color deviations for open sun dried and solar samples were 137.68 and 139.2, respectively.
Dubey et al. [83]	FCMMSD	Grapes	• Ash content • Protein amino acid and sugar • Lipid and fatty acid • Mineral composition • Bacterial load	Solar dried samples showed negligible bacterial growth as compared to open sun dried samples.
Kondareddy et al. [98]	FCMMSD	Black turmeric	• Color analysis • Antioxidant activity • Total phenolic content • Total flavonoid content	The dryer resulted in higher color deviation as compared to open sun drying.
Watson et al. [99]	Forced convection solar bed dryer	Red chili	• Microbial growth	The solar bed dryer reduced the drying time and hence the chances of microbial growth.

can be a very appropriate solution to overcome these problems. A number of modeling techniques have been used by researchers for analyzing various solar drying technologies. Some of the modeling techniques used for analyzing domestic solar dryers are given in Fig. 9.

Computational fluid dynamics (CFD) is one of the most widely used computer assisted process engineering tools to analyze and investigate solar drying systems. It can produce quantitative predictions about the behavior of the fluid flow inside the drying chamber based on the laws of conservation of mass, momentum, and energy given in Appendix C [100–103]. A flow chart of the process of CFD simulation has been shown in Fig. 10. Kam et al. [104] used COMSOL multiphysics software for CFD analysis to predict the velocity, temperature, and pressure distributions inside a natural convection greenhouse type solar dryer. Gyawali et al. [97] used CFD analysis in ANSYS Fluent software for the prediction of the temperature and behavior of airflow inside a forced convection mixed mode solar dryer. Andharia et al. [105] studied the effect of sensible and latent heat storage systems on the airflow and temperature distribution in a small-scale mixed mode solar dryer tested for Indian gooseberry. Dhalsamant [112] estimated the values of temperature and moisture ratio of potato cylinders in a mixed-mode solar dryer by using CFD analysis in COMSOL Multiphysics. The outcomes of CFD analysis were compared and found to be much accurate as compared to the results of an artificial neural network based model.

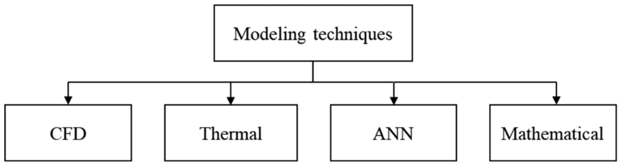


Fig. 9 Modeling techniques for analyzing domestic solar dryers

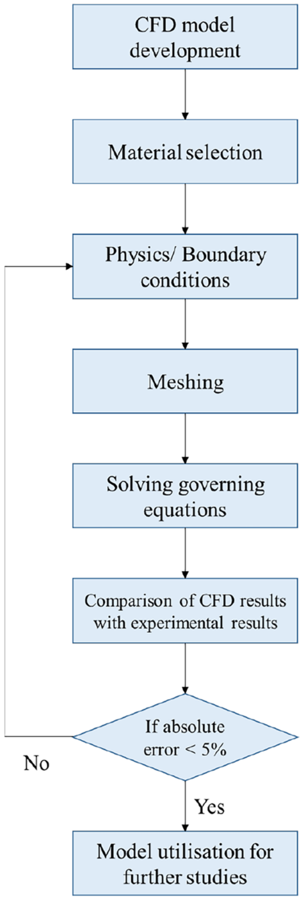


Fig. 10 Flow chart for CFD simulation

Thermal modeling has been used by many researchers for investigating various solar drying systems. It considers the inflow and outflow of energy through the solar dryer that follows the principle of energy balance. This technique has been widely employed to estimate various temperatures associated with a particular drying system such as product temperature and drying air temperature at inlet, outlet, and inside the drying chamber [106–108]. Spall and Sethi [109] have applied thermal modeling for the analysis of a cabinet type forced convection solar dryer having north wall reflector. The model was also validated with the experimental data using root mean square error given in Appendix C.

