Mathematical Modelling of Date Palm Drying using Far-infrared Radiation and Heat Pump Dryer

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Abstract

The literature traversed disclosed information that the thin-layer drying characteristic of date palm under intergraded far-infrared radiation (FIR) and heat pump dryer has not been investigated. Widespread throughout the world, the date palm fruit is currently gaining popularity for its health-protective properties and nutritional qualities. The mathematical modelling of the date palm drying was evaluated. The 'deglet nour' variety was used in this experimentation. The variables of drying were far-infrared intensity, air temperature, and initial moisture content of the deglet nour, the values of drying variables were 650, 750 and 850 W/m^2, 0.3 m/s, 40^{o}C and 74% d.b., respectively. Newton, Henderson and Pabis, Logarithmic, Two-term, and Wang & Singh were fitted to predict the moisture ratio (MR) of the deglet nour. Four statistical tools, correlation coefficient (R^2), efficiency model (EF), root mean square error (RMSE) and chi-square were used to analyze the fittings. The results from the experiments found that the moisture content of the deglet nour was decreased exponentially with drying time. The drying rate is increased with the increase of far-infrared intensity. Among the models proposed, the Two-term model precisely represented the deglet nour drying under combined far-infrared radiation and heat pump drying with a correlation coefficient (R^2) and efficiency model (EF) of determination higher than 0.9968 and 1.0000, respectively. The root mean square error (RMSE), and chi-square was lower than 0.0082 and 0.00009, respectively. The deglet nour is very interesting and acceptable for the food industry in Thailand.

Keywords: Deglet nour drying, Mathematical modelling, Thin-layer drying

Introduction

The date palm *Phoenix dactylifera* L (family *Arecaceae*) is a tree that grows in arid and semi-arid regions, and was essentially a major staple food in arid areas such as North Africa, the Middle East and Western Asia (Botes & Zaid, 2002; El-Deek et al., 2010; Janick & Paull, 2008; Zaid & Arias-Jimenez, 2002). The date palm fruit is considered as a major source of carbohydrates which includes simple sugars like glucose, fructose, and sucrose. The Thai date palm was bred by using Deglet Nour and Barhi as the progenitor and cultivated mainly in Chiang Mai province of Thailand. Kanokwan et al. (2015) and Thapat et al. (2012) reported the evaluation and comparison between biodiesel (Palm oil) with ordinary diesel oil. In addition, the potential impact on the environmental life cycle of palm biodiesel production used in comparison with conventional diesel production is evaluated. (Trakarn et al., 2017).

The drying process is to remove moisture in the product to a certain threshold by evaporation, which allows storage for a long time with the decrease in water activity of the product. The microbiological activity is reduced; the changes of physical and chemical properties during storage were minimized (Hosain & Eisa, 2012).

In the treatment of post-harvest crops, there are many techniques. Each of these techniques has different advantages and disadvantages. In Thailand, the most common method used on farms is drying with hot air. The advantages of hot air drying are low cost, easy to maintain, and it is easier for farmers to procure when compared to other methods, such as microwave drying. The drying process with hot air is dependent on the temperature interaction, drying time and moisture content of the product (Sakchai et al., 2011). The main drawbacks of air drying compared to other methods are the longer drying time and the low drying rates in the falling rate period. Others are the impairment of the taste, the worsening of color in the products, loss of nutritional value, higher drying temperature, low energy efficiency and high costs, which was undesirable for the food industry (Wang & Singh, 1978). The infrared radiation was applied in the drying process to prevent significant quality loss and achieve fast and effective thermal processing. In recent years, however, the combination of drying technology was continually increased due to different advantages of each technology. (Abe & Afzal, 1997; Afzal & Abe, 1998; Afzal et al., 1999; Meeso et al., 2007).

The most relevant aspect of drying technology is the development of mathematical models of thin-layer drying to predict product change behavior such as a moisture change, a color change, nutrition changes, etc. The mathematical model of thin-layer drying is a function of drying variables (Hosain & Eisa, 2012).

Therefore, the objective of this research was to study the effect of drying parameters on the moisture content of a deglet nour. In addition, the drying kinetics was evaluated. The highlight of this work, the improved methodology is a combination of the traditional and modern methods. The physical quality of a deglet nour drying was accepted by the consumer.

