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Thin Layer Modeling and Solar Drying Characteristics of Forced Convective Hybrid Photovoltaic Thermal (PV-T) Solar Dryer Assisted with Evacuated Tube Collector for Drying of Untreated Potato Slices

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Abstract
In the present work, a forced convective hybrid photovoltaic thermal (PV-T) solar dryer assisted with an evacuated tube collector (ETC) is set up to investigate the thin layer drying of potato slices. The drying experiment is compared with the traditional sun drying method without PV-T system under the meteorological conditions of Thanjavur, Tamilnadu. The initial moisture content of potato slices used for the study is 91% (wb). The drying experiment was carried out at different air temperature levels of 50, 55 and 60 °C. Nine numerical models are used to study the drying kinetics of untreated potato slices. Using IBM SPSS 23 statistical package, non-linear regression analysis was performed to estimate correlation coefficient (R^2), reduced chi-square (χ^2) and root mean square error (RMSE). The model developed by Midilli *et al.*, is the most appropriate one to describe potato slices thin layer drying behavior in a hybrid dryer. The effective moisture diffusivity (D_{eff}) determined using Fick's second law of diffusion was found to vary from 2.12463×10^{-8} to 2.79233×10^{-8} m^2/s. The activation energy (E_a) determined using the Arrhenius equation was found to be 16.4276 KJ/mol for drying of potato slices.

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Hybrid photovoltaic thermal solar dryer
Thin layer drying kinetics

Introduction
Potato (*Solanum Tuberosum* L.), a root vegetable is a starchy tuber of the plant. This potential crop is a rich source of carbohydrate, calcium, protein, vitamin B_6, vitamin C and potassium. Potato is a high moisture food and rich in enzymes called peroxidases. India is the 3rd largest country in potato yield after Russia and China with a production of 294.94 million tons per year. It is the 4th most supplement food crop after rice, maize and wheat due to its great production potential and rich nutritive values. The protein-carbohydrate ratio is greater in potatoes than in cereals and other tuber crops (Doymaz, 2011; Hafezi *et al.*, 2015; Kavak Akpinar *et al.*, 2005; Marwaha *et al.*, 2009).

The high moisture content of potatoes leads to post harvest decay and loss of fresh products. Degradation in quality causes a reduction in the economic value of agricultural produce. Drying is one of the most generally used postharvest preservation techniques performed for two main reasons (i) to reduce the water activity that finally increases the shelf-life of the product and (ii) to reduce the weight of the product for easy transport and storage.

Drying is a complex moisture removal process carried by an unsteady state of heat and mass transfer (Amiri Chayjan, 2012; Gupta, Biswas, *et al.*, 2022; Gupta *et al.*, 2021; Gupta, Das, Biswas, Mondol, 2022; Gupta, Das, Biswas, & Jayanta Mondol, 2022; Gupta *et al.*, 2022; Sundari & Subramanian, 2017). The popular method of energy transforming from a heat source to a food material is through convection. Many works have been carried out to study the drying kinetics of agricultural crops of different shapes using different mechanical dryers such as hot air dryer, tray dryer, fluidized dryer and superheated steam dryer. These drying methods cause some loss in the quality of the dried food such as color, odour and texture. These methods are also found to be highly energy consuming (Azimi-Nejadian & Hoseini, 2019; Bakal *et al.*, 2012; Darvishi, 2012; Darvishi *et al.*, 2013; Doymaz, 2012; Hassini *et al.*, 2007; Lin *et al.*, 2005; Reyes, Moyano, *et al.*, 2007; Saravacos, 2005; Srivastava *et al.*, 2015).

Several solar dryers have been developed in recent years overcoming the disadvantages of mechanical dryers to dry high moisture crops. Among different solar dryers available in the literature, evacuated tube collector (ETC) based solar dryers are found to be practically attractive (Veeramanipriya & Sundari, 2021; Veeramanipriya & Sundari, 2019).

Food structure plays a vital role in moisture diffusion. The moisture transfer can take place in two different categories such as surface evaporation and internal liquid-vapour diffusion (Meziane, 2011). During drying, one of the significant physical changes is the reduction of its external volume. The loss of water and heat causes stress in the cellular structure of the food resulting in a change in shape and reduction in dimension (Hafezi *et al.*, 2015).

Many researchers are used Fick's second law of diffusion to determine diffusion coefficient and Arrhenius type relation to determine activation energy and hence illustrate the moisture diffusion and energy required to remove moisture from the food crops respectively (Felizardo *et al.*, 2021; Kaveh *et al.*, 2018; Komolafe *et al.*, 2019; Mugi & Chandramohan, 2021; Shi *et al.*, 2020).

Literature survey reveals that a study on drying characteristics of untreated potato slices using hybrid photovoltaic thermal (PV-T) solar dryer with ETC has not been reported so far. Also, it is observed that drying temperature and drying time affects the nutritive value and quality of the drying sample. In the present study, an attempt has been made to develop a hybrid photovoltaic thermal (PV-T) solar dryer using an evacuated tube collectors aiming to reduce drying time and maintain the quality of the dried sample. The present work aims to report on thin layer mathematical modeling, effective moisture diffusivity and activation energy of untreated potato slices using the developed hybrid solar dryer under different drying temperatures.

Materials and methods

The initial moisture content of untreated potato slices is determined from the ratio of the difference in mass between the fresh sample before drying and the sample after drying in a hot air oven at a temperature of 105 °C for 24 h.

