Journal of Engineering Science and Technology
Vol. 9, No. 1 (2014) 123 - 135

EFFECT OF PRE-TREATMENT ON THE DRYING KINETICS AND PRODUCT QUALITY OF STAR FRUIT SLICES

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Abstract

Start fruit (*Avverhoa carambola*) is rich in nutrients and contains dietary antioxidants which are beneficial to human health. Currently, the commercial potential of this fruit has not been fully explored especially in its dried form. The objectives of this research were to investigate the effect of pre-treatment on the drying kinetics and product quality of star fruit slices. The various pre-treatment methods investigated were hot water blanching and dipping in sugar solution. The star fruit was cut into thin slices (5 mm) for drying (60°C-80°C) using a hot air ventilated oven. Mathematical modelling showed that the Page model was able to describe the moisture diffusion process during drying. Effective diffusivity values were found within the order reported for most food materials (10^{-8}-10^{-12} m^2/s). A decreasing trend in shrinkage ratios was observed with decreasing moisture ratios which corresponds to the greater rate of moisture removal especially at the falling rate period. Overall colour changes were more significant in the blanched samples which could be due to the non-enzymatic browning.

Keywords: Drying, Pre-treatment, Colour, Star fruit, Shrinkage.

1. Introduction

Star fruit (*Averrhoa carambola*) is believed to be originated from Indochina, Malaysia and Indonesia [1]. This fruit is also known as Belimbing (Malaysia and Indonesia), Babingbing (Philippines), Yang-tao (Chinese), Ma fueng (Thailand), Fuang (Laos) and Khe (Vietnam). It is about 5 - 12 cm long and 3 - 6 cm across. In cross section, the fruit resembles a five pointed acute star. Ripen

Nomenclatures

a, b, k, g, n	Constants in empirical models
D_e	Effective diffusivity (m^2/s)
E	Equilibrium
Exp	Experimental value
F	Final sample
I	Initial sample
L^*a^*b	CIE colour space parameters
M_e	Equilibrium moisture content (g H_2O/g dry solids)
M_i	Initial Moisture content (g H_2O/g dry solids)
M_t	Moisture content (g H_2O/g dry solids)
N	Number of observations
O	Reference sample
Pre	Predicted values
R^2	Coefficient of determination
T	Thickness, mm
T_o	Initial thickness, mm
t	Time, min
Z	Nubmer of constants

Greek Symbols

ΔE	Overall colour change

Abbreviations

MR	Moisture ratio
RMSE	Root mean square error

star fruit changes it colour from green to yellow/orange colour. It takes about 60-75 days for the fruit to mature on the tree and eventually ripen.

In general, a mature fruit tree can produce about 112-160 kg or more of fruits annually. The main harvesting seasons are normally from June through February with peak season from August to October and December to February [2]. The whole fruit is edible including the waxy skin and is normally consumed in the fresh form with or without the skin layer. The taste of the fruit is a mixture of sweet and sour taste which is like a cross between apple and grape taste. It can also be used in cooking such as in chutney, curry and pastry. Star fruit is also a very good source of antioxidants and can effectively scavenge free radicals. Epicatechin and proanthocyanidins are the major phenolic compounds present in star fruit that contribute towards the antioxidant activity [3].

To date, eleven types of local fruits namely the star fruit, dragon fruit, pineapple, rambutan, durian, pomelo, papaya, mango, mangosteen, jack fruit and guava have been identified as the new export earners for Malaysia. These “exotic” fruits are fast gaining popularity worldwide with an estimated market worth of over USD10 billion annually [4]. Table 1 shows the planted area and production of star fruit as compared to other fruits typically planted in Malaysia. Malaysia is also one of the biggest exporters of start fruit in the world [5].

Typically most fruits or any agriculture products can be dried for the purpose of preservation by using tunnel dryer [6], heatpump dryer [7, 8], vacuum dryer [9], freeze dryer [10], solar dryer [11, 12] and natural sun dryer [13]. Pre-treatment prior to drying is usually carried out to preserve the nutrients and to enhance the appearance of the dried product. To date, none of the reported studies investigate the drying of star fruits under the influence of drying temperatures and pre-treatments. Star fruit is also under-utilized and commercially not available in processed or dried forms. Therefore, the objectives of the studies were to carry out hot air drying of pre-treated start fruit slices and examine the product quality in terms of shrinkage and colour. The pre-treatment methods investigated were hot water blanching and dipping with sugar solution.

