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Drying Kinetics and Quality Characteristics of Saffron Dried with a Heat Pump Assisted Hybrid Photovoltaic-thermal Solar Dryer

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ABSTRACT

In the present study, saffron was dried using a heat pump-assisted hybrid photovoltaic-thermal solar dryer. The effect of different drying air temperatures at three levels (40, 50, and 60°C) and two different modes of the dryer (with and without heat pump system) were investigated on drying behaviour of saffron. After collecting the pertinent data, eleven drying models were used to describe drying characteristics of saffron. Quality characteristics of the dried products (including: colouring, aromatic strength and bitterness) were also evaluated. The results indicated that drying time decreased by 62% with increasing air temperature from 40 to 60°C. Moreover, applying heat pump with the dryer reduced RH of drying air and, consequently, enhanced drying rate and shortened drying period by 40%. A two-term drying model presented a relatively higher R^2 and lower χ^2, *MBE*, and *RMSE* values at both modes of drying and, therefore, was selected to explain drying behaviour of saffron among the other models. The results of saffron quality evaluation showed that colouring characteristics of saffron improved with drying temperature and heat pump system. Meanwhile, aromatic strength of saffron increased with increasing air temperature. But, no significant change in bitterness was observed at different levels of temperature and heat pump system.

Keywords: PV-T dryer, Mathematical modelling, Quality drying, Two-term model.

INTRODUCTION

Dried red stigma of saffron is the most expensive spicy food. This golden agricultural product is widely used in food industries due to its unrivalled colour, flavour, and aroma. Moreover, medicinal properties of saffron have been known since thousands years ago and, so far, many research works have been conducted on various medicinal properties of saffron components (Das *et al.*, 2010; Hariri *et al.*, 2011; Hayaloglu *et al.*, 2007; Kanakis *et al.*, 2009; Shamsa *et al.*, 2009). Drying process is one of the most important stages in edible saffron production, which has an impressing effect on final product quality. For this reason, some researchers have investigated the effect of drying methods on quality of dried saffron (Atefi *et al.*, 2004; Carmona *et al.*, 2005; Rania *et al.*, 1996; Taslimi *et al.*, 2006).

Drying is a high energy consumption process as 7-15% of total industrial energy in most industrialized countries is used for this process (Chua *et al.*, 2000). Because of increase in fossil fuel prices and their environmental concerns, renewable energies and specifically solar energy have been increasingly considered as alternatives to

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fossil fuels. Hence, various solar dryers have been designed, evaluated, and compared with the conventional industrial dryers (which are mostly hot air dryers) and traditional open sun drying method. The review of literature on the subject indicates that solar dryers have higher thermal efficiency than hot air dryers whose efficiencies often vary from 25 to 50%. Furthermore, solar dryers can shorten drying time period and improve product quality, compared to open sun drying method (Fadhel *et al.*, 2005; Pangavhane *et al.*, 2002; Sacilik *et al.*, 2006; Tiris *et al.*, 1995).

Hybrid Photovoltaic-Thermal (PV-T) solar dryers are new approaches in solar dryer systems. In a hybrid PV-T solar dryer, a photovoltaic panel is usually utilized to convert solar irradiance to both thermal and electrical power for supplying thermal energy required for moisture removal from the products and electrical power for a fan to circulate air through the dryer. Many researchers have investigated the performance of hybrid PV-T solar-powered systems (Gaur and Tiwari, 2010; Kalogirou, 2001; Kumar and Tiwari, 2009; Mortezapour *et al.*, 2012a; Punlek *et al.*, 2009; Sarhaddi *et al.*, 2010; Tiwari and Sodha, 2006). A short survey of their results shows that such hybrid systems have higher overall energy efficiency than each system, separately.

Incorporation of a heat pump system into a hot air dryer leads to a combined dryer which is so-called heat pump dryer. Due to recovery of the waste heat in heat pump dryers, they can reduce energy consumption and hence are more efficient, compared to conventional hot air dryers. Meanwhile, since heat pump dryers are able to control drying air conditions (including temperature and relative humidity), they produce better quality products and are suitable for heat-sensitive materials (Chua *et al.*, 2002; Erbay and Icier, 2009; Mortezapour *et al.*, 2012b; Namsanguan *et al.*, 2004; Pal *et al.*, 2008; Prasertsan and Saen-Saby, 1998).

The present research work was aimed at investigation of drying behaviour of saffron in a hybrid PV-T solar dryer equipped with a heat pump system. Although many mathematical models have been presented by various researchers to describe drying behaviour of different materials (Chin *et al.*, 2009; Ghazanfari *et al.*, 2006; Ghodake *et al.*, 2006; Goyal *et al.*, 2007; HacIhafIzoglu *et al.*, 2008; Janjai *et al.*, 2011; Kavak Akpinar *et al.*, 2006; Liu *et al.*, 2009; Vega-Gálvez *et al.*, 2010; Zomorodian and Dadashzadeh, 2009), there is no known model available for saffron drying. Moreover, the performance parameters of a heat pump-assisted hybrid PV-T solar dryer (including energy consumption, solar fraction, dryer efficiency, solar collector efficiency and specific moisture extraction rate) were investigated by Mortezapour *et al.* (2012b), but the effect of this type of dryers on final quality of dried product has not been studied, so far.