Experimental Setup

A forced convection hybrid photovoltaic thermal (PV-T) solar dryer is employed for the present study. The hybrid dryer encompasses evacuated tube collector, solar PV panel, data logger, blower motor, drying chamber and chimney. The schematic diagram of (PV-T) hybrid solar dryer is shown in Fig. (1a).

The solar PV panel is used to convert solar energy into electricity which is stored in a battery. The energy stored provides electricity to run the blower motor. A blower motor is used to suck the air from the surrounding into the ETC.

The Evacuated tube collector consists of a number of rows of parallel transparent glass tubes connected to a header pipe and which is used in place of the blackened heat absorbing plate of the collector. These glass tubes are cylindrical in shape. Therefore, the angle of the sunlight is always perpendicular to the heat absorbing tubes which enables these collectors to perform well even when sunlight is low such as when it is early in the morning or late in the afternoon, or when shaded by clouds. Evacuated tube collectors are particularly useful in areas with cold, cloudy wintry weathers.

In the present study, 6 evacuated tube collectors with copper header are used for heat exchange. The twin glass ETC is made of borosilicate of thickness 1.6 mm and space between the glass tubes is evacuated. The inner tube of the collector is coated with three layer magnetron sputter coating (SS-Al N/Cu). This collector technology is used to minimize the heat loss due to conduction, convection and radiation. Also, it can withstand high temperature.

The collector traps solar energy and heats the flowing air. The hot air is made to pass into the drying chamber where the samples are placed. The hot air removes the moisture from the sample and escapes through the vent in the chimney. The photographic view of the photovoltaic thermal hybrid solar dryer assisted with ETC is illustrated in Fig. (1b).

Table (1) shows the error and uncertainty analysis of various parameters such as temperatures at various places (ETC inlet and outlet, drying chamber inlet and outlet, chimney and ambient temperature), relative humidity, wind velocity, solar insolation and weight loss using appropriate instruments.

Fig. 1. Photovoltaic thermal hybrid solar dryer assisted with ETC, a). Schematic diagram and b). Photographic view

Table 1. Uncertainty analysis of various parameters on drying of potato slices (Veeramanipriya *et al.*, 2020)

S. No.	Instrument	Range	Accuracy	Resolution	Error %	Uses
1	Spectrum technology RTD pt100 sensor	50~500 °C	0.1 °C	0.1 °C	0.2	Temperature measurement
2	MASTECH MS 6252B digital anemometer	Wind velocity 0.80~30 m/s	±2.0%+50	0.01 m/s	0.0141426	Measurement of wind speed
		ambient temperature-10~60 °C	±1.5 °C	0.1 °C	0.141426	Measurement of ambient temperature
		relative humidity 20~80%	±3.0%	0.1%	0.141426	Measurement of relative humidity
3	TES-1333 solar power meter	2000 W/m^2	±5% or ±10 W/m^2	0.1 W/m^2	0.141426	Measurement of solar insolation
4	D-sonic digital scale	10-15 kg	0.1 g	0.1 g	0.141426	Measurement of weight loss

Experiment procedure

Fresh untreated potato slices of thickness 1±0.5 mm were spread uniformly on three perforated aluminium trays placed inside the drying chamber of the hybrid PV-T solar dryer. The mass of potato taken for the drying experiment was 250 g. Experimental runs for different air temperatures of 50, 55 and 60 °C were carried out at Thanjavur, Tamilnadu, India from 09:00 am to 06:00 pm. Data logger with a temperature controller circuit is used to control the temperature of the drying chamber. The temperature sensor observes the temperature and converts it into an analog signal that is directly fed to the microcontroller board through the temperature sensor transmitter. The microcontroller unit drives the motor to control the blower for controlled drying. The controlled temperature suitable for the particular crop i.e., the optimum temperature is fixed using program coding. When the temperature inside the drying chamber is reached to a particular temperature, the blower automatically runs, resulting in maintaining optimum temperature required for the experiment. To determine the moisture content of the sample at different drying times, the mass of the sample was recorded on hourly basis during the experimental period. Drying experiment was performed till the sample reached equilibrium moisture content (EMC). Dried samples were tightly packed in air tight bags to avoid moisture gain. Hourly variation of ambient conditions such as solar insolation, ambient temperature, relative humidity and wind velocity were also noted during the entire experimental process.

Data analysis

Thin layer drying kinetics

The moisture content (MC) of the sample is determined according to (Bahammou *et al.*, 2019; Bhardwaj *et al.*, 2019; Chandra *et al.*, 2021; Ferreira *et al.*, 2020; Inyang *et al.*, 2018; Jomlapelatikul *et al.*, 2016; Onwude *et al.*, 2018; Panchal *et al.*, 2019; Subramanian *et al.*, 2014; Sundari & Subramanian, 2017; Veeramanipriya & Sundari, 2019; Veeramanipriya *et al.*, 2019) as:

$$MC = \frac{m_i - m_f}{m_i} \times 100\,\% \quad (1)$$

Where, m_i and m_f are initial and final mass of potato respectively. For long drying time, equilibrium moisture content (EMC) is considered negligible. Hence moisture ratio (MR) is simplified as (Chandra *et al.*, 2021; Ferreira *et al.*, 2020; Jomlapelatikul *et al.*, 2016; Onwude *et al.*, 2018; Panchal *et al.*, 2019; Subramanian *et al.*, 2014; Sundari & Subramanian, 2017; Sundari & Veeramanipriya, 2017; Veeramanipriya & Sundari, 2019):

$$MR = \frac{M}{M_0} \quad (2)$$

Where, M and M_0 are moisture content of potato at any time and initial moisture content of potato respectively. Moisture diffusion from inner layer to the outer layer is defined as drying rate (DR) and is expressed using equation (Komolafe *et al.*, 2019; Sengar *et al.*, 2012) as:

$$DR = \frac{\Delta M}{\Delta t} \quad (3)$$

Where, ΔM is the loss of the mass of the potato slices and Δt is the interval of time.

