Numerical Analysis of Thin Layer Drying Kinetics of Untreated Carrot Slices using Photovoltaic Thermal Solar Dryer

E.Veeramanipriya, AR. Umayal Sundari, EA. Monisha

Abstract—The present work demonstrates the drying kinetics of untreated carrot slices using photovoltaic thermal hybrid solar dryer assisted with Evacuated Tube Collector (ETC). The moisture content of carrot is reduced from 85% to 9.3% which is considered to be a safe level in 8 hours with the designed dryer. Open sun drying takes 14 hours to reach the equilibrium moisture content. The efficiency of the designed ETC assisted solar dryer (32.26%) in drying of carrot slices is much greater than open sun drying (24.04%). Nine developed mathematical models are applied to evaluate the drying kinetics of carrot slices for both ETC assisted hybrid solar dryer and open sun drying using IBM SPSS 23 package. Results show that Midilli et al model has high value of correlation coefficient (R2) and least value of reduced chi-square and root mean square error (RMSE) for the designed ETC dryer and sun drying showing the more suitability of fit for drying of carrot slices. It is also observed that the quality and appearance of the solar dried carrot slices using ETC aided hybrid solar dryer is more acceptable than the open sun dried carrots.

Index Terms— photovoltaic, hybrid dryer, mathematical modeling, untreated carrot slices, equilibrium moisture content, drying kinetics, open sun drying

1 INTRODUTION

Energy plays a very important role in day to day life and there is an expeditious need for energy. Energy in several ways runs our economy, globalization even satisfying our own needs. The world energy need is intended to be doubled by 2050 and will be tripled by the end of the century. There are numerous ways to extricate energy, on which conventional source are found to be highly contaminative and extortionate due to the burning of fossil fuel. For these reasons renewable non-conventional source of energy has gained momentum. One such clean and green source of energy is the sun. Solar energy is illimitable, affordable, and environment friendly. The easy and the most proficient way employed for transforming it into solar energy into thermal energy for heating applications by using dryers [1]. Carrot (Daucus Carota) is an essential root crop around the world and it carries considerable amount of the vitamins B1, B2, B6 and B12. It also has large amount of β Carotene content [2 – 6]. β Carotene is a precursor material of vitamin A. Globally carrot is a rich source of fibre content which leads to the healthy diet and used to prevent cancer [7 – 8]. It is a superior source of vitamin A & C, potassium, magnesium, folic acid, thiamine and cholesterol lowering pectin. Dried carrots are used in soups and pastries in the form of powder [9]. The life time of carrot is only 2 – 3 days at normal surrounding temperature and for 10 – 14 days at 0℃. Therefore the post harvest loss becomes very high which occurs due to microbial infestation [10]. Drying extensively used in diverse thermal applications ranging from food drying to wood drying [11]. Drying is extensively used in diverse thermal applications ranging from food drying to wood drying [11]. Drying is minimizing moisture from the products and it is commonly used in preserving agricultural products. Also, it has a great influence on the quality of the dried products [12]. The impetus of a dryer is to furnish the product with more heat than the neighboring to remove the unbound moisture. Further, these moisture reduced products could be stored for a prolonged span of time. Sun drying is the typical practice used to preserve agricultural products throughout the world. It has difficulty associated with the contaminants such as dust, soil, sand particles and insects [13]. Unexpected weather change could cause discrepancy in drying. Also, this process is very slow. To evade these demerits and the demerits of mechanical dryers, solar drying with the aid of gadgets called solar collectors are used. Solar collectors occupy a significant place among implementation of solar energy utilization.

Mathematical model acquires the potential to indicate the drying behavior of food product and find out the consequence of processing parameters, and hence reduces the cost of drying [14]. Several thin layer drying mathematical models are examined for studying the characteristics of various agricultural products such as red chili [15], potato [16], thymine and mint [17], apricot [18], tomato [19], banana blossom [20], mango and cluster beans [21] and carrot [22]. Thin layer drying characteristics of carrot has reported by various researchers, Sonmete [23], Doymaz [24], Gomez – Daz [25], Aghbashlo [26], Erenturk [27], Archana Mahapatra [28], Hosain Drvishi [29], Arivars Aboltins [30], Navneet Kumar [31], Gornicki [32], Raees – ul haq [33] and Changjiang [34]. Many research works are performed to process the carrot though sun drying [35], air drying [36], freeze drying [37], microwave heating and air or vacuum drying [38], convection microwave drying [39 - 40] and solar drying [41]. Moreover, to the researcher's findings, it is observed that drying of carrot