MATERIALS AND METHODS

Experimental Setup

A schematic diagram of heat pump assisted hybrid PV-T solar dryer used in the present study is shown in Figure 1. This apparatus is comprised of two main units including hybrid PV-T solar dryer and heat pump system. The hybrid PV-T solar dryer is made up of a hybrid PV-T solar air collector, a drying chamber, a DC fan, and an auxiliary electrical heater. The sides and back wall of the solar air collector were constructed from wood and insulated by glass wool. A glass sheet was used as the transparent front cover of the solar collector and a photovoltaic panel was fixed at the middle of collector sides with equal distances from the wooden back wall and the top glass cover to work as the solar irradiance absorber plate. This configuration allowed the drying air to pass along both sides of the PV panel, simultaneously. This type of solar collectors is the so-called parallel (or two-way) solar air collector. A

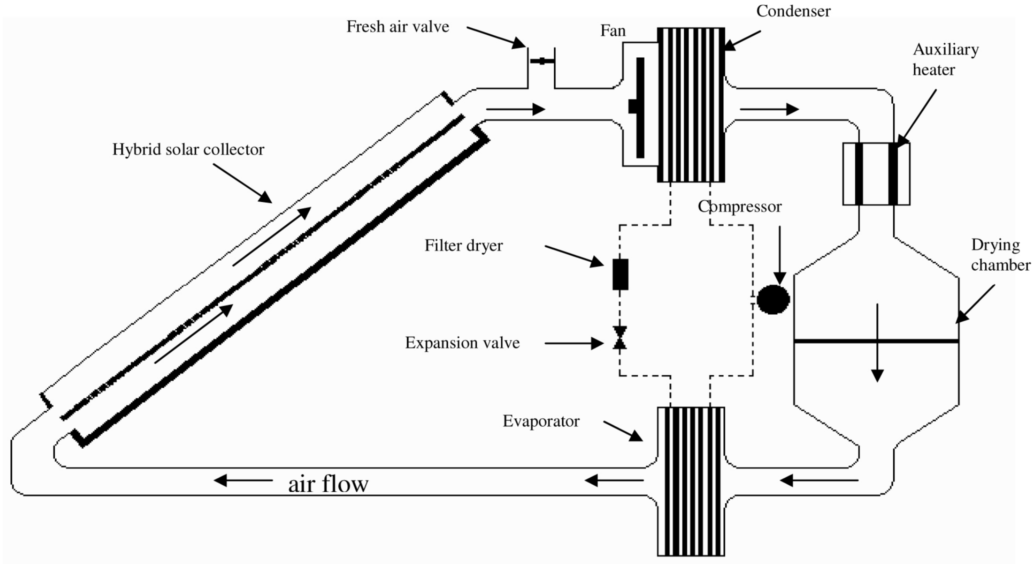

Figure 1. Schematic diagram of heat-pump assisted hybrid PV-T solar dryer.

12V battery that was chargeable by the PV panel was employed to power the DC fan.

The heat pump system contained a finned aluminium condenser and evaporator, a hermetic compressor, a capillary tube-type expansion valve and a filter-dryer. The arrangement of the dryer's components and the heat pump system, which were connected together by glass wool-insulated round ducts, provided a condition under which the drying air was circulated in a closed-cycle through the evaporator, solar air collector, condenser, auxiliary heater, and drying chamber, respectively.

Two load cell sensors (OBU-1, Bongshin Co., S. Korea) were installed inside the drying chamber, where the tray of products was mounted on it, to measure variations of the product mass during the drying process. Furthermore, a temperature sensor (SMT 160, TIKA Eng. Co., Iran) and a relative humidity sensor (TMH-1, TIKA Eng. Co., Iran) were positioned at the inlet of the drying chamber to measure air temperature and relative humidity before the products surface. Measured data of each sensor was displayed and recorded on a Human Machine Interface (HMI). Meanwhile, the HMI was able to control drying air temperature and relative humidity by actuating the auxiliary heater and a fresh air valve. The fresh air valve had been deployed to let the ambient fresh air to enter the dryer's duct and mix with the drying air while temperature and relative humidity of the drying air were more than their desirable set values. The ambient temperature and solar intensity were also measured using a temperature sensor (SMT 160) and a solar power meter device (TES 1333R, TES company, Taiwan), respectively. The solar power meter was installed parallel to the collector surface.

Uncertainty Analysis

Errors and uncertainties are usually incorporated in experimental measurements and can increase due to instrument selection, calibration, observation, and test planning (Holman, 1994). In the present study, the instrument used for measuring temperature and relative humidity of drying air, solar radiation intensity, and weight of products were relatively accurate. The uncertainties that occurred during the experiments were calculated using the method described by Holman and the following equation:

$$W = \left[x_1^{\,2} + x_2^{\,2} + x_3^{\,2} + \ldots + x_n^{\,2}\right]^{0.5} \qquad (1)$$

Where, W and x_n are the total uncertainty and the error of n^{th} factor, respectively. The result of uncertainty analysis is shown in Table 1.