Materials and Methods

Experimental Setup

Fig. 1 showed the schematic diagram of the dryer which was developed in the Department of Mechanical Engineering, Chaiyaphum Rajabhat University, Thailand. The main components of the dryer are a compressor at 0.75 kW, a drying chamber consisting of 2 kW far-infrared radiators varied by power regulator, an evaporator, a condenser, a variable speed fan, both a pre-heater and re-heater at 1.5 kW, a cooling unit, and a climatic chamber. Air circulation is by a fan and fresh air inlet controlled by dampers. The temperature was controlled by a PID controller (accuracy ± 2°C), which was measured by K-type thermocouples (accuracy ± 1°C). A hot-wire anemometer measured the drying air velocity (accuracy ± 1 m/s).

Experimental Procedure

The deglet nour used in this study was grown in Chaiyaphum province, Thailand. The value of the initial moisture content of deglet nour was estimated at 74% d.b. The deglet nour samples were stored in the refrigerator to maintain initial moisture content at a temperature between 3-6°C for a period of 1 week. Before drying, the deglet nour was taken out of the refrigerator and left in the room until it reached room temperature. The conditions of drying were with a far-infrared intensity of 650, 750 and 850 W/m². The drying air velocity and drying air temperature were 0.3 m/s and 40°C, respectively. While in operation, the weight of the deglet nour was continuously measured. The moisture content of the deglet nour sample was evaluated in an electrical oven at 103°C, 72 hr, and calculated on a dry basis (d.b.).

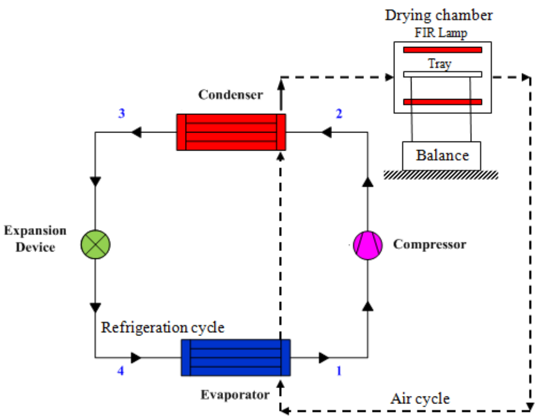

Fig. 1 Schematic diagram of a dryer

Mathematical Modelling of Drying Curves

The data of the moisture content of the deglet nour was converted into the moisture ratio (MR) and then fitted against drying time, using the Newton, Henderson and Pabis, Logarithmic, Two-term, Wang & Singh models as shown in Table 1. In this table:

$$MR = \frac{M(t)-M_e}{M_0-M_e} \quad (1)$$

where M (t), M_0, and M_e are the moisture content of the deglet nour at any time, the initial moisture content and the equilibrium moisture content, respectively. The values of M_e were negligible when compared to the values of M_0.

Table 1. Mathematical models used for modelling of drying curves

No	Model names	Model equations	References
1.	Newton	MR = exp(-kt)	Ayensu, 1997
2.	Henderson and Pabis	MR = aexp(-kt)	Westerman et al., 1973
3.	Logarithmic	MR = aexp(-kt)+c	Yagcioglu et al., 1990
4.	Two-term	MR = aexp(-k_0t)+bexp(-k_1t)	Madamba et al., 1996
5.	Wang & Singh	MR = 1+at+bt²	Wang & Singh, 1978

Correlation coefficients and error analyses

The values correlation coefficient (R^2), efficiency model (EF), root mean square error (RMSE) and chi-square are calculated according to the equations (2)-(5) (Duygu, 2012). The wellness of the model was best when the correlation coefficient and efficiency model value was at the highest value (close to 1) for the root mean square error and the chi-square value was the lowest value (close to 0).

$$R^2 = 1 - \frac{\sum_{i=1}^{N}(X_{pre,i}-X_{exp,i})^2}{\sum_{i=1}^{N}(X_{pre,ave}-X_{pre,i})^2} \quad (2)$$

$$EF = \frac{\sum_{i=1}^{N}(X_{exp\,d,i}-X_{exp,ave})^2-\sum_{i=1}^{N}(X_{pre,i}-X_{exp,i})^2}{\sum_{i=1}^{N}(X_{exp,i}-X_{exp,ave})^2} \quad (3)$$

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

$$\chi^2 = \frac{\sum_{i=1}^{N}(X_{pre,i}-X_{exp,i})^2}{N-z} \quad (5)$$

where X_{exp}, $X_{pre,i}$, N and z is the *i*th experimental values, the *i*th predicted values, the number of observations and the number of constants, respectively.