Table 1. Typical Tropical Fruits Planted in Malaysia.

Fruit name	Planted area (Ha)	Production (metric tonne)
Star fruit	1,276	11,820
Papaya	3,403	49,760
Durian	104,655	300,470
Langsat	6,925	25,660
Mango	9,760	25,510
Jackfruit	3,962	27,459
Banana	29,790	294,530
Rambutan	25,460	82,740
Watermelon	11,750	238,050

2. Materials and Methods

2.1. Drying procedure

Star fruit was bought from a local supermarket at Semenyih town, Selangor. Matured and ripen fruits without brown spots were selected, washed and then sliced transversely using a sharp knife into 5 mm thickness at 10 gm each. The seeds were removed from the samples prior to drying. About 12 pieces of fruit slices were arranged on a perforated meshed tray before placing it into the hot air oven.

Drying was carried out using an air ventilated oven (Memmert, Germany) as described in Table 2. Figure 1 shows the schematic diagram of the air ventilated oven. The oven temperature can be adjusted to the accuracy of 0.1°C. The direction of air flow is parallel to the samples on the tray which was position in the middle of the drying compartment. The velocity of airflow was about 0.8 m/s and the moisture laden air was ventilated through a small aperture at the back of the oven. The weight of the sample was determined every hour until the sample reached constant weight. Drying was terminated at this stage and the final reading was used as the equilibrium moisture content. Moisture content was determined by drying the sample inside the oven at 105°C for at least 24 hours until constant weight was achieved [14]. The drying kinetics was determined based on the moisture content, Eq. (1) and moisture ratios, Eq. (2).

$$\text{Moisture content: } M_t = \frac{\text{Mass sample (g) -Bone dry mass (g)}}{\text{Bone dry mass (g)}} \tag{1}$$

$$\text{Moisture Ratio (MR)} = \frac{M_t\text{-}M_e}{M_i\text{-}M_e} \tag{2}$$

Table 2. Drying Conditions in the Oven.

Treatment	Drying temperatures (°C)	Code
Control		C60, C70, C80
Sugar dipped	60, 70, 80	S60, S70, S80
Blanched		B60, B70, B80

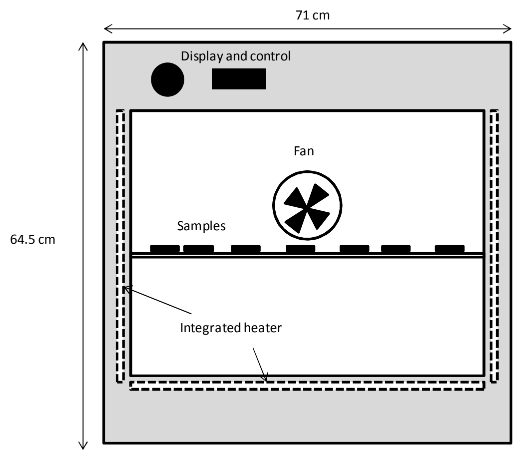

Fig. 1. Schematic Diagram of the Drying Oven.

Two types of pre-treatment methods were applied to the samples namely sugar pre-treatment and blanching. Sugar pre-treatment was carried out by dipping the samples in a sugar solution (0.9975 kg solute/kg solution) at room temperature for 30 minutes. The idea of sugar pre-treatment was to provide a subtle sweetness to mask the astringency and sourness of the samples and not for the purpose of osmotic dehydration. Blanching was carried out by immersing the samples in 700 ml hot water at 80°C on a hot plate for 2 minutes. The purpose of blanching was to inactivate the oxidase enzyme that is responsible for enzymatic browning. At the end of blanching, the samples were blotted dry to remove the excess water and let cool to room temperature.

2.2. Product quality

Dried product quality was determined for overall colour changes and shrinkage ratios. Colour was measured by using a handheld colour meter (Accuprobe, USA) according to the CIE ($L^*a^*b^*$) colour space. The overall colour change (ΔE) was calculated based on Eq. (2).

$$\Delta E^2 = \left(L_f^* - L_o^*\right)^2 + \left(a_f^* - a_o^*\right)^2 + \left(b_f^* - \mathrm{b}_\mathrm{o}^*\right)^2 \tag{3}$$

where subscript o and f refer to the reference (before drying) and final dried samples respectively.

Shrinkage was determined by measuring the thickness (T) of the sample using a vernier calliper (Mitutoyo, Japan) during drying with reference to the initial thickness (T_o). Shrinkage ratio was determined as T/T_o.