Experiment Procedure

In order to investigate saffron drying behaviour by the fabricated dryer, the experiments were carried out in Qaen, a city located in South Khorasan Province, Iran, during the month of November 2010 from 9 am to 15 pm. During the test period, solar irradiance and ambient temperature varied between 725-1,015 W m^{-2} and 12- 26°C, respectively.

The experiments were conducted at three levels of drying air temperature (40, 50 and 60°C) and two different modes of the dryer (with and without heat pump system). The air mass flow rate was retained constant (around 0.008 kg s^{-1}) during the experiment. The fresh air valve was adjusted to be opened at *RH* above 5%. In each trial, 0.5 kg fresh saffron stigmas were dried spreading on the silky tray. The drying process was continued until product mass decreased to about 112 g.

In order to determine the quality parameters of dried saffron, after terminating each experiment, a sample of the dried product was selected and its colouring, aromatic strength, and bitterness were analyzed following the ISIRI (Institute of Standards and Industrial Research of Iran) standard 259-2. The main chemical compounds of saffron responsible for such attributes are crocins, a group of glycoside derivates from the carotenoid crocetin, terpenic aldehyde known as safranal and a glycoside terpenoid, picrocrocin, respectively (Carmona *et al.*, 2005). Measurements of $E^{\%1}$ of an aqueous saffron extract at 440 (for Crocin), 330 (for safranal), and 257 nm (for picrocrocin) were conducted using a 1cm pathway cell.

Modelling of Drying Curves

Moisture ratio was obtained from $MR=(M-M_e)/(M_o-M_e)$, where M, M_o and M_e are the product moisture content (db) at time t i.e. during the test, initially, and at equilibrium conditions, respectively. Since M_e value is relatively small and negligible compared with M and M_o values, the simplified equation $MR=M/M_o$ is usually used for mathematical modelling of drying curves (Dissa *et al.*, 2011; Evin, 2012; Mousavi and Javan, 2009; Zomorodian and Moradi, 2010). In this study, drying curves were fitted with eleven different mathematical equations (Table 2) which have been widely used in previous research works. In order to select the best model, the correlation coefficient (R^2) is the primary criterion. Furthermore, the reduced chi-square (χ^2) (the mean of the deviations between the experimental and predicted data), Mean Bias Error (MBE), and Root Mean Square Error analysis (RMSE) are also widely employed to specify the best model. The selected model should have the highest R^2 and the lowest χ^2, *MBE,* and *RMSE* values (Hayaloglu *et al.*, 2007; Wang *et al.*, 2007).

These parameters were calculated using the following equations:

Table 1. Total uncertainties of measured parameters.

Measurement	unit	Error
Drying air temperature	°C	± 0.7
Ambient temperature	°C	± 0.7
Relative humidity of drying air	%	0.31
Solar radiation intensity	W m^{-2}	10
Weight of product	g	0.14

Table 2. Mathematical models used for modelling of the drying curves of saffron.

Model name	Model expression	Reference
Lewis	$MR = \exp(-kt)$ *	(Bruce, 1985)
Page	$MR = \exp(-kt^n)$	(Agrawal and Singh, 1977)
Modified Page	$MR = \exp(-kt)^n$	(Diamante and Munro, 1993)
Henderson and Pabis	$MR = a.\exp(-kt)$	(Chhinman, 1984)
Logarithmic	$MR = a.\exp(-kt) + c$	(Togrul and Pehlivan, 2002)
Two-term	$MR = a.\exp(-k_0 t) + b.\exp(-k_1 t)$	(Henderson, 1974)
Wang and Singh	$MR = 1 + at + bt^2$	(Wang and Singh, 1978)
Modified Henderson and Pabis	$MR = a.\exp(-kt) + b.\exp(-gt) + c.\exp(-ht)$	(Karathanos, 1999)
Verma *et al.*	$MR = a.\exp(-kt) + (1-a).\exp(-gt)$	(Verma *et al.*, 1985)
Geometric	$MR = at^{-n}$	(Chandra and Singh, 1995)
Midilli *et al.*	$MR = a.\exp(-kt^n) + bt$	(Midilli *et al.*, 2002)

* *k, n, a, k_0, k_1, b, g, h* and c are empirical constants of the drying models.

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

$$MBE = \frac{\sum_{i=1}^{N}(MR_{\exp.i} - MR_{pre.i})}{N} \quad (3)$$

$$RMSE = \sqrt{\frac{\sum_{i=1}^{N}(MR_{\exp.i} - MR_{pre.i})^2}{N}} \quad (4)$$

Where, $MR_{\exp.i}$ is the i th measured moisture ratio, $MR_{pre.i}$ is the i th calculated moisture ratio, *N* and *Z* are the number of observations and the number of model constants, respectively. Since the *MBE* and *RMSE* separately can lead to a false model selection, mean comparison of experimental and theoretical data using t-statistic analysis was carried out using the method described by Stone (1993). Based on this method, there must not be a significant difference between the measured data and the model data.