Results and Discussion

Changing the moisture content of deglet nour

The moisture content of the deglet nour was evaluated under different drying conditions. The results of the moisture content versus the drying time are as shown in Fig. 2. In this figure, it is found that the initial moisture content was approximately 74% d.b. During drying, the moisture content was reduced from initial moisture content to the final moisture contents of 18.32, 20.97 and 23.91% d.b. for the intensity of far-infrared radiation of 650, 750 and 850 W/m², respectively. The drying rate was rapidly decreased at the beginning of the drying period, then gradually decreased throughout the drying period. This phenomenon occurs because the water molecules at the penetrating layer are absorbed with more radiation energy, resulting in a faster drying rate at the beginning of drying, which was reported in the works of Dilip and Pankaj (2004), Meeso et al. (2004), Meeso et al. (2007), Sakai and Hanzawan (1994), and Sharma et al. (2005). Additionally, Sakchai et al. (2011) have drawn attention to the fact that the drying rate was decreased for as much as the reduction of moisture content leading to the lower concentration difference as a result of the driving force of mass transfer.

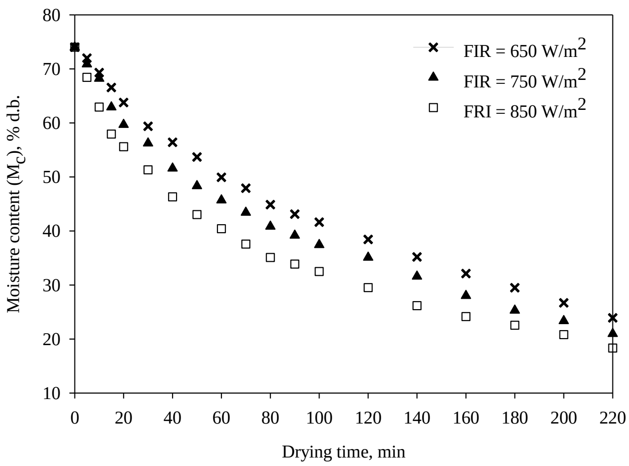

Fig. 2 Moisture content of the deglet nour under different drying conditions

Modelling of drying curves

Fig. 3 presents the experimental data obtained for far-infrared radiation power and drying air velocity at 650, 750 and 850 W/m² and 0.3 m/s, respectively. The result of the moisture ratio (MR) in terms of a function of drying time (t) was fitted to five thin-layer drying models (Newton, Henderson and Pabis, Logarithmic, Two-term, and Wang & Singh model). The form of the equation is shown in Table 1. This mathematical modelling was investigated based on R^2, EF, RMSE and chi-square. The regression coefficients for various thin-layer drying models to explain the changes in moisture ratio are presented in Table 2. It can be seen in this table that the coefficient value of correlation and efficiency model of the Two-term regression model has the highest value for $R^2 > 0.9986$ and EF = 1.0000. Similarly, the value of root mean square error and chi-square has the lowest value at RMSE < 0.0082 and chi-square < 0.00009. Therefore, the Two-term model was given a preferable prediction than the other models, and successfully described the drying kinetics behavior of the deglet nour for the drying conditions in this study. The mathematical modelling of drying characteristics is necessary for the design process. The investigation of mathematical modelling aimed to derive basic kinetic information for a system to describe the reaction rate in terms of a function of experimental variables such as drying time, drying temperature, air velocity and infrared radiation intensity, etc. In addition, the predicted changes in a particular food during drying and monitoring the quality of the final product were used (Van Boekel, 1996).