The determination of the drying kinetics of the food is a very complex process. Many mathematical models are proposed by researchers for thin layer drying kinetics of food products. Various mathematical models used in the present study to observe the drying kinetics of untreated potato slices are given in Table (2). The obtained data from the experiments are analyzed statistically using IBM SPSS 23 statistical package with a significance of $P<0.005$. Non-linear regression is used to determine the constants and coefficients of the given mathematical models. Where *k*, *n*, *a*, *c* and *b* are drying constants and *t* is the drying time. Correlation coefficient (R^2), reduced χ^2 and root mean square error (RMSE) are determined using the expressions given below (Bhardwaj *et al.*, 2019; Lingayat & Chandramohan, 2021; Onwude *et al.*, 2018). The model that has lowest reduced χ^2, lowest root mean square error (RMSE) and highest R^2 is considered to be the most suitable model to describe the drying kinetics of the sample.

$$R^2 = \frac{\sum_{i=1}^{n}(MR_{exp,i} - \overline{MR_{exp}}) \cdot \sum_{i=1}^{n}(MR_{pre,i} - \overline{MR_{pre}})}{\sqrt{\sum_{i=1}^{n}(MR_{exp,i} - \overline{MR_{exp}})^2 \cdot \sum_{i=1}^{n}(MR_{pre,i} - \overline{MR_{pre}})^2}} \quad (3)$$

$$\chi^2 = \frac{\sum_{i=1}^{n}(MR_{exp,i} - MR_{pre,i})^2}{N-n} \quad (4)$$

$$RMSE = [\frac{1}{N} \sum_{i=1}^{n}(MR_{pre,i} - MR_{exp,i})^2]^{\frac{1}{2}} \quad (5)$$

Moisture diffusivity & activation energy

Diffusion in drying of solid food involves molecular diffusion, hydrodynamic flow, capillary flow, Knudsen flow and surface diffusion. For the drying process that occurs in the falling rate period, the moisture transfer is controlled by internal diffusion throughout drying. Fick's second law of diffusion is used to represent the drying process in the falling rate period (Anabel *et al.*, 2018; Karathanos, 1999; Komolafe *et al.*, 2018; Mirzaee *et al.*, 2009; Pimpaporn *et al.*, 2007; Vega-Gálvez *et al.*, 2010). The moisture diffusion process is described by the following Eq. (6):

$$\frac{\partial M}{\partial t} = D_{eff}\, \nabla^2 M \quad (6)$$

Where, D_{eff} is the effective diffusivity ($m^2\ s^{-1}$). According to Crank, one dimensional transport in an infinite slab is assumed (Ezeanya, 2018) and moisture ratio is given by Eq. (7):

$$MR = \frac{8}{\pi^2} \exp \sum_{i=0}^{\infty} \frac{1}{(2i+1)^2} \exp[\frac{-(2i+1) D_{eff} \pi^2 t}{4\, L^2}] \quad (7)$$

Where, *L*, and *t* are the half thickness of the slab (m), and the drying time (s), respectively. For longer drying times, first term in the series expansion gives the best evaluation of the solution and is given by Eq. (8):

$$MR = \frac{8}{\pi^2} \exp[\frac{-D_{eff} \pi^2 t}{4\, L^2}] \quad (8)$$

Effective moisture diffusivity (D_{eff}) is determined by plotting ln(MR) versus drying time. D_{eff} value is obtained from the slope of the straight line given by Eq. (9):

$$Slope\ (S) = \frac{-D_{eff} \pi^2 t}{4\, L^2} \quad (9)$$

Activation energy is the minimum energy required to initiate the drying process. It is determined using Arrhenius's equation given by (10):

$$D_{eff} = D_0 \exp\left[\frac{-E_a}{RT}\right] \quad (10)$$

The graph of ln(D_{eff}) versus the reciprocal of the absolute temperature (T^{-1}) presents a straight line. The slope of the straight line gives the value of activation energy described by Eq. (11) as:

$$Slope = \frac{-E_a}{RT} \quad (11)$$

Table 2. Mathematical models applied to drying curves

S. No.	Models	Model Equations	Reference
1	Lewis (Newton)	MR= exp (-kt)	(Lingayat & Chandramohan, 2021)
2	Page	MR= exp ($-kt^n$)	(Veeramanipriya & Sundari, 2021)
3	Henderson & Pabis	MR= a exp (-kt)	(Chasiotis *et al.*, 2022)
4	Logarithmic	MR= a exp (-kt) + c	(Hendorson, 1961)
5	Two term	MR= a exp ($-k_0t$)+(1- a) exp ($-k_1t$)	(Yağcıoğlu *et al.*, 1999)
6	Verma *et al.*	MR= a exp (-kt)+(1- a) exp (-gt)	(Madamba *et al.*, 1996)
7	Wang & Singh	MR = $1+at+bt^2$	(R. Verma *et al.*, 1985)
8	Midilli *et al.*	MR= a exp ($-kt^n$) + bt	(Wang & Singh, 1978)
9	Modified Henderson & Pabis	MR= a exp (-kt)+ b exp (-gt)+ c exp (-ht)	(Midilli *et al.*, 2002)