RESULTS AND DISCUSSION

Drying Behaviour of Saffron

Effect of different drying air temperatures on reduction of moisture ratio with and without heat pump system is indicated in Figure 2. It is clear that drying rate increased and, consequently, drying time decreased with increasing air temperature. It was observed that the average of drying time was reduced by 62% when the air temperature rose from 40 to 60°C. This is mainly because

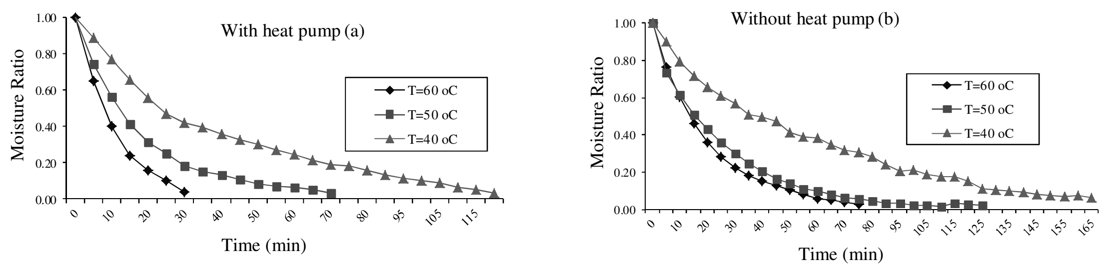

Figure 2. Variation of saffron moisture ratio at different air temperatures with heat pump (a) and without heat pump (b).

partial vapour pressure difference between drying air and products increases when air temperature increases. This enhances vaporization speed from the product surface and hence improves drying rate and shortens drying period. Similar observations were reported by previous researchers (Gorjian *et al.*, 2011; Lee *et al.*, 2012; Momenzadeh *et al.*, 2012; Rafiee *et al.*, 2009; Tahmasebi *et al.*, 2011)

Comparing Figures 2-a and 2-b, it can be observed that utilizing the heat pump system for drying saffron could improve drying rate. A reduction of 40% in drying time was achieved with applying the heat pump system. Since the heat pump's evaporator works as a desiccator, it removes some of the existing vapour from the air flow. Therefore, relative humidity of the drying air incident on the product's surface decreases when applying the heat pump system. Lower relative humidity of the air causes a greater partial vapour pressure difference between air and the material subjected to drying and, consequently, leads to an increase in vaporization rate. . Figure 3 shows the effect of the heat pump system on the changes in *RH* of drying air during the time of drying. The *RH* of circulating air rose abruptly after placing the tray of the material in the dryer. When relative humidity of the drying air reached 5%, the fresh air valve was actuated to let ambient air to mix with the drying air and reduce its relative humidity. Similar results were reported by previous a study (Aktaş *et al.*, 2009). However, the lowest drying period was found to be 32 minutes at air temperature of 60°C, utilizing heat pump system.

The variation of drying rate of saffron versus its moisture content is shown in Figure 4. It is clear that drying rate decreased continuously with reduction of moisture content. Meanwhile, as it can be seen, all of the drying process occurred in the falling rate period and no constant-rate drying behaviour was observed in drying curves.

Drying Curve Fitting

Table 3 shows the models coefficients and the corresponding statistical criteria used for evaluation of the goodness of fit. The values of R^2, χ^2, *MBE* and *RMSE* varied between 0.832 and 0.999, 4.84854E-05 and 1.072275246, 0.00440579 and 0.738353053, and 0.006140915 and 0.993223654, respectively. Generally, based on higher R^2 and lower χ^2, *MBE* and *RMSE* values, the two-term model developed by Henderson (1974) was selected to describe drying behaviour of saffron for both modes of drying (with and without heat pump system). Furthermore, as it can be seen in Table 3, the selected model presented a relatively small t-value and no significant mean difference was observed.

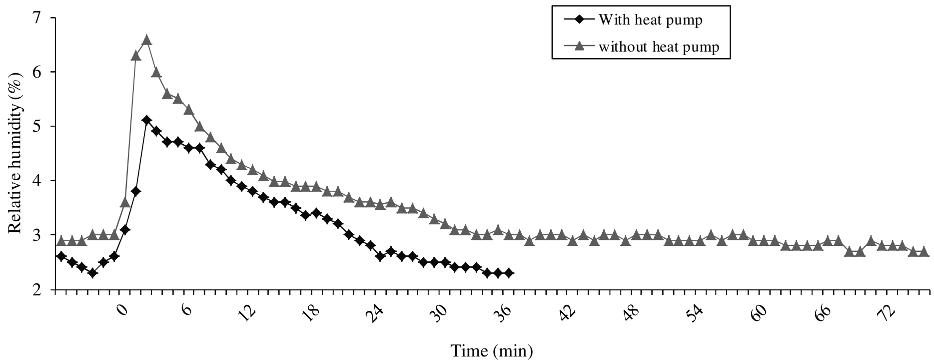

Figure 3. Variation of RH of drying air during the test period.