All the above measurements were carried out at the same spot on the star fruit slices as indicated in Fig. 2 at the middle section (indicated by the dotted circle) of the cut slices.

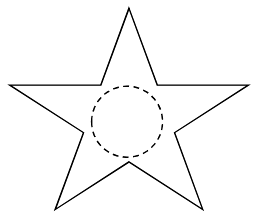

Fig. 2. Measuring Spot on Star Fruit Slice.

2.3. Mathematical modeling

Mathematical modelling was carried out by fitting the semi-empirical models to the experimental drying curve as shown in Table 3. Regression analyses were performed using SOLVER (MS Excel 2007, MS office, USA). The criterions for selecting the best model were based on the highest R^2, the lowest chi-square, Eq. (4) and RMSE, Eq. (5) values [15].

Effective diffusivity (D_e) was determined based on the first term of the Fick's law analytical solution in slab form, Eq. (6). The equation can be linearized by applying natural logarithm at both sides, Eq. (7). The slope from the linear graph was used to determine for effective diffusivity [16].

Table 3. Semi-empirical Models.

Model	Equation
Newton	$\mathrm{MR} = \exp(-kt)$
Page	$\mathrm{MR} = \exp(-kt^n)$
Logarithmic	$\mathrm{MR} = a.\exp(-kt) + c$
Two-term	$\mathrm{MR} = a.\exp(-kt) + b.\exp(-gt)$

$$\text{Chi-square}=\frac{\sum_{i=1}^{N}\left(\mathrm{MR}_{Pre,i}-\mathrm{MR}_{exp,i}\right)^2}{N-Z} \qquad (4)$$

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

$$\mathrm{MR}=\frac{8}{\pi^2}\exp\left(-\frac{\pi^2 \mathrm{D_e t}}{T^2}\right) \qquad (6)$$

$$\ln\mathrm{MR}=\ln\left(\frac{8}{\pi^2}\right)-\left(\frac{\pi^2 D_e t}{T^2}\right) \qquad (7)$$

The stabilized compacted specimens of the various mixtures were cured at their molding water content for four days at the laboratory temperature (21 + 2°C) before testing.

3. Results and Discussion

3.1. Drying kinetics and modeling

Tables 4 to 6 show results of the regression analyses carried out based on the four semi-empirical models. Mathematical modelling showed that the Page model was able to predict the experimental data with reasonably good accuracy based on the highest R^2, the lowest chi-square and RMSE values.

Table 4. Results of Mathematical Modeling (Control).

Equation	Constants	R^2	Chi-square	RMSE
60°C				
Newton	k = 0.0096	0.9914	0.0022	0.0443
Page	n = 1.3233	0.9985	0.0003	0.0144
	k = 0.0021			
Logarithmic	a = 1.0233	0.9929	0.0021	0.0380
	k = 0.0090			
	c = -0.0233			
Two-term	A = 0.6590	0.9914	0.0033	0.0443
	k = 0.0096			
	c = 0.3410			
	g = 0.0096			
70°C				
Newton	k = 0.0109	0.9908	0.0023	0.0449
Page	n = 1.3409	0.9988	0.0002	0.0130
	k = 0.0023			
Logarithmic	a = 1.0258	0.9924	0.0022	0.0382
	k = 0.0102			
	c = -0.0258			
Two-term	A = 0.6590	0.9908	0.0036	0.0449
	k = 0.0109			
	c = 0.3410			
	g = 0.0109			
80°C				
Newton	k = 0.0109	0.9889	0.0023	0.0449
Page	n = 1.3409	0.9982	0.0002	0.0130
	k = 0.0023			
Logarithmic	a = 1.0258	0.9925	0.0022	0.0382
	k = 0.0102			
	c = -0.0258			
Two-term	a = 0.6590	0.9889	0.0036	0.0449
	k = 0.0109			
	c = 0.3410			
	g = 0.0109			

Table 5. Results of Mathematical Modeling (Sugar Dipped).