Artificial neural network (ANN) is a mathematical data processing technique inspired from the human neurons system. It consists a several nodes also called as neurons connected with each other in at least three layers. The first and last layers are called as input and output layers having neurons equal to the number of input and output variables, respectively. All the middle layer are called as hidden layers. The application procedure of ANN technique mainly consists of three steps, namely, training, validation, and testing. The accuracy of ANN model is generally tested by calculating the values of coefficient of correlation (R), mean absolute error (MAE), root mean square error (RMSE), and standard error (SE) given in Appendix C [102, 110–112]. Sadadou et al. [111] studied and recommended the application of ANN modeling for the prediction of the drying behavior (moisture ratio and drying rate) of fruits in the open sun and direct solar drying. Dhalsamant [112] used ANN modeling for the estimation of the temperature and moisture ratio of potato cylinders during solar drying. A multilayer feed-forward neural network was formed in neural network toolbox of MATLAB 2015b. Levenberg–Marquardt algorithm was used for the training of the program. Experiments were performed to get the data for training and testing sets. Three measurable parameters, namely, ambient temperature, solar insolation, and drying time, were considered as the three inputs nodes to the input layer of the model. The values of temperature and moisture ratio of the potato cylinders were obtained from the two nodes of the output layer. A total 197, 300, and 213 number of experimental data points were supplied for each input parameter for training of the model. For the testing of the model 14, 18, and 21, output data points were used. A representation of the developed ANN model is shown in Fig. 11. The ANN model having 9, 8, and 6 neurons with Levenberg–Marquardt algorithm and tansig transfer function was observed to be the best for predicting various parameters during the drying process for different diameters potato samples.

Mathematical modeling has been widely employed to estimate the drying characteristics of various drying commodities using different solar dryers. The moisture ratio of the drying commodity is calculated using experimental data and then fitted to different mathematical drying models. The accuracy of the drying models can also be tested by calculating the values of parameters given in Appendix C [44, 49, 57, 98, 113]. Daud and Simate [81] tested twelve mathematical thin layer drying models and purposed the suitability of Middilli model to estimate the moisture ratio of pineapple slices dried in an NCDSD. Table 9 shows various mathematical models recommended for different domestic solar dryers and drying commodities.

Developments in modeling techniques for domestic solar dryers have improved the span of the analysis and accuracy of the results. From the literature, it is observed that finite element–based computer software such as ANSYS and COMSOL are comparatively better than ANN models in terms of accuracy of the results. However, there is a scope of developing a dedicated model for a particular drying system considering real time conditions with least assumptions for the most accurate outcomes. Table 10 summarizes the modeling technique used for the analysis of domestic solar dryers.

Discussion, Implications, and Recommendations

Present investigation indicates that the performance of a solar drying system can be evaluated on the grounds of thermal, drying kinetic, environmental, economic analyses and quality aspects of dried products. It is observed that there is no study available in the literature showing a complete performance assessment of a domestic solar dryer. Thermal efficiency, moisture content, drying time, cost, and payback period are some of the most reported performance parameters. The values of thermal efficiency of different domestic solar dryers were observed to be varying in the range of 3.74–67.78% that can be further improved by using various design modifications (such as incorporation of solar collectors for higher energy collection, heat storage arrangements for continuous and fluctuation free operation, better insulations for reduced heat losses, and adequate ventilations for easy moisture removal and least energy losses) and process (including mass of the drying

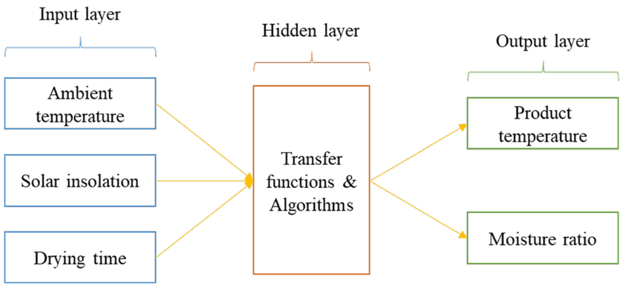


Fig. 11 ANN model [112]