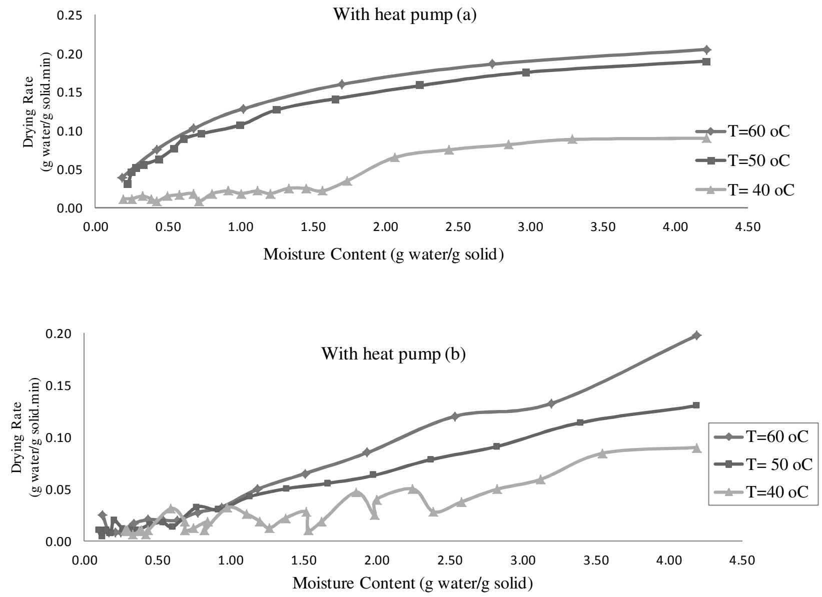

Figure 4. Variation of drying rate versus the moisture content.

The effect of drying air temperature (T) on model constants for both modes of drying was determined using multiple regression analysis. The results were as follow:

For drying without heat pump unit

$a= 0.0037T^2 - 0.3331T + 7.456$ $R^2= 0.99$

$k_1= -0.0394T^2 + 3.9335T - 94.168$ $R^2= 0.99$

$b= -0.0037T^2 + 0.3289T - 6.346$ $R^2= 0.99$

$k_2= -0.0002T^2 + 0.0223T - 0.514$ $R^2= 0.77$

And for drying using heat pump unit

$a= -0.002T^2 + 0.2397T - 6.176$ $R^2= 0.99$

$k_1= 0.0002T^2 - 0.0173T + 0.473$ $R^2= 0.88$

$b= 0.002T^2 - 0.2456T + 7.35$ $R^2= 0.99$

$k_2= 0.0033T^2 - 0.2957T + 6.59$ $R^2= 0.99$

Comparison of experimental and predicted moisture ratio by the selected two-term model for drying saffron using hybrid PV-T solar dryer with and without heat pump are illustrated in Figure 5. Clearly, the data cluster around a straight line which means that there is a good agreement between experimental and calculated values of moisture ratio.

Quality Characteristics of Dried Saffron

Analysis of variance (ANOVA) for the investigation of the effect of different air temperatures and drying modes on the quality parameters of dried saffron is shown in Table 4. It is clear from the table that the temperature had a significant effect on the crocin content. Figure 6-a illustrates how the crocin content changed with temperature. Clearly, increasing the air temperature improved the colour strength of the dried product. This is mainly because the retention of crocin content is highly affected by drying time. On the other hand, since rising the temperature reduced the drying time, it could improve the crocin content of saffron. Similar results were reported by previous researches (Carmona *et al.*, 2005; Rania *et al.*, 1996). Furthermore, as it can be seen

Table 3. Results of statistical analysis of different drying models.