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slices using photo-voltaic thermal hybrid solar dryer aided with Evacuated Tube Collector (ETC) has not been reported so far. Therefore, an attempt is held to preserve the precious root crop by dehydration or drying using photovoltaic thermal hybrid solar dryer assisted with evacuated tube collector and investigates the performance of the dryer using carrot slices.

2 METHODOLOGY

2.1 Experimental Setup

The schematic diagram of photovoltaic thermal hybrid solar dryer assisted with evacuated tube collector applied for the present work is shown in the Figure 2.1. The major parts of the hybrid dryer are PV panel, battery, inverter, blower, evacuated tube collector, drying chamber and chimney. The PV panel is used to convert the solar energy into electricity which is stored in a battery. This produces the necessary power to operate the centrifugal blower.

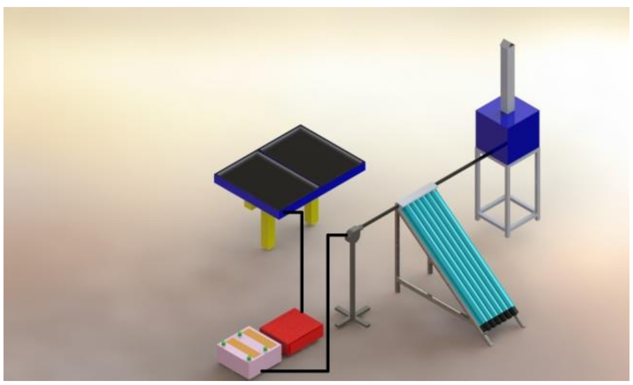

Fig. 1. Schematic diagram of Photovoltaic Thermal hybrid Solar Dryer assisted with ETC.

2.2 Drying Procedure

First, the initial moisture content of the untreated carrot slices is found using hot – air oven, by holding the sample at the temperature of 105 ℃ for 24 hours. Next, in the hybrid dryer, fresh untreated carrot slices are taken and spread uniformly on three perforated aluminium trays. The set-up is placed inside the drying chamber. The atmospheric air is taken into the collector as the blower is turned on and gets heated up. This hot air is blown into the drying chamber and it helps to remove the moisture content of the carrot slices. The experiment is performed from 09.00 am to 06.00 pm. The various external parameters are measured on hourly basis. To avoid the moisture gain as well as contamination, the dried samples are kept in an air tight container. The experiment is continued the next day from 09.00 am till the sample attains equilibrium moisture content.

2.3 Drying Kinetics

Mathematical modeling for thin layer drying is typically applied to understand the drying characteristics of the products. The moisture content of the sample is defined using the formula (1) and the moisture ratio is determined by (2) [20 - 22], [42 – 43], [45 – 46];

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

$$MR = \frac{M}{M_o} \qquad (2)$$

Nine mathematical models used in the present study to determine the drying kinetics of untreated carrot slices are mentioned in the Table 2.1. The constants and coefficients of the models are determined by non – linear regression using IBM SPSS 23 statistical package.

Table 2.1: Mathematical Models applied for drying of untreated carrot slices

S. No.	Models	Model Equations	Reference
1	Lewis (Newton)	MR = exp (-kt)	[47]
2	Page	MR = exp (-kt^n)	[48]
3	Henderson and Pabis	MR = a exp (-kt)	[49]
4	Logarithmic	MR = a exp (-kt) + c	[50]
5	Two term	MR = a exp (-k$_0$t) + (1- a) exp (-k$_1$t)	[51]
6	Verma et al.,	MR = a exp (-kt) + (1- a) exp (-gt)	[52]
7	Wang and Singh	MR = 1 + at + bt^2	[53]
8	Midilli et al	MR = a exp (-kt^n) + bt	[54]
9	Modified Henderson & Pabis	MR = a exp (-kt)+ b exp (-gt)+ c exp (-ht)	[55]