Table 9 Mathematical models recommended for different domestic solar dryers

Sr No.	Study	Dryer	Drying commodity	Preferred/recommended model
1.	Saleh and Badran [44]	NCDSD	Jew's mallow	$MR = \exp(-kt)$
2.	Sharma et al. [49]	FCISD	Tomato slices	$MR = at^3 + bt^2 + ct + d$
3.	Borah et al. [57]	NCDSD	Turmeric	$MR = \exp(-kt^n)$
4.	Daud and Simate [81]	NCDSD	Pineapple slices	$MR = a \times \exp(-kt^n) + bt$
5.	Kondareddy et al. [98]	FCMMSD	Black turmeric	$MR = \exp\left[-(kt)^n\right]$

commodity, rate of flow of the drying air, and temperature distribution inside the drying chamber) optimization techniques such as CFD simulation using ANSYS or COMSOL. The drying time for different commodities under various solar dryers was found to be varying in the range of 5.5–240 h. Some of the dryers took quite higher drying time, which generally depends on the type of drying commodity, its initial and final moisture content values, and ambient conditions. Hybridization of solar dryers seems a solution to reduce the drying time in places where solar insolation is not so significant. Environmental impact assessment has been widely used by researchers for other solar technologies and has great significance in today's time when global climate change has been considered

Table 10 Modeling techniques for domestic solar dryers

Study	Drying method	Product	Modeling technique	Parameters studied	Remarks
Jain et al. [35]	NCDSD	-	CFD numerical simulation	• Static pressure • Temperature • Heat radiation flux • Absorbed visible solar flux	ANSYS Fluent 14.0 simulation software was used.
Saleh and Badran [44]	NCDSD	Jew's mallow	Mathematical modeling	• Drying kinetics	Exponential model was recommended.
Moghimi et al. [48]	FCISD	Tomato	CFD numerical simulation	• Temperature contour • Air streamlines	Fluent simulation was used.
Sharma et al. [49]	FCISD	Tomato slices	Mathematical modeling	• Drying kinetics	Prakash and Kumar model was recommended.
Borah et al. [57]	NCDSD	Turmeric	Mathematical modeling	• Drying kinetics	Page model was found as the most suitable.
Poonia et al. [63]	NCDSD and FCDSD	Ber (*Zizyphus mauritiana*)	Mathematical modeling	• Drying kinetics	Recommended logarithmic model.
Daud and Simate [81]	NCDSD	Pineapple slices	Mathematical modeling	• Drying kinetics	Middilli model showed highest congruence with experimental results.
Chavan et al. [82]	NCDSD	-	CFD modeling	• Air velocity	Employed ANSYS Fluent software.
Kondareddy et al. [98]	FCMMSD	Black turmeric	Mathematical modeling	• Drying kinetics	Modified page model was found more suitable.
Dhalsamant [112]	NCMMSD	Potato cylinders	Finite and ANN modeling	• Temperature • Moisture ratio	Finite modeling in COMSOL software was found better.
Terres et al. [114]	NCDSD	Lemon slices	CFD numerical simulation	• Temperature • Density • Air currents	ANSYS Fluent was used.
Chavan et al. [115]	NCDSD	Potato slices	CFD modeling	• Air velocity	Used ANSYS Fluent software.
Sandali et al. [116]	NCDSD	-	CFD modeling	• Temperature evolution	Employed Fluent CFD software.
Alonge and Obayopo [117]	FCDSD	Fish	CFD numerical simulation	• Temperature profile • Velocity contour	Used ANSYS Fluent simulation.

the biggest threat to life on the earth. The environmental impact assessment of domestic solar dryers has been reported very less in the literature. The initial cost and payback period for various domestic solar dryers were observed in the range of \$3.61–500 and 0.25–3.26 years, respectively. The cost of a domestic solar dryer can be controlled by using local materials and the payback period can be reduced by operating at optimum conditions. The

Table 11 Performance assessment index (PAI) for a domestic solar dryer

Type of dryer:
Drying commodity:
Location:
Month:

Sr. No.	Parameter	Dryer 1	Dryer 2	Preferred value
Thermal indicators				
1	Pickup efficiency			Higher
2	Drying efficiency			Higher
3	Energy efficiency			Higher
4	Exergy efficiency			Higher
5	Exergetic indicators:			
	• Exergy loss			Lower
	• Waste exergy ratio			Lower
	• Improvement potential			Lower
	• Sustainability index			Higher
6	Specific energy consumption			Lower
7	Specific moisture extraction rate			Higher
8	Heat utilization factor			Higher
9	Coefficient of performance			Higher
10	Convective and evaporative heat transfer coefficients			Higher
Drying kinetics indicators				
11	Final moisture content			Should be in acceptable range
12	Moisture ratio			Lower
13	Drying rate			Higher
14	Effective moisture diffusivity			Higher
15	Activation energy			Lower
Environmental indicators				
16	Embodied energy			Lower
17	Energy payback time			Lower
18	CO_2 emissions			Lower
19	CO_2 mitigation potential			Higher
20	Carbon credit earned			Higher
Economic indicators				
21	Life cycle cost			Lower
22	Life cycle benefit			Higher
23	Payback period			Lower
Product quality indicators				
24	Sensory: color, texture, taste, and flavor			Should be as per the requirements
25	Ash content			Higher
26	Rehydration ratio			Higher
27	Shrinkage			Should be as per the requirements
28	Nutritional values			Higher

In addition to above mentioned indicators, the following points should be considered:

- Ease of operation and maintenance
- Safety and size
- Durability and portability

quality of the dried products under domestic solar dryers, which is one of the significant performance indicators, has also been reported rarely in the literature. The change in color of the dried product compared to the fresh product is the most reported product quality indicator. Solar drying has several effects on dried product quality, which, if controlled, can result in high quality products with higher market value. It would improve the earnings of the local farmers and their participation in the dried food market contributing to SDG-12 (i.e., responsible consumption and production). Higher quality products would also result in higher health benefits for consumers which is a contribution to SDG-3 (i.e., good health and well-being). Computational fluid dynamics (CFD) and thermal modeling have been widely used for analyzing and predicting temperature and air velocity inside the drying chamber of domestic solar dryers. Drying commodity is an integral part of the drying process, and hence, modeling and simulation of domestic solar dryers considering the drying commodity is a need for better observations. However, mathematical modeling has been widely used only for predicting the drying behavior of various drying commodities.

In the present era, saving of fossil fuels and environment during drying of various commodities using conventional methods is the major implication for renewable energy utilization. The domestic solar dryers could be highly beneficial along with fossil fuel conservation and pollution control by efficiently utilizing solar energy. This study would be of great significance to researchers in designing and developing a better domestic solar dryer and analyzing its performance. It would also motivate readers toward responsible consumption and production. Moreover, it would increase the awareness among household people around the globe who are keenly interested in combating hunger, climate change and pollution.

There are several criteria for the performance assessment of a domestic solar dryer. After careful and in-depth evaluation of the literature in the present study, a performance assessment index (PAI) for domestic solar dryers has been developed (Table 11). This PAI is recommended for the comparison of the performances of different domestic solar dryers which could be quite useful in standardization and certification of a solar dryer.

Summary

The performance of any system is one of the most responsible factors that lead to new developments. There have been significant advancements in the field of solar dryers in the last few decades and so in their performance evaluation techniques. This manuscript presents a comprehensive review of the methods used for the evaluation and analysis of solar drying systems with a particular emphasis on domestic solar dryers. For the assessment of domestic solar dryers, thermal, drying kinetic, and economic analyses have been performed by the researchers in various studies. However, the continuous environmental degradation is forcing researchers to reduce the carbon footprints (greenhouse gases) in new developments; thus, environmental impact assessment becomes quite essential. Quality of the dried product should always be considered in the development of a domestic solar dryer. Both the environmental and quality assessments are rarely reported in the literature based on domestic solar dryers. This work would be a one-stop solution for designing an efficient solar dryer and assessing its performance. A performance assessment index (PAI) for domestic solar dryers has been suggested in this regard.

Appendix

Appendix A

The value of savings (S) for the life of j number of years can be given as

$$S_j = S_d \times D(1 + i)^{j-1} \tag{A1}$$

where S_d = savings per day and D = number of operating days/year.

The value of S_d can be given as

$$S_d = \frac{S_b}{D_b} \tag{A2}$$

where S_b = saving per batch and D_b = days/batch.

The value of S_b can be given as

$$S_b = S_{kg} \times M_d \tag{A3}$$

where S_{kg} = savings/kg and M_d = mass of dried product/batch.

The value of S_{kg} can be given as follows [118]:

$$S_{kg} = C_b - C_{sd} \tag{A4}$$

where C_b = market cost of the branded dried product and C_{sd} = cost of one kg of dried product.