Model	Drying mode	Air temp. (°C)	Model constants				R^2	χ^2	MBE [a]	RMSE [b]	t-value
Lewis	Without	40	*k= 0.017*				0.986	0.000949299	0.021451836	0.030340284	0.999815
	heat	50	*k= 0.041*				0.991	0.000550317	0.015873097	0.022984872	0.954844
	pump	60	*k= 0.048*				0.992	0.000476363	0.018754094	0.021210808	1.89269
	With	40	*k= 0.025*				0.991	0.000713773	0.020829186	0.026154012	1.316886
	heat	50	*k= 0.055*				0.995	0.000363896	0.016323837	0.018429231	1.908354
	pump	60	*k= 0.092*				0.999	0.000145366	0.007984706	0.011162425	1.023645
Page	Without	40	*k= 0.027*	*n= 0.897*			0.991	0.000660873	0.018798222	0.024916259	1.149471
	heat	50	*k= 0.069*	*n= 0.852*			0.998	0.000128604	0.008895069	0.010877285	1.420838
	pump	60	*k= 0.071*	*n= 0.883*			0.997	0.000188197	0.010755804	0.012933919	1.497347
	With	40	*k= 0.037*	*n= 0.896*			0.995	0.000379008	0.013741014	0.01863931	1.091078
	heat	50	*k= 0.073*	*n= 0.909*			0.998	0.00014635	0.010032274	0.011262177	1.9603365
	pump	60	*k= 0.097*	*n=1.063*			0.999	0.004193528	0.04773327	0.054730037	1.782741
Modified Page	Without	40	*k= 0.018*	*n= 0.897*			0.991	0.000660875	0.018798223	0.024916258	
	heat	50	*k= 0.043*	*n= 0.852*			0.998	0.000128604	0.008895071	0.010877285	
	pump	60	*k= 0.050*	*n= 0.883*			0.997	0.000188197	0.010755805	0.012933917	
	With	40	*k= 0.025*	*n= 0.896*			0.995	0.000379008	0.013741014	0.01863931	
	heat	50	*k= 0.056*	*n= 0.909*			0.998	0.00014635	0.010032274	0.011262177	
	pump	60	*k= 0.111*	*n= 1.063*			0.999	0.004193528	0.04773327	0.054730037	
Henderson and Pabis	Without	40	*a= 0.952*	*k= 0.016*			0.990	0.000748248	0.019086431	0.026512263	1.037232
	heat	50	*a= 0.942*	*k= 0.039*			0.995	0.000341547	0.012237998	0.017726355	0.954304
	pump	60	*a= 0.974*	*k= 0.047*			0.993	0.000441666	0.01738013	0.019813939	1.826724
	with	40	*a= 0.970*	*k= 0.024*			0.992	0.000652709	0.019711177	0.024460509	1.360894
	heat	50	*a= 0.983*	*k= 0.054*			0.996	0.000354559	0.015823398	0.017529537	2.097613
	pump	60	*a= 1.008*	*k= 0.093*			0.999	0.000161175	0.008830036	0.010729643	1.448604
Logarithmic	Without	40	*a= 0.945*	*k= 0.017*	*c= 0.012*		0.990	0.000737679	0.019781685	0.025896274	1.673945
	heat	50	*a= 0.935*	*k= 0.041*	*c= 0.018*		0.996	0.000267741	0.009264228	0.015349664	1.070504
	pump	60	*a= 0.995*	*k= 0.055*	*c= 0.044*		0.999	0.000305299	0.01119543	0.015950418	1.393572
	With	40	*a= 0.950*	*k= 0.027*	*c= 0.039*		0.994	0.000548836	0.017322896	0.021914182	1.82524
	heat	50	*a= 0.964*	*k= 0.061*	*c= 0.036*		0.999	6.59338E-05	0.005322206	0.007262718	1.523082
	pump	60	*a= 1.032*	*k= 0.087*	*c=-0.029*		0.999	0.000106359	0.006783816	0.007795935	2.497459
Two-term	Without	40	*a= 0.100*	*k1= 0.158*	*b= 0.906*	*k2= 0.016*	0.992	0.000667119	0.016984362	0.024212731	1.704733
	heat	50	*a= 0.126*	*k1= 4.927*	*b= 0.874*	*k2= 0.036*	0.999	5.54091E-05	0.004889041	0.006822289	1.779661
	pump	60	*a= 0.898*	*k1= 0.059*	*b= 0.104*	*k2= 0.011*	0.999	4.84854E-05	0.00440579	0.006140915	1.783859
	With	40	*a= 0.238*	*k1= 0.075*	*b= 0.780*	*k2= 0.020*	0.996	0.000337988	0.012404556	0.01678264	1.900656
	heat	50	*a= 0.849*	*k1= 0.068*	*b= 0.155*	*k2= 0.020*	0.999	5.31661E-05	0.005172188	0.006244074	2.560936
	pump	60	*a= 1.063*	*k1= 0.098*	*b=-0.063*	*k2= 0.677*	0.999	0.000132423	0.005658168	0.007533448	1.9704
Wang and Singh	Without	40	*a= -0.013*	*b= 4.953E-5*				0.961	0.004695158	0.052512474	0.066412369
	heat	50	*a= -0.024*	*b= 0.000*				0.879	1.072275246	0.738353053	0.993223654
	pump	60	*a= -0.031*	*b= 0*				0.917	0.798915312	0.617412515	0.842702168
	With	40	*a= -0.019*	*b= 9.838E-5*				0.956	0.003527173	0.046835357	0.056861605
	heat	50	*a= -0.038*	*b= 0.000*				0.948	0.831306599	0.626609819	0.848802521
	pump	60	*a= -0.070*	*b= 0.001*				0.992	0.028075411	0.103368314	0.14161167
Modified Henderson and Pabis	Without	40	*a= 0.154*	*K= 0.111*	*b= 8.915*	*g= 0.010*	0.993	0.012806927	0.094582722	0.10236403	4.184771
	heat		*c= -8.062*	*h= 0.010*							
	pump	50	*a= 0.122*	*k= 4.023*	*b= 2.23E-5*	*g= 0.053*	0.999	5.95813E-05	0.00458226	73.24743774	1.61055
			c= 0.878	*h= 0.036*							
		60	*a= 0.986*	*k= 0.054*	*b= -0.111*	*g= 0.037*	0.999	0.001470248	0.028137679	0.031307596	3.550310
			c= 0.124	*h= 0.036*							
	With	40	*a= 0.771*	*k= 0.041*	*b= -2.144*	*g= 0.005*	0.998	0.0295148	0.124943114	0.148782056	2.678996
	heat		*c= 2.392*	*h= 0.004*							
	pump	50	*a= 0.849*	*k= 0.068*	*b= 0.077*	*g= 0.020*	0.999	6.35819E-05	0.005129244	0.006176497	2.581895
			c= 0.077	*h= 0.020*							
		60	*a= 1.006*	*k= 0.092*	*b= 0.023*	*g= 0.552*	0.999	0.000816814	0.008178856	0.010802208	2.007542
			c= -0.023	*h= 0.552*							
Verma *et al.*	Without	40	*a= 0.906*	*k= 0.016*	*g= 0.154*		0.992	0.000665851	0.016874716	0.024230907	1.680815
	heat	50	*a= 0.874*	*k= 0.036*	*g= 5.596*		0.999	5.58905E-05	0.004889041	0.006822289	1.779661
	pump	60	*a=0.100*	*k= 0.010*	*g= 0.059*		0.999	5.06626E-05	0.004490947	0.006497601	1.461916
	With	40	*a=0.775*	*k= 0.020*	*g= 0.068*		0.996	0.000340878	0.012480356	0.017270452	1.780807
	heat	50	*a=-0.594*	*k= 0.055*	*g= 0.055*		0.995	0.000424546	0.016323837	0.018429231	3.305366
	pump	60	*a=-1.908*	*k= 0.061*	*g= 0.070*		0.999	9.9202E-05	0.006693264	0.007529067	3.362492