The formula applied to predict the correlation co – efficient (R^2), reduced χ^2 and Root Mean Square Error (RMSE) are determined using [20 - 22], [44]:

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

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

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

The model which has highest R^2, lowest reduced χ^2 and lowest root Mean Square Error (RMSE) are listed as the most applicable model for thin layer drying. The efficiency of the PVT – hybrid dryer is determined using the equation is (6) [21 – 22], [43, 44, 46]:

$$\eta_d = \frac{ML}{IAt} \qquad (6)$$

3 RESULTS AND DISCUSSION

The experiment is carried out in the designed photovoltaic thermal hybrid solar dryer assisted with ETC and also by sun drying under the metrological conditions of Thanjavur, Tamilnadu, India. The parameters measured during the experimental period is listed in Table 3.1 The ambient temperature is observed vary from 30.2 to 34.2 ºC while the ETC outlet temperature varies from 68 to 91 ºC and the temperature of the drying chamber varies from 41 to 57 ºC. As the temperature of drying chamber and ETC outlet are much greater than the ambient temperature, it is observed that the performance of the photovoltaic thermal hybrid solar dryer assisted with ETC increases the drying rate. The initial moisture content of the untreated carrot slices determined using hot air oven is 85% (wb). The photovoltaic thermal hybrid dryer takes 8 hours to reach the final moisture content of 9.3% (wb) which is observed to be the closet moisture content for safe storage. Sun drying takes 14 hours to reach the equilibrium moisture content of 9.5%. Figure 3.1 and 3.2 shows the variation of moisture content with respect to drying time and variation of moisture ratio with respect to drying time respectively for both PV – Thermal hybrid solar dryer and sun drying of untreated carrot.

Table 3.1 Hourly variations of different parameters are recorded for day 1 and 2

Time	Solar Insolation	Wind Velocity	RH	Temperature (°C)						
				Ambient	chimney	Upper Tray	Middle Tray	Lower Tray	ETC outlet	ETC inlet
Hours	W / m²	m/s	%	T_0	T_1	T_2	T_3	T_4	T_5	T_6
09.00 am	298.4	0.92	64	31.5	40	45	45	44	71	51
10.00 am	362.8	0.54	63.5	31.7	42	42	42	46	76	48
11.00 am	420.1	0.27	62.5	32	43	41	41	44	82	48
12.00 nn	719.8	1.61	62	33.7	47	48	48	56	83	49
01.00 pm	856.4	2.44	60	34.2	49	49	49	57	91	51
02.00 pm	806	0.45	60.2	33.6	47	48	48	54	89	55
03.00 pm	542.4	1.38	58.3	33.8	46	47	47	49	79	52
04.00 pm	444.8	0.6	61.8	33.2	45	46	46	48	77	46
05.00 pm	432.6	0.53	60.1	31.5	43	44	44	46	72	43
06.00 pm	389.1	1.33	59.4	30.2	42	43	43	45	68	40
09.00 am	532.65	0.86	61	30.8	-	-	-	-	-	-
10.00 am	587	1.03	62	30.9	-	-	-	-	-	-
11.00 am	602	0.89	63.2	31.2	-	-	-	-	-	-
12.00 nn	765	1.08	61.5	31.6	-	-	-	-	-	-

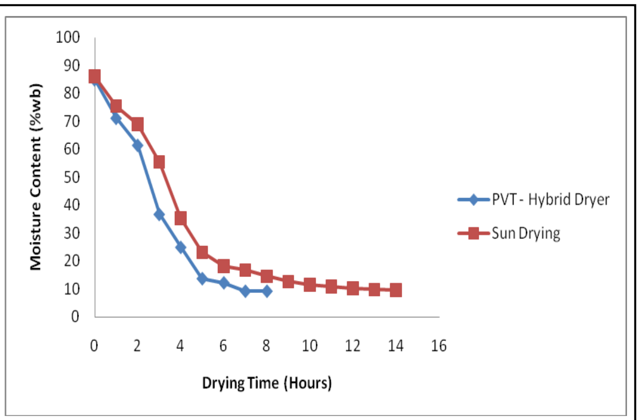

Fig. 3.1. Moisture Content Vs Drying Time for PVT – Hybrid Solar Dryer and Sun Drying