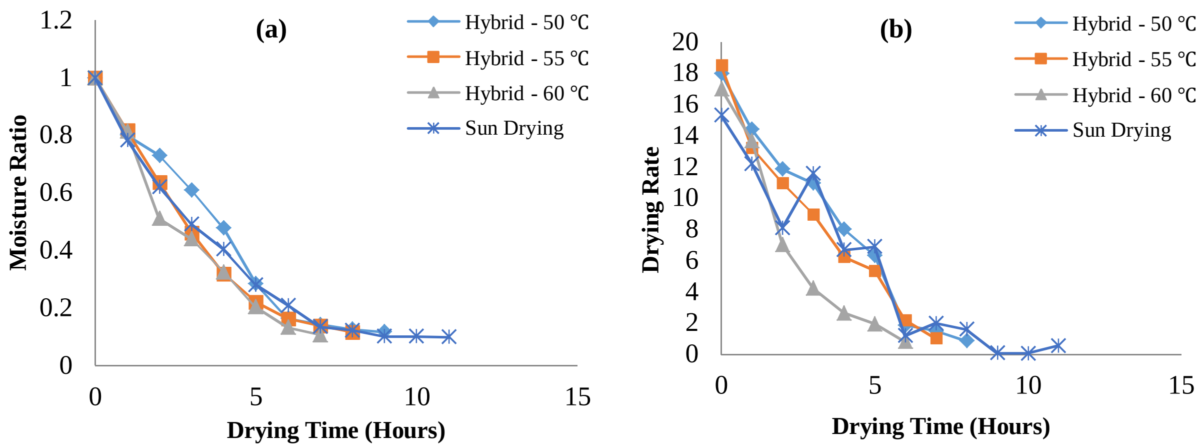

Fig. 2. a) Moisture ratio vs drying time for PV-T-hybrid solar dryer under various temperatures for untreated potato slices and b) Drying rate vs drying time for drying of untreated potato slices under various drying methods

Results & discussion

Experimental characteristics of drying curves

Variation of moisture ratio with respect to drying time is illustrated in Fig. (2). It is observed that moisture ratio decreases with drying time and gets saturated at equilibrium moisture content (EMC). During the experiment, the solar radiation varies from 235 to 1150 W/m^2 and the ambient temperature vary from 33.2 to 46.2 °C. The initial moisture content of the untreated potato slices is 91 % (wb).

Time taken by the designed solar dryer at 60 °C to reach the equilibrium moisture content of 9.79 (% wb) is 7 h whereas the dryer at 55 °C takes 8 h and the dryer at 50 °C takes 9 h to reach the equilibrium moisture content (EMC) of 10.56 (%wb) and 10.69 (%wb) respectively. The experiment is compared with the traditional sun drying of 11 h to reach the EMC of 10.96% (%wb). The drying experiment of untreated potato slices is performed in the falling rate period. The efficiency of the dryer at 60 °C is observed to be 33% whereas the dryer at 55 and 50 °C is found to be 31 and 28% respectively whereas the efficiency of traditional sun drying is found to be 25%. Based on the results it is observed that the increasing drying temperature reduces the drying time respectively. The variation of drying rate concerning to drying time for different temperatures and sun drying is illustrated in Fig. (2). At first, the drying rate is high and is observed to be decreasing as time increases. This is due to the removal of moisture from the crop surface followed by the movement of moisture from the internal part of the product to its surface. This exhibits that the diffusion in physical mechanism controls moisture movement in the samples.

Table 3. Hourly variations of different parameters recorded for drying untreated potato slices

Designed hybrid (PV-T) solar dryer

Time (Hours)	Drying temperature (50 °C)				Drying temperature (55 °C)				Drying temperature (60 ∘C)			
	Solar insolation	RH	Wind velocity	Ambient temperature	Solar insolation	RH	Wind velocity	Ambient temperature	Solar insolation	RH	Wind velocity	Ambient temperature
	W/m^2	%	m/s	°C	W/m^2	%	m/s	°C	W/m^2	%	m/s	°C
09.00	695	52	1.15	36	913.1	56.3	1.21	33.2	896	46	2.17	37.7
10.00	765	50.5	1.23	38.5	884.6	60	0.27	33.5	1054	45	1.38	38
11.00	826	40.7	1.38	40.7	984.8	57.7	1.42	34.5	1150	48	1.26	46.2
12.00	742	42	1.09	39	1012	54.7	1.04	35.1	1104	48.2	1.33	35.7
13.00	963	36	1.47	42.2	1054	53.5	2.62	35.4	1127	43.7	1.47	37
14.00	896	35.5	1	41.8	812.1	52.5	1.86	35.8	986.4	41.5	1.38	37.5
15.00	746	37.2	1.80	40.2	280.1	48	3.06	35.5	764.5	47.5	2.08	37.2
16.00	520	45.2	0.87	38.5	260	50	4.55	35.2	698	48	1.94	35
17.00	443	48.7	0.75	37.2	235	60.5	4.82	34.7	-	-	-	-
18.00	325	50.6	0.82	36.4	-	-	-	-	-	-	-	-

Traditional sun drying

Day	Time (Hours)	Solar Insolation	RH	Wind velocity	Ambient temperature
		W/m^2	%	m/s	°C
1	09.00	523	0.8	59.6	31.4
	10.00	657	0.96	59	31.8
	11.00	896	0.75	58.2	32.3
	12.00	1015	1.05	57	33.2
	13.00	1075	1.02	56.8	33.7
	14.00	890	1.08	56.8	33.7
	15.00	560	0.95	57.2	33.2
	16.00	456	0.88	57.3	33.2
	17.00	438	0.96	59	31.6
	18.00	389	1.07	59.8	30.4
2	10.00	614	1.02	60.1	30.8
	11.00	789	0.89	60	31.2
	12.00	982	0.92	59.2	31.6
	13.00	1056	0.97	59	30.2

The hourly variations of different parameters recorded for drying of untreated potato slices under different drying methods are listed Table (3).