[a] Mean Bias Error, [b] Root Mean Square Error, (continued)

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Table 3. (continued)

Model	Drying mode	Air temp. (°C)	Model constants				R^2	χ^2	MBE [a]	RMSE [b]	t-value
Geometric	Without	40	*a= 2.513*	*n= 0.515*			0.832	0.00939527	0.083587297	0.093946048	1.949156
	heat	50	*a= 2.802*	*n= 0.737*			0.875	0.00532421	0.061429425	0.069987663	1.831717
	pump	60	*a=2.921*	*n= 0.770*			0.927	0.00333611	0.045795569	0.054455775	1.554226
	With	40	*a= 2.658*	*n= 0.587*			0.890	0.006017501	0.063436422	0.074270066	1.642382
	heat	50	*a= 3.006*	*n= 0.811*			0.937	0.002876495	0.042372693	0.049929578	1.604384
	pump	60	*a= 3.643*	*n= 1.018*			0.956	0.002614385	0.034749105	0.043213632	1.352691
Midilli *et al.*	Without heat	40	*a= 1.002*	*k= 0.034*	*b= 0.000*	*n= 0.820*	0.992	0.001621833	0.027926403	0.037752452	1.904028
	pump	50	*a= 0.988*	*k= 0.066*	*b= -1.29E-5*	*n= 0.860*	0.998	0.000132595	0.008954036	0.010553662	2.776306
		60	*a= 1.002*	*k= 0.058*	*b= 0.000*	*n= 0.960*	0.999	0.000579458	0.017288844	0.021229456	2.430587
	With heat	40	*a= 1.020*	*k= 0.045*	*b= 0.000*	*n= 0.847*	0.996	0.000479235	0.014999545	0.019984049	1.967413
	pump	50	*a= 1.003*	*k= 0.064*	*b= 0.000*	*n= 0.904*	0.999	0.00224361	0.033937747	0.04056247	2.645946

[a] Mean Bias Error, [b] Root Mean Square Error.

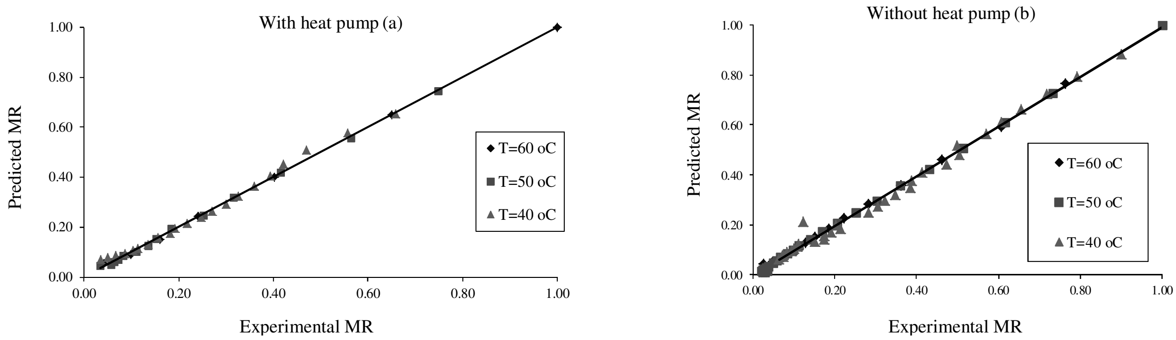

Figure 5. Predicted moisture ratio (MR) versus experimental moisture ratio at different air temperatures with heat pump (a) and without heat pump (b)

from Table 4 and Figure 6-a, utilizing heat pump system with the dryer caused an increase in crocin content, mainly due to reduction of drying time with heat pump system. Table 4 shows that different air temperatures had a significant effect on aromatic strength of saffron. Meanwhile, Figure 6-b illustrates that safranal content slightly decreased as the temperature increased. This occurred, perhaps, because of higher conversion of picocrocin to safranal at lower temperatures. This finding is in agreement with the results of Rania *et al.* (1996). Table 4 shows that no significant difference in aromatic strength of dried products was observed when using heat pump system. This is probably because the drying temperature, which is the main factor in production and retention of safranal content, was constant at both modes of

Table 4. Effect of temperature and heat pump system on quality characteristics of dried saffron.