Equation	Constants	R^2	Chi-square	RMSE
60°C				
Newton	k = 0.0090	0.9919	0.0022	0.0444
Page	n = 1.3138	0.9987	0.0002	0.0136
	k = 0.0020			
Logarithmic	a = 1.0324	0.9939	0.0018	0.0358
	k = 0.0082			
	c = -0.0324			
Two-term	a = 0.6590	0.9920	0.0033	0.0444
	k = 0.0090			
	c = 0.3410			
	g = 0.0090			
70°C				
Newton	k = 0.0114	0.9911	0.0021	0.0433
Page	n = 1.3362	0.9990	0.0002	0.0116
	k = 0.0025			
Logarithmic	a = 1.0212	0.9925	0.0021	0.0378
	k = 0.0108			
	c = -0.0212			
Two-term	a = 0.6590	0.9913	0.0034	0.0434
	k = 0.0114			
	c = 0.3410			
	g = 0.0114			
80°C				
Newton	k = 0.0145	0.9907	0.0018	0.0395
Page	n = 1.3317	0.9991	0.0001	0.0105
	k = 0.0035			
Logarithmic	a = 1.0457	0.9913	0.0018	0.0336
	k = 0.0132			
	c = -0.0457			
Two-term	a = 0.6334	0.9908	0.0031	0.0395
	k = 0.0145			
	c = 0.3666			
	g = 0.0145			

Table 6. Results of Mathematical Modeling (Blanched).

Equation	Constants	R^2	Chi-square	RMSE
60°C				
Newton	k = 0.0088	0.9900	0.0027	0.0486
Page	n = 1.3438	0.9983	0.0003	0.0158
	k = 0.0017			
Logarithmic	a = 1.0360	0.9926	0.0022	0.0394
	k = 0.0080			
	c = -0.036			
Two-term	a = 0.6591	0.9902	0.0039	0.0486
	k = 0.0088			
	c = 0.3410			
	g = 0.0088			

70°C				
Newton	k = 0.0133	0.9920	0.0018	0.0401
Page	n = 1.3130	0.9992	0.0002	0.0108
	k = 0.0034			
Logarithmic	a = 1.0685	0.9937	0.0013	0.0288
	k = 0.0116			
	c = -0.0685			
Two-term	a = 0.6582	0.9921	0.0032	0.0402
	k = 0.0133			
	c = 0.3418			
	g = 0.0133			
80°C				
Newton	k = 0.0165	0.9921	0.0014	0.0349
Page	n = 1.3084	0.9994	0.0001	0.0088
	k = 0.0045			
Logarithmic	a = 1.0317	0.9924	0.0015	0.0310
	k = 0.0154			
	c = -0.0317			
Two-term	a = 0.6332	0.9922	0.0024	0.0349
	k = 0.0165			
	c = 0.3668			
	g = 0.0165			

Figure 3 shows the comparison between the experimental and predicted drying curves for the various drying treatments (control, blanched and sugar dipped). The close fitting between the Page model and the experimental data can be seen clearly in the charts. The application of Page model has been used widely in modelling of other fruit products [16-18]. The basic form of the page model is similar to the Newton model except for the correction factor '*n*' that is added to the equation to improve its fitting accuracy. Exact reason for such inclusion of this factor is unknown and has not been reported elsewhere. It is believed that the factor 'n' is merely an empirical constant that has no theoretical reasoning at all.

Table 7 shows the effective diffusivity values (D_e) which range from 9.5×10^{-8} to 1.0×10^{-7} m^2/s. The diffusivity values are well within the range reported for most food materials in the magnitude of 10^{-12}-10^{-8} m^2/s [19] and also from those reported by Mauro et al. [20].

Table 7. Effective Diffusivity Values of Star Fruit Slices.

	Effective diffusivity (m^2/s)		
Temperature (°C)	**Control**	**Sugar-dipped**	**Blanched**
60	9.45×10^{-8}	7.51×10^{-8}	7.72×10^{-8}
70	9.33×10^{-8}	9.54×10^{-8}	1.08×10^{-7}
80	1.21×10^{-7}	7.68×10^{-8}	8.10×10^{-8}
Average	1.03×10^{-7}	8.24×10^{-8}	8.87×10^{-8}
Mauro et al. [20]		$2.49 - 4.54\times10^{-10}$	