Mathematical modeling of thin layer drying kinetics

To determine the extent of fitness, the experimental data obtained for different drying temperatures are fitted to 9 different models available in the literature and the most exclusive model is chosen based on highest correlation coefficient (R^2), lowest reduced chi-square (χ^2) and lowest root mean square error (RMSE) value. Non-linear regression analysis using IBM SPSS 23 statistical package is carried out to estimate these values.

The model constants and coefficients of the thin layer model fitted for potato slices for different drying temperatures are shown in Tables (4) and (5).

The results show that Midilli *et al.* model could adequately illustrate the drying behaviour of untreated potato slices in (PV-T) hybrid solar dryer assisted with evacuated tube collector irrespective of the drying temperature. Similar reports have been reported for different solar dryers available in literature used to dry potato slices (Amiri Chayjan, 2012; Azimi-Nejadian & Hoseini, 2019; Darvishi *et al.*, 2013; Lee & Kim, 2009; Naderinezhad *et al.*, 2016; Srivastava *et al.*, 2015).

From the Table (4), it is observed that the value of R^2 value ranges from 0.949 to 0.991, χ^2 value ranges from 0.018281 to 0.048494 and RMSE value ranges from 0.002285 to 0.008082 for the designed solar dryer at 50 °C. Similarly, for solar dryer at 55 °C it is found that R^2 value ranges from 0.945 to 0.998, χ^2 value ranges from 0.001932 to 0.045214 and RMSE value ranges from 0.000276 to 0.009043 and for the drying temperature at 60 °C, the corresponding values vary from 0.986 to 0.999, 0.007015 to 0.032805 and 0.001169 to 0.008201.

In traditional drying without PV-T, the value of R^2 varies from 0.994 to 0.998 while the value of reduced χ^2 varies from 0.001887 to 0.007906 and RMSE varies from 0.018001 to 0.102773. The correlation coefficient (R^2) values are found to be greater than 0.99 for all the drying models. The Midilli *et al*. model was chose to present the thin layer drying kinetics of sun dried potato corresponds to the highest correlation coefficient (R^2) value and the lowest values of RMSE and reduced χ^2.

Table 4. Results of different thin layer mathematical models applied for drying of potato slices in (PV-T) hybrid solar dryer assisted with ETC

Temperature	S.No.	Model	Constants	R^2	χ^2	RMSE
50	1	Newton	k=0.224	0.949	0.048494	0.008082
	2	Page	k=0.129, n=1.360	0.957	0.040341	0.004482
	3	Henderson & Pabis	k=0.235, a=1.048	0.961	0.036597	0.004575
	4	Logarithmic	k=0.147, a=1.302, c= -0.288	0.975	0.024074	0.003439
	5	Two-Term	a=20.762, b=-19.747, k_0=0.093, k_1=0.088	0.989	0.023373	0.003895
	6	Verma *et al.*	k=0.081, a=-13.593, g=0.088	0.975	0.023688	0.003384
	7	Wang & sing	a=- 0.175, b=0.008	0.979	0.019514	0.002439
	8	**Midilli *et al*.**	**k=0.013, a=0.857, b= -0.093, n=0.000**	**0.991**	**0.018281**	**0.002285**
	9	Modified Henderson & Pabis	k=0.110, a=2.896, b= -0.941, g=0.068, c= -0.941, h=0.070	0.975	0.023428	0.005857
55	1	Newton	k=0.271	0.989	0.009291	0.001161
	2	Page	k=0.290, n=1.189	0.997	0.002557	0.000365
	3	Henderson & Pabis	k=0.281, a=1.038	0.991	0.007197	0.001028
	4	Logarithmic	k=0.244, a=1.095, c= -0.069	0.993	0.005757	0.000959
	5	Two-Term	a=19.094, b= -18.069, k_0=0.175, k_1=0.171	0.994	0.005303	0.001061
	6	Verma *et al.*	k=0.153, a=-13.565, g=0.106	0.993	0.006110	0.001018
	7	Wang & sing	a= -0.222, b=0.014	0.945	0.045214	0.009043
	8	**Midilli *et al*.**	**k=0.058, a=0.847, b= -0.098, n=-0.000**	**0.998**	**0.001932**	**0.000276**
	9	Modified Henderson & Pabis	k=0.201, a=1.912, b= -0.482, g=0.139, c= -0.406, h=0.135	0.944	0.005341	0.001780
60	1	Newton	k=0.289	0.986	0.032805	0.008201
	2	Page	k=0.253, n=1.130	0.990	0.010086	0.001441
	3	Henderson & Pabis	k=0.307, a=1.027	0.988	0.009049	0.001508
	4	Logarithmic	k=0.258, a=1.101, c= -0.087	0.990	0.007498	0.001500
	5	Two-Term	a=7.593,b=-6.580, k_0=0.188, k_1=0.174	0.990	0.007435	0.001859
	6	Verma *et al.*	k=0.164, a=-7.899, g=0.176	0.990	0.007652	0.001530
	7	Wang & sing	a=- 0.240, b=0.016	0.988	0.009049	0.004525
	8	**Midilli *et al*.**	**k=0.078, a=0.829, b=-0.102, n=0.000**	**0.991**	**0.007015**	**0.001169**
	9	Modified Henderson & Pabis	k=0.307, a=0.719, b=0.154, g=0.307, c=0.154, h=0.307	0.989	0.007828	0.001305