Source	*df*	Colouring strength (crocin content)		Aromatic strength (Safranal content)		Bitterness (Picrocrocin content)	
		MS	*F*	*MS*	*F*	*MS*	*F*
Temperature	2	938.469	36.825**	18.871	4.633*	11.721	0.616ns
Heat pump	1	388.276	15.236**	1.422	0.349ns	9.202	0.484ns
Interaction	2	4.389	0.172ns	0.056	0.014ns	0.989	0.052ns
Error	12	25.484		4.073		19.025	
Total	18						

**: Significant at P< 0.01;*: Significant at P< 0.05, ns: Not significant.

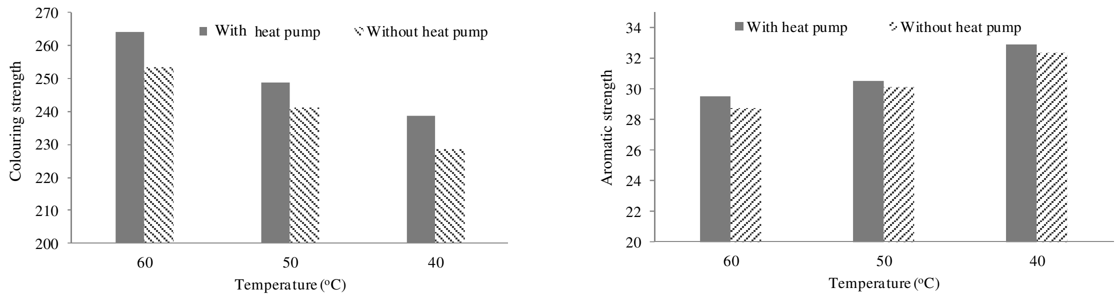

Figure 6. Comparison of colouring and aromatic strength of dried saffron under different drying conditions.

drying. It can also be observed from Table 4 that different levels of temperature and heat pump system had no significant effect on bitterness of dried saffron, and picrocrocin content of the product did not change under different drying conditions.

CONCLUSIONS

In the present study, saffron drying behaviour was investigated using a heat pump assisted hybrid PV-T solar dryer. The experiments were conducted under different drying air temperature and two different modes of dryer (including the dryer equipped with heat pump system and that without heat pump system). Eleven drying models were applied to describe the drying characteristics of saffron. Quality characteristics of dried saffron were also determined according ISIRI 259-2. The results showed that drying time decreased by 62% as air temperature increased from 40 to 60°C. Utilizing heat pump system with the hybrid solar dryer improved drying rate and shortened drying time to 60%. The two-term model presented the best agreement with the experimental data at both modes of drying. Colouring characteristics of saffron improved when drying temperature increased and heat pump system was applied. Aromatic strength of saffron increased with increasing air temperature. No significant change in bitterness of saffron was observed at different conditions of drying.

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سینتیک خشک شدن و صفات کیفی زعفران خشک شده در خشک کن خورشیدی ترکیبی فتوولتائیک- گرمائی مجهز به پمپ حرارتی

ح. مرتضی پور، ب. قبادیان، م. ه. خوش تقاضا و س. مینائی

چکیده

در تحقیق حاضر از یک خشک کن خورشیدی ترکیبی فتوولتائیک-گرمایی برای خشک کردن زعفران استفاده شد. اثر دمای هوای خشک‌کننده در سه سطح (۴۰، ۵۰ و ۶۰ درجه‌ی سیلسیوس) و روش خشک کردن در دو حالت (با و بدون پمپ حرارتی) بر رفتار خشک شدن زعفران مورد بررسی قرار گرفت. از یازده مدل ریاضی مختلف برای تعیین بهترین مدل برای توصیف فرایند خشک شدن زعفران استفاده شد. همچنین ویژگی‌های کیفی زعفران خشک شده (شامل رنگ، عطر و طعم) مورد ارزیابی قرار گرفت. نتایج تحقیق نشان داد که با افزایش دما از ۴۰ به ۶۰ درجه‌ی سیلسیوس، زمان خشک شدن محصول ۶۲٪ کاهش یافت. بعلاوه استفاده از پمپ حرارتی در خشک‌کن سبب کاهش رطوبت نسبی هوای خشک‌کننده و درنتیجه کاهش ۴۰٪ مدت زمان خشک‌شدن شد. در نهایت مدل two-term با دارا بودن بیشترین مقدار R^2 و کمترین مقادیر χ^2 ، MBE و RMSE در هر دو حالت با پمپ حرارتی و بدون پمپ حرارتی به عنوان بهترین مدل برای توصیف رفتار خشک شدن زعفران از میان سایر مدل‌ها انتخاب گردید. نتایج ارزیابی کیفیت زعفران خشک شده نشان داد که افزایش دمای هوای خشک‌کننده و پمپ حرارتی سبب بهبود رنگ زعفران گردیدند. بعلاوه، افزایش دما کاهش عطر زعفران خشک را بدنبال داشت. اما، تغییرات دما و روش خشک کردن نتوانست سبب ایجاد تغییر معنی داری در ویژگی طعم زعفران شود.

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