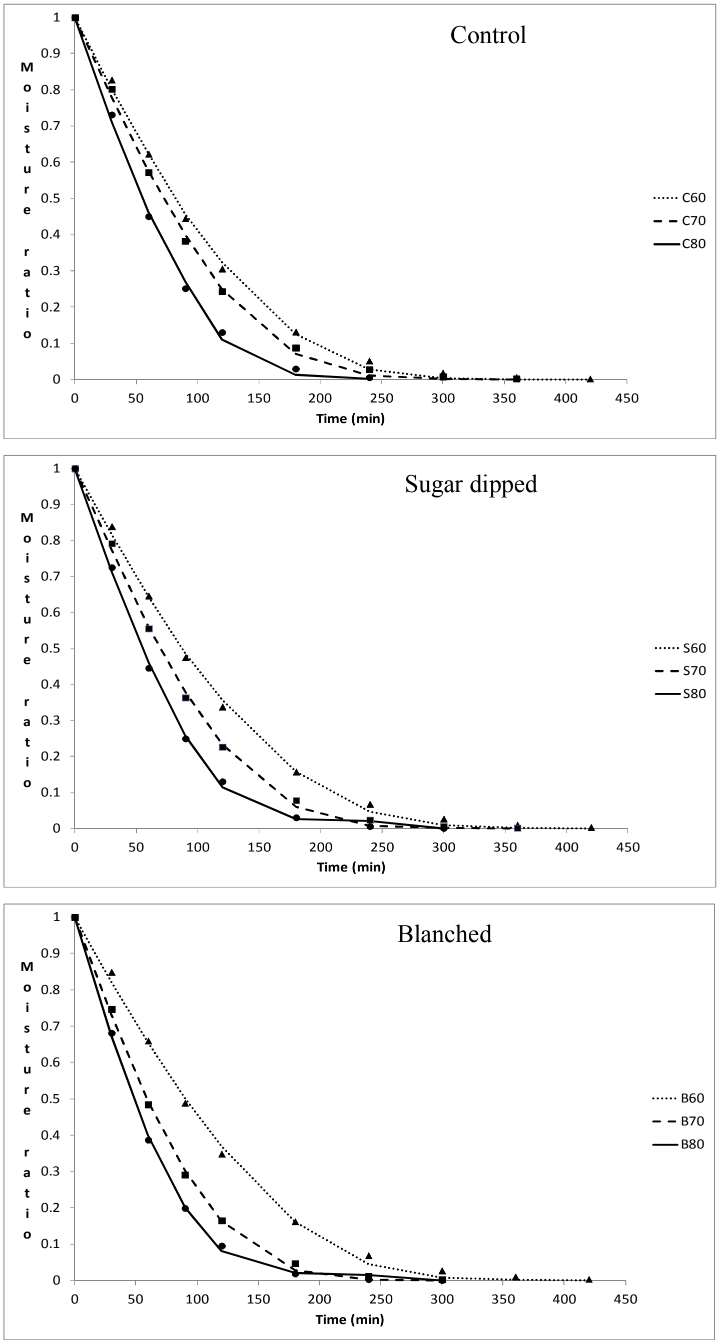

Fig. 3. Comparison between the Predicted and Experimental Data Based on Page Model.

There is no obvious trend that describes the relationship between the diffusivity values and the temperatures in each treatment except for the control samples which still show an increasing trend with temperature. Several reasons could have attributed to the observations in the sugar-dipped and blanched samples. Firstly, this could be due to the inadequacy of the analytical solution where only the first term was used for estimation and secondly, upon dipping and blanching some modifications have been made to the fruit's tissue which changed the moisture diffusion path during drying. However, this can only be verified with microstructure analyses by using scanning electron microscopy but was not done in this study. Thirdly, it must be noted that diffusivity was determined from Eq. (6) which assumed negligible shrinkage during drying. Inclusion of shrinkage would imply a variable diffusivity model due to the reducing diffusion path/thickness which was not determined in this study.

However, in average the sugar dipped samples showed lower values compared to the control and blanched samples, which could be due to the sugar syrup that coated the external surface of the fruit slices and added an additional layer of resistance to mass transfer.

3.2. Product quality

Overall colour changes of the star fruit slices during drying are as shown in Table 8. All the values are within the range from 12.6 to 22.4 which mostly indicates very obvious colour change as compared to the fresh samples [21].

Table 8. Overall Colour Changes of Star Fruit Slices.

	Overall Colour Change (ΔE)		
Temperature (°C)	**Control**	**Sugar dipped**	**Blanched**
60	12.8	12.7	24.4
70	12.6	12.6	14.7
80	13.1	13.7	15.1
Average	12.8	13.0	18.1

In average, the blanched samples showed a greater colour change as compared to the control and sugar dipped samples. Star fruit is known to contain high amount of ascorbic acids/sugars and upon blanching coupled with thermal treatment, this could lead to non-enzymatic browning [22]. This is further confirmed by the work from Campos et al. [23] where the non-treated star fruits showed greater browning upon blanching and resulted in greater overall colour change (ΔE = 16).