Table 2. Regression coefficients of the deglet nour drying

No	FIR intensity, W/m²	Model coefficients	Correlation parameters			
			R^2	EF	RMSE	Chi-square
1	650	k = 0.0056	0.9854	0.9998	0.0272	0.00078
	750	k = 0.0067	0.9685	0.9995	0.0437	0.00201
	850	k = 0.0084	0.9392	0.9990	0.0665	0.00467
		average	0.9643	0.9994	0.0458	0.00248
	650	a = 0.9664	0.9898	0.9999	0.0211	0.00050
		k = 0.0053				
2	750	a = 0.9399	0.9785	0.9998	0.0321	0.00115
		k = 0.0060				
	850	a = 0.8955	0.9596	0.9995	0.0449	0.00226
		k = 0.0070				
		average	0.9759	0.9997	0.0327	0.00130
	650	a = 0.7633	0.9973	1.0000	0.0108	0.00014
		k = 0.0085				
		c = 0.2288				
3	750	a = 0.7349	0.9931	0.9999	0.0179	0.00038
		k = 0.0109				
		c = 0.2443				
	850	a = 0.7014	0.9916	0.9999	0.0200	0.00048
		k = 0.0149				
		c = 0.2563				
		average	0.9940	0.9999	0.0162	0.00033
	650	a = 0.1621	0.9992	1.0000	0.0058	0.00004
		k_0 = 0.0312				
		b = 0.8465				
		k_1 = 0.0042				
4	750	a = 0.2166	0.9986	1.0000	0.0082	0.00009
		k_0 = 0.0421				
		b = 0.7942				
		k_1 = 0.0046				
	850	a = 0.3117	0.9991	1.0000	0.0066	0.00006
		k_0 = 0.0449				
		b = 0.6860				
		k_1 = 0.0046				
		average	0.9989	1.0000	0.0068	6.33E-05
	650	a = -0.0058	0.9906	0.9999	0.0209	0.00049
		b = 1.3258E-005				
5	750	a = -0.0070	0.9760	0.9997	0.0359	0.00144
		b = 1.7881E-005				
	850	a = -0.0085	0.9510	0.9993	0.0552	0.00341
		b = 2.4753E-005				
		average	0.9725	0.9996	0.0373	0.00178

Fig. 3 Shows the predicted moisture ratio from the Two-term model. It can be seen in the figure that the coefficient of correlation was more than 0.9989, the efficiency model equals 1.0000, and the value of root mean square and chi-square was less than 0.0068 and 6.33E-05, respectively. These exhibitions can be used for estimating the moisture ratio of the date palm drying under all experimental drying conditions.

Fig. 4 shows that the comparison of the estimated or predicted moisture ratio at any particular drying condition of the Two-term model was confirmed validation. From the figure, the predicted data of the Two-term model was generally banded around the straight line, which showed the suitability of the model for the deglet nour drying.

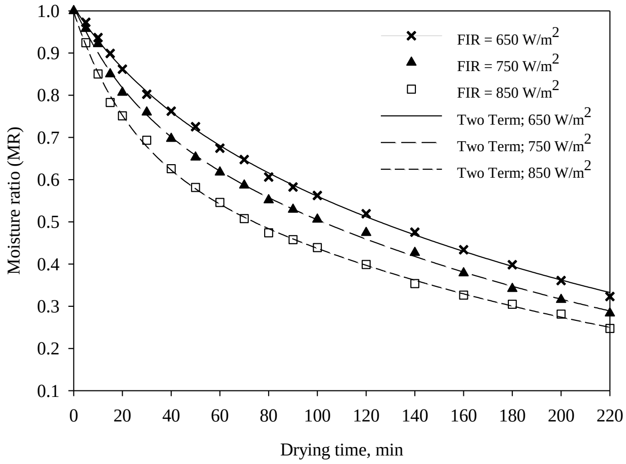

Fig. 3 Experimental and predicted moisture ratio changes by the mathematical model

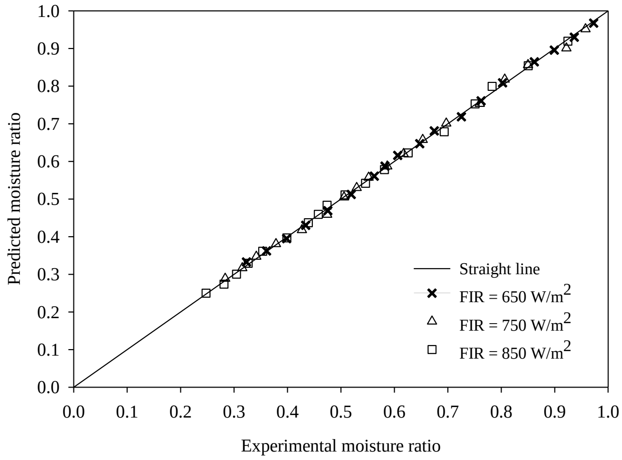

Fig. 4 Comparison of moisture ratios between experimental and predicted by Two-term model

Conclusion

The study has demonstrated that the combined far-infrared radiation and heat pump dryer can be applied in the commercial use of the deglet nour drying. The drying condition was affected by moisture content change. Newton, Henderson and Pabis, Logarithmic, Two-term, Wang & Singh models were used to describe the drying kinetics of the deglet nour. The Two-term model gave the best fit. The researchers believe that this method of drying can be applied to the deglet nour drying industry in Thailand.

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