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A COMPARATIVE STUDY ON HEAT PUMP, MICROWAVE AND FREEZE DRYING OF FRESH FRUITS

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ABSTRACT

Drying of fresh tropical fruits, namely guava, mango and honeydew, were carried out making use of heat pump, microwave and freeze dryer to compare the influence of different modes of drying on the dried products in terms of quality, appearance and color. Moisture diffusion coefficient, shrinkage of volume and thickness and color change were used for comparison. Fick's second law of diffusion is used to calculate the moisture diffusion coefficient. It is found that freeze-drying has the least shrinkage, while heat pump drying promotes a moderate shrinkage, and microwave drying leads to severe shrinkage of the dried fruits. It is found that the color change follows zero order kinetics except at low moisture contents. Freeze-drying has the least effect on the total color change of the fruits. Heat pump appears to provide better control of drying conditions, which enables drying to be performed at low temperature and low relative humidity, leading to better retention of appearance.

INTRODUCTION

The fresh fruits need to be processed to prolong their shelf life. Drying is one of the traditional methods for preservation of fruits. The main purpose of drying is to reduce the moisture content to such a level where spoilage due to the various reactions is minimized. Among the various drying methods, heat pump, microwave and freeze drying are the most commonly used methods for drying of food materials. Heat pump dryer is a high-energy efficiency convective type dryer. It enables drying under low temperature conditions. In a heat pump dryer, the air velocity, temperature, relative humidity can be controlled independently. Microwave drying uses the irradiated energy. Its drying efficiency is much higher than the convective drying and freeze-drying. Freeze drying has the advantage of obtaining the best quality for dried product. But it has the lowest energy efficiency. Mango, guava, honeydew were selected for the measurements of shrinkage and colour change during drying under different conditions and methods. Color change experiments were also conducted using three other fruits (apple, pear, papaya) samples.

EXPERIMENT

The heat pump drying system consisted of an air blower, electrical heating section, drying chamber, evaporator section, and condenser section. It was fitted with anemometer, humidity sensor, thermocouples for wet and dry bulb temperatures measurements. Air temperature, humidity and velocity could be controlled independently in the heat pump drying system.

Microwave dryer: A household microwave oven (SHARP MICROWAVE OVEN, Model R-398B, 1000W, 2450MHz, internal volume $0.037m^3$) with time and power level control was used for microwave heating. The airflow rate through the oven was $0.166m^3/s$.

Freeze dryer: Freeze drying system consisted of the freezer (MODULYO, EDWARDS), vacuum system (High Vacuum Pump, EDWARDS) and a drying chamber, which was connected to the vacuum system. The vacuum system can decrease the system pressure to 0.06mbar.

The fresh fruits used in this study were acquired from the local market and stored in the refrigerator at 4^oC. The fruits were taken out of refrigerator an hour before the experiment and were peeled and sliced to the square shapes (15mm×15mm) with certain thickness.

ANALYSIS

Following procedures are used to analyze the drying results.

Shrinkage

During drying, sample undergoes shrinkage. Shrinkage has a close relationship to moisture content for biological materials. One common expression has been employed by many researchers (Konstance and Panzer, 1985; Kechaou et al., 1987; Vagenas and Marinos-Kouris, 1991; Simal et al., 1994; Bowser and Wilhelm, 1996; Querioz and Nebra, 1996) as:

$$S_b = \frac{V}{V_0} = p\frac{C}{C_0} + q \quad (1)$$

For sample thickness, Uddin et al. (1990) used an exponential function to relate shrinkage to moisture content. Exponent η is assumed to be constant for any specific material:

$$\frac{L}{L_0} = \left(\frac{C}{C_0}\right)^{\eta} \quad (2)$$

Drying kinetics

Fick's 2^{nd} Law of diffusion is used for vapor diffusion within the material during the falling rate period of