Shrinkage ratios show a decreasing trend with decreasing moisture ratios in Fig. 4. Drastic change in thickness can be seen from MR = 1 to 0.1 which corresponds to the greater rate of moisture removal during the falling rate period.

Visual inspections showed a drastic collapse of the fruit pulps structure as moisture is removed from the pulp tissue. The slight increment in shrinkage ratios

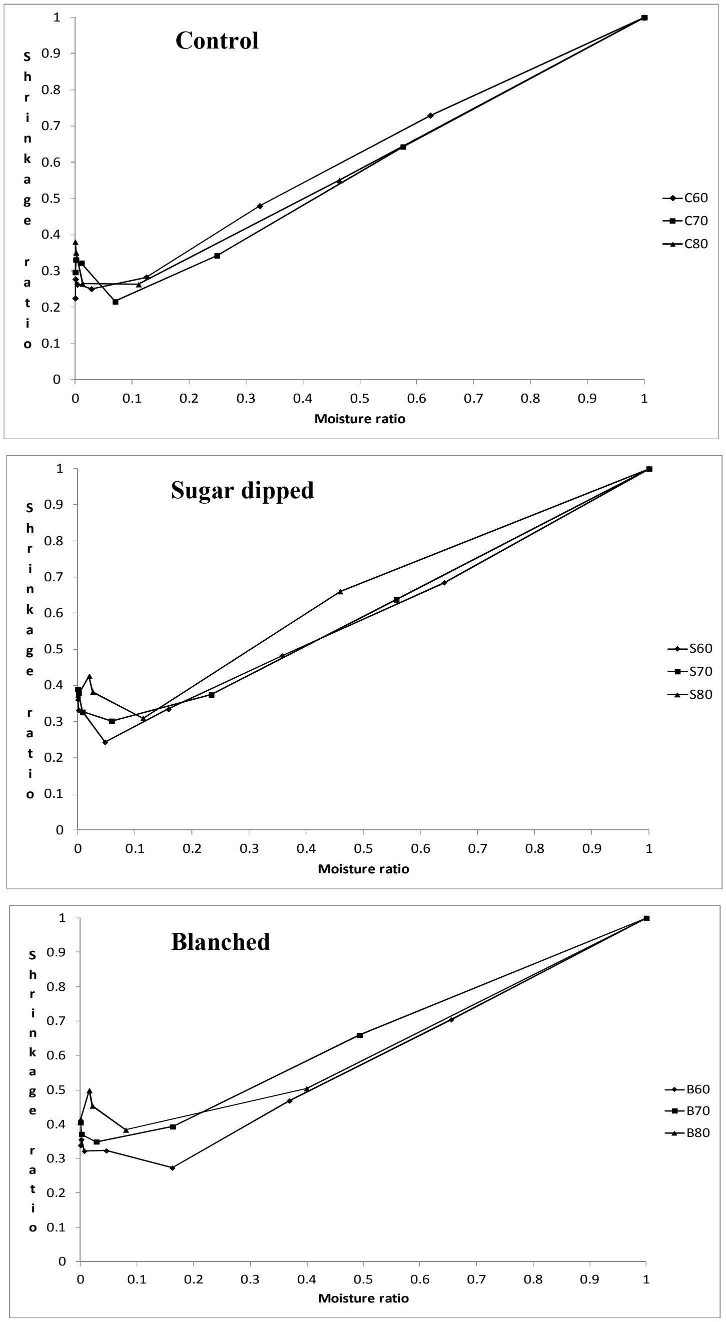

Fig. 4. Shrinkage Ratios (T/T_o) of Star Fruit Slices.

at moisture ratios of 0.1 and below could be due to the puffing effect. Since all the samples were dried at fast drying rates at temperature of more than 60°C, this could result in formation of crust on the product surface. Together with moisture vaporization, large internal pressure started to build-up and resulted in puffing which caused slight volume expansion [24].

4. Conclusions

The drying studies showed that Page model was found able to predict the experimental data well and effective diffusivity values were found within the range as reported for food materials. However, the sugar dipped samples showed lower diffusivity values which could be due to extra mass transfer resistance from the sugar syrup coating. Overall colour changes were more significant in the blanched samples which could be due to non-enzymatic browning since star fruit contains high amount of ascorbic acids and sugars. Drastic change in shrinkage was observed in the falling rate period but puffing was observed at the lower moisture content level.

Acknowledgement

The authors would like to acknowledge the research support given by the Faculty of Engineering, University of Nottingham, Malaysia Campus.

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