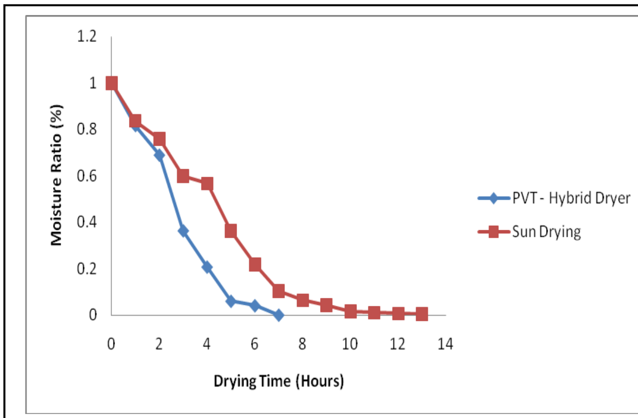

Fig. 3.2. Moisture Ratio Vs Drying Time for PVT – Hybrid Solar Dryer and Sun Drying

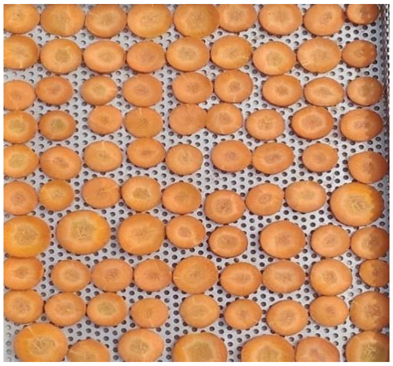

Fig. 3.3. Photograph of untreated carrot slices before drying

Fig. 3.4 (a). Photograph of untreated carrot slices after drying (PVT – Hybrid Dryer)

Fig. 3.4 (b). Photograph of untreated carrot slices after drying (Sun Drying)

The photograph of carrot slices before drying is shown in Figure 3.3 and after drying in PVT – hybrid dryer and sun drying is shown in Figure 3.4 (a) & (b) respectively. It is observed that the moisture content decreases with drying time. Also, decrease in drying rate is observed. The specific moisture extraction ratio is found to be 0.07725 kWh/kg. The efficiency of the designed hybrid dryer is 32.26% and that of sun drying of 24.04%. Also it is observed that the quality and appearance of the hybrid solar dried carrot slices are more satisfactory than sun dried carrot slices. Table 3.2 & 3.3 shows the results of thin layer drying kinetics of untreated carrot slices using hybrid dryer as well as sun drying. In hybrid dryer, the value of R^2 varies from 0.926 to 0.993 while the value of RMSE varies from 0.007547 to 0.083980 and reduced χ^2 varies from 0.001887 to 0.013097. In sun drying, the value of R^2 varies from 0.938 to 0.989 while the value of reduced χ^2 varies from 0.001887 to 0.007906 and RMSE varies from 0.018001 to 0.102773. Results show that Midilli et al model has the highest value of R^2 and lowest value of reduced χ^2 and RMSE for both hybrid solar dryer and sun drying. From the results, it is concluded that Midilli et al d model has the best fit to determine the drying kinetics of both the solar as well as sun drying of carrot slices.

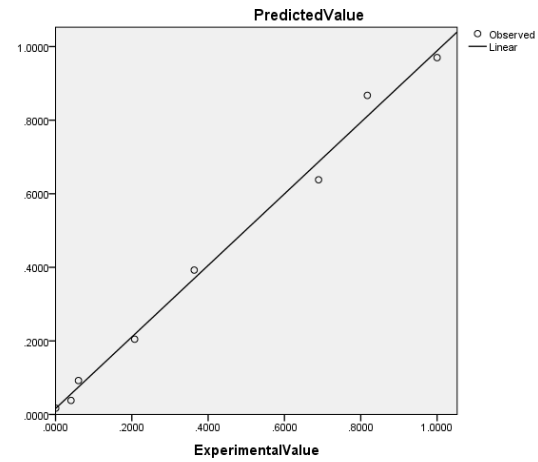

Fig. 3.5. Experimental value Vs Predicted Value for Hybrid dried carrot slices for Midilli et al model