The value of C_{sd} can be given as

$$C_{sd} = C_{dp} + C_s \tag{A5}$$

where C_{dp} = cost of fresh product per kg of dried product and C_s = drying cost/kg of dried product, whose values can be calculated as

$$C_{dp} = C_{fp} \frac{M_i}{M_d} \tag{A6}$$

$$C_s = \frac{C_a}{M_y} \tag{A7}$$

where C_{fp} = cost of fresh product, M_i = initial mass of product/batch, M_d = mass of dried product/batch, C_a = annualised cost, and M_y = mass of product dried/year.

The values of C_a and M_y can be given as follows [118]:

$$C_a = C_{ac} + C_m - S_a + C_f \tag{A8}$$

$$M_y = \frac{M_d \times D}{D_b} \tag{A9}$$

where C_{ac} = annualised capital cost, C_m = annual maintenance cost (10% of C_{cc}), S_a = annualised salvage value, and C_f = operational cost in case of fan.

The values of C_{ac}, S_a and C_f can be given as follows [119]:

$$C_{ac} = C_{cc} \times F_c \tag{A10}$$

$$S_a = S_v \times F_s \tag{A11}$$

$$C_f = N_f \times P_f \times C_{eu} \tag{A12}$$

where F_c = capital recovery factor, S_v = salvage value (3% of C_{cc}), F_s = salvage fund factor, N_f = number of annual operating hours of fan, P_f = rated power consumed by the fan during operation, and C_{eu} = cost of electricity/unit.

The values of F_c and F_s can be given as follows [120]:

$$F_c = \frac{i(1+i)^j}{(1+i)^j - 1} \tag{A13}$$

$$F_s = \frac{i}{(1+i)^j - 1} \tag{A14}$$

Appendix B

Continuity equation

$$\frac{\partial \rho}{\partial t} + \nabla(\rho \vec{v}) = 0 \tag{B1}$$

Momentum equation

$$\frac{\partial}{\partial t}(\rho \vec{v}) + \nabla(\rho \vec{v} \otimes \vec{v}) = -\nabla P + \nabla \bar{\bar{\tau}} + \rho \vec{g} + S_m \tag{B2}$$

Energy equation

$$\frac{\partial}{\partial t}(\rho E) + \nabla\{\vec{v}(\rho E + P)\} = \nabla\left(-\vec{q} + \bar{\bar{\tau}}.\vec{v}\right) + S_n \tag{B3}$$

where $\nabla = \frac{\partial}{\partial x}\vec{i} + \frac{\partial}{\partial y}\vec{j} + \frac{\partial}{\partial z}\vec{k}$, ρ = density of the fluid, $\vec{v}$ = velocity of fluid, P = pressure, $\bar{\bar{\tau}}$ = stress tensor, S_m = momentum source term, E = total energy, $\vec{q}$ = flux vector (positive inside), and S_n = energy source term.

Appendix C

$$R = \frac{N\sum_{i=1}^{N} MR_{exp,i}MR_{pre,i} - \left(\sum_{i=1}^{N} MR_{exp,i}\right)\left(\sum_{i=1}^{N} MR_{pre,i}\right)}{\sqrt{N\sum_{i=1}^{N} {MR_{exp,i}}^2 - \left(\sum_{i=1}^{N} MR_{exp,i}\right)^2}\sqrt{N\sum_{i=1}^{N} {MR_{pre,i}}^2 - \left(\sum_{i=1}^{N} MR_{pre,i}\right)^2}} \tag{C1}$$

$$MAE = \frac{\sum_{i=1}^{N}(MR_{exp,i} - MR_{pre,i})}{N} \tag{C2}$$

$$RMSE = \sqrt{\frac{\sum_{i=1}^{N}\left(MR_{exp,i} - MR_{pre,i}\right)^2}{N}} \tag{C3}$$

$$SE = \frac{\sqrt{\sum_{i=1}^{N}\left(MR_{exp,i} - MR_{pre,i}\right)^2}}{N-1} \tag{C4}$$

where MR_{exp} = experimental value of MR and MR_{pre} = predicted value of MR.

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Declarations

Competing Interests The authors declare no competing interests.

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