Table 5. Results of different thin layer mathematical models applied for drying of potato slices in traditional sun drying without PV-T system

S.No	Model	Constants	R^2	RMSE	χ^2
1	Newton	k=0.228	0.994	0.102773	0.007906
2	Page	k=0.076, n=1.657	0.996	0.023231	0.001936
3	Henderson & Pabis	k=0.246, a=1.091	0.996	0.088361	0.007363
4	Logarithmic	k=0.159, a=1.269, c= -0.223	0.994	0.044873	0.004079
5	Two-Term	a=30.340, b= -29.294, k_0=0.099, k_1=0.095	0.997	0.041593	0.004159
6	Verma *et al.*	k=0.084, a= -19.962, g=0.088	0.994	0.045197	0.004109
7	Wang & sing	a= -0.164, b=0.007	0.996	0.029032	0.002419
8	**Midilli *et al*.**	**k=0.052, a=0.924, b= -0.001, n=1.840**	**0.998**	**0.018001**	**0.001800**
9	Modified Henderson & Pabis	k=0.114, a=3.211, b=0.602, g=0.078, c= -1.083, h=0.079	0.997	0.041761	0.005220

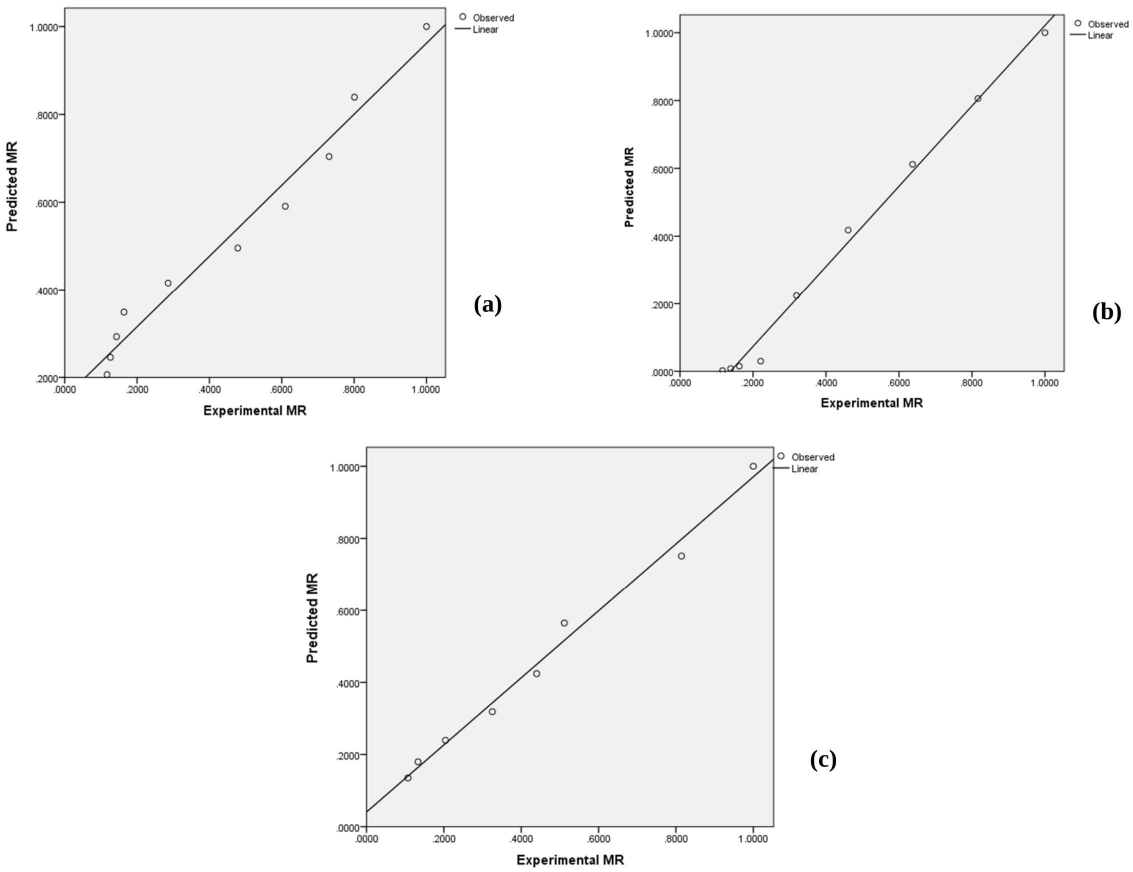

Fig. 3. Experimental vs predicted moisture ratio for drying of potato in the designed solar dryer; a) 50, b) 55, and c) 60 °c for Midilli *et al*. model

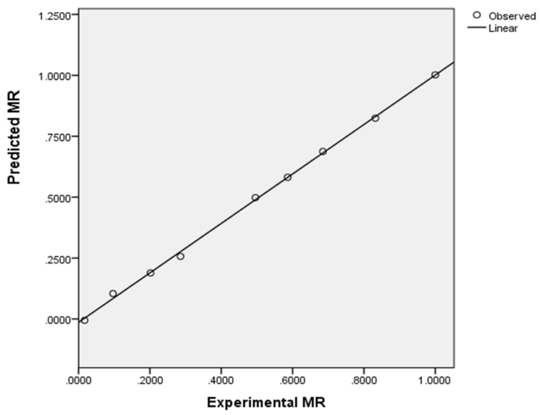

Fig. 4. Experimental vs predicted moisture ratio of drying of potato in traditional sun drying for Midilli *et al*. model

The experimental moisture ratio and predicted moisture ratio are compared for Midilli *et al*. model at different drying temperatures and sun drying shown in Figs. (3) and (4). Predicted value is in close agreement with the experimental value irrespective of the drying temperature and hence Midilli *et al*. model is considered to be the most relevant model to describe the drying kinetics of potato slices in the designed solar dryer and sun drying.

Effective moisture diffusivity and activation energy

The effective moisture diffusivity of the untreated potato slices at different drying temperatures and sun drying is determined by plotting a graph of ln (MR) versus drying time (t) as shown in Fig. (5) and the results are listed in Table (6). From the table, it is observed that the value of D_{eff} of untreated potato slices increases significantly (P<0.05) with drying temperature. This phenomenon addresses the diffusion of water molecules in food samples which is consequently increasing the moisture diffusivity (Rizvi, 1995).

Table 6. Values for effective moisture diffusivity for drying of untreated potato slices in different drying methods

S. No.	Drying method	Drying time (h)	D_{eff} (m^2/s)
1	Traditional sun drying	11	2.12463×10^{-8}
2	Hybrid dryer at 50 (°C)	9	2.42035×10^{-8}
3	Hybrid dryer at 55 (°C)	8	2.44789×10^{-8}
4	Hybrid dryer at 60 (°C)	7	2.79233×10^{-8}

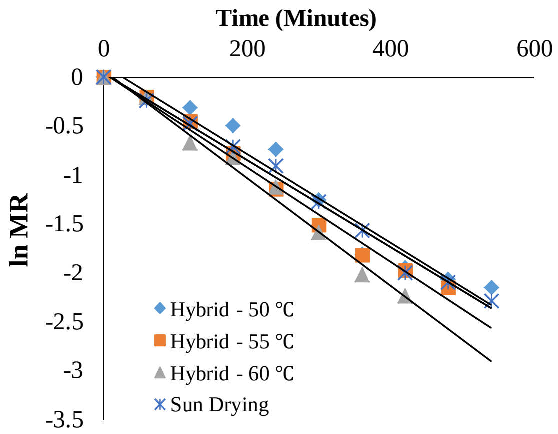

Fig. 5. ln MR vs drying time for drying of untreated potato slices under various drying methods

The results show that the effective moisture diffusivity (D_{eff}) value ranges from 2.12463×10^{-8} to 2.79233×10^{-8} m^2/s. The estimated D_{eff} values are consistent with the given range for food materials (10^{-11} to 10^{-6} m^2/s) (Beigi, 2016; Torki-Harchegani *et al.*, 2016).

The obtained diffusivity values are in good agreement with the reported values of potato slices in the literature such as Darvishi *et al.* (2013) (0.025×10^{-8}-3.05×10^{-8} m^2/s), Azimi-Nejadian & Hoseini (2019) (1.155×10^{-8}-6.654×10^{-8} m^2/s), Srivastava *et al.* (2015) (1.17×10^{-7}-10.00889×10^{-8} m^2/s), Hassini *et al.* (2007) (1.92×10^{-9}-3.55×10^{-10} m^2/s), Darvishi *et al.* (2013) (1.013×10^{-8}-3.799×10^{-8} m^2/s), Amiri Chayjan (2012) (4.29×10^{-9}-15.70×10^{-9} m^2/s), Srikiatden & Roberts (2006) (4.55×10^{-10}-5.32×10^{-10} m^2/s), Markowski *et al.* (2009) (1.17×10^{-9}-4.73×10^{-9} m^2/s), Beigi (2017) (4.32×10^{-9}-6.11×10^{-9} m^2/s), Doymaz (2011, 2012) (9.32×10^{-10}-1.75×10^{-9} m^2/s) and Reyes, Cerón, *et al.* (2007) (5.87×10^{-10}-1.01×10^{-9} m^2/s). The different values reported for the moisture diffusivity is obtained from the various methods of processing the potato into slices, pretreatments and the type of drying system used (Amiri Chayjan, 2012; Azimi-Nejadian & Hoseini, 2019; Beigi, 2017; Darvishi, 2012; Darvishi *et al.*, 2013; Doymaz, 2011, 2012; Hassini *et al.*, 2007; Markowski *et al.*, 2009; Olanipekun *et al.*, 2015; Srikiatden & Roberts, 2006; Srivastava *et al.*, 2015).

Activation energy is the energy required to begin the process of water diffusion from the internal area of the drying sample. It is calculated by plotting the graph of ln(D_{eff}) versus the reciprocal of absolute dryer temperature ($1/T_{abs}$) is shown in Fig. (6). The value of activation energy (E_A) for the thin layer drying of untreated potato slices is found to be 28.5763 KJ/mol. The activation energy (E_A) is within the range of reported values for the food materials (1.27-110 KJ/mol) in literature (Reyes, Moyano, *et al.*, 2007).