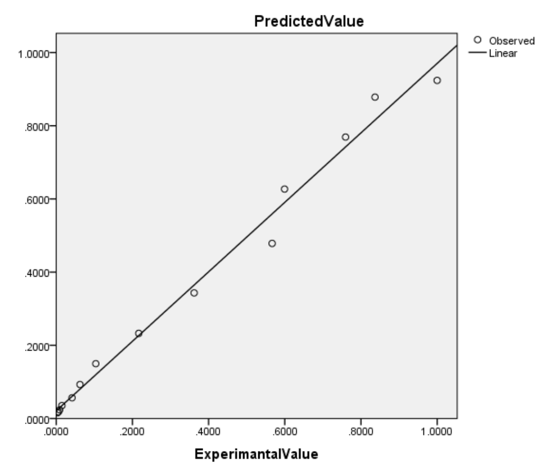

Fig. 3.6. Experimental value Vs Predicted Value for Sun dried carrot slices for Midilli et al model

Figure 3.5 & 3.6 shows the comparison between the experimental value and predicted value for Midilli et al model for both Hybrid dryer and sun drying of untreated carrot slices. It is observed that the experimental value is in close agreement with the predicted value for Midilli et al model.

Table 3.2 Results of mathematical models of photovoltaic thermal hybrid solar dryer with ETC for drying of untreated carrot slices

S. No.	Model	Constants	R2	RMSE	χ2
1	Newton	k=0.344	0.926	0.078420	0.011203
2	Page	k=0.127, n=1.843	0.992	0.083980	0.004100
3	Henderson & Pabis	k=0.371, a=1.088	0.936	0.067692	0.011282
4	Logarithmic	k=-0.185, a=1.514, c= -0.470	0.974	0.027129	0.005426
5	Two – Term	a=23.294,b=-22.294, k0=0.111, k1=0.104	0.975	0.026066	0.006571
6	Verma et al.,	k=0.086, a=-19.0790, g=0.094	0.973	0.028879	0.005776
7	Wang & sing	a= -0.242, b=0.013	0.977	0.024686	0.004114
8	**Midilli et al.,**	**k=0.113, a=0.970, b=-0.001, n=1.901**	**0.993**	**0.007547**	**0.001887**
9	Modified Henderson & Pabis	k=0.139, a=3.091, b=-1.022, g=0.073, c= -1.023, h=0.075	0.975	0.02619	0.013097

Table 3.3 Results of mathematical models of sun drying for drying of untreated carrot slices

S.No	**Model**	**Constants**	**R2**	**RMSE**	**χ2**
1	Newton	k=0.228	0.938	0.102773	0.007906
2	Page	k=0.076, n=1.657	0.986	0.023231	0.001936
3	Henderson & Pabis	k=0.246, a=1.091	0.947	0.088361	0.007363
4	Logarithmic	k=0.159, a=1.269, c= -0.223	0.973	0.044873	0.004079
5	Two – Term	a=30.340, b=-29.294, k0=0.099, k1=0.095	0.975	0.041593	0.004159
6	Verma et al.,	k=0.084, a=-19.962, g=0.088	0.973	0.045197	0.004109
7	Wang & sing	a= -0.164, b=0.007	0.982	0.029032	0.002419
8	**Midilli et al.,**	**k=0.052, a=0.924, b=-0.001, n=1.840**	**0.989**	**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	0.975	0.041761	0.005220

4 CONCLUSION

The designed photovoltaic thermal hybrid solar dryer takes only 8 hours to reduce the moisture content of carrot slices from 85% to 9.3%. But, open sun drying takes 14 hours to reach equilibrium moisture content. The efficiency of the designed ETC assisted solar dryer (32.26%) in drying of carrot slices is much greater than open sun drying (24.04%). Nine developed mathematical models are applied to evaluate the drying kinetics of carrot slices for both ETC assisted hybrid solar dryer and open sun drying using IBM SPSS 23 package. Results show that Midilli et al model has highest value of correlation coefficient (R^2) and least value of reduced chi-square and root mean square error (RMSE) for the designed ETC dryer showing the more suitability of fit for drying of carrot slices. It is also observed that the quality and appearance of the solar dried carrot slices using ETC aided hybrid solar dryer is more acceptable than the open sun dried carrot slices.

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