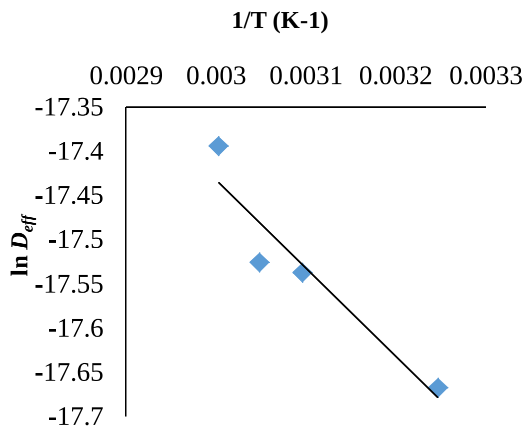

Fig. 6. ln D_{eff} vs reciprocal of absolute temperature (1/T)

Conclusions

In this current study, thin layer mathematical modeling and drying kinetics of untreated potato slices is investigated using a forced convective (PV-T) hybrid solar dryer assisted with evacuated tube collector under various temperatures. According to the obtained results, the time taken to dry the potato slices at 50, 55 and 60 °C in the designed dryer are 9, 8 and 7 h respectively. ETC solar dryer takes 8 h to reach the EMC of 10.71% (%wb) which is compared with the traditional sun drying of 11 h to reach the EMC of 10.96% (%wb). The predicted moisture ratio is in close agreement with the experimental value irrespective of the drying temperature and Midilli *et al*. model is considered to be the most relevant model to describe the drying kinetics of potato slices in the designed solar dryer that is predicted from the results.

The effective moisture diffusivity ranges from 2.12463×10^{-8} to 2.79233×10^{-8} m^2/s. The activation energy is found to be 16.4276 KJ/mol for the thin layer drying of potato slices. The efficiency of the dryer at 60 °C is observed to be 33% whereas the dryer at 55 and 50 °C is found to be 31 and 28% respectively. In ETC solar dryer, the efficiency is calculated to be 32% and for traditional sun drying method is 25%. The results show that temperature controlled at 60 °C shows minimum duration of drying with maximum efficiency. Furthermore, the ETC based hybrid solar dryer is pollution free and can be designed to dry almost all agricultural and non-agricultural products.

Author contributions

AR. Umayal Sundari: Presenting the research idea and study design, Revising and editing the manuscript, Supervising the study, Approval of the final version; **E. Veeramanipriya:** Data collection, Data analysis, Writing the draft of the manuscript, Data analysis and interpretation.

Conflict of interest

The authors declare that they do not have any conflict of interest.

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مدل‌سازی لایهٔ نازک و ویژگی‌های خشک‌کردن خورشیدی خشک‌کن خورشیدی ترکیبی فتوولتائیک حرارتی هم‌رفتی اجباری (PV-T) با کمک جمع‌کنندهٔ لولهٔ تخلیه‌شده برای خشک‌کردن برش‌های سیب‌زمینی تیمارنشده

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چکیده

در پژوهش حاضر، یک خشک‌کن خورشیدی حرارتی فتوولتائیک ترکیبی هم‌رفتی اجباری (PV-T) با کمک یک جمع‌کنندهٔ لولهٔ تخلیه (ETC) برای بررسی خشک‌شدن لایهٔ نازک برش‌های سیب‌زمینی راه‌اندازی شده است. آزمایش خشک‌کردن با روش سنتی خشک‌کردن خورشیدی بدون سیستم PV-T تحت شرایط هواشناسی تانجاور، تامیلنادو مقایسه شده است. میزان رطوبت اولیهٔ برش‌های سیب‌زمینی مورد استفاده برای مطالعهٔ 91 درصد (wb) است. آزمایش خشک‌کردن در سطوح مختلف دمای هوا 50، 55 و 60 درجهٔ سانتی‌گراد انجام شد. 9 مدل عددی برای مطالعهٔ سینتیک خشک‌شدن برش‌های سیب‌زمینی تیمارنشده استفاده می‌شود. با استفاده از آزمون آماری IBM SPSS (نسخهٔ 23)، تحلیل رگرسیون غیرخطی برای تخمین ضریب همبستگی (R^2)، کای دو کاهش‌یافته (χ^2) و ریشهٔ میانگین مربعات خطا (RMSE) انجام شد. مدل توسعه‌یافته توسط Midilli و همکاران، مناسب‌ترین مدل برای توصیف رفتار خشک‌کردن لایهٔ نازک برش‌های سیب‌زمینی در خشک‌کن هیبریدی است. نفوذ رطوبت مؤثر (D_{eff}) تعیین‌شده با استفاده از قانون دوم انتشار فیک از $2/12463\times10^{-8}$ تا $2/79233\times10^{-8}$ مترمربع بر ثانیه متغیر بود. انرژی فعال‌سازی (Ea) تعیین‌شده با استفاده از معادلهٔ آرنیوس 16/4276 کیلوژول بر مول برای خشک‌کردن برش‌های سیب‌زمینی است.

واژه‌های کلیدی: انرژی فعال‌سازی، جمع‌کنندهٔ لولهٔ تخلیه، خشک‌کن خورشیدی حرارتی فتوولتائیک ترکیبی، سینتیک خشک‌کردن لایهٔ نازک، نفوذ رطوبت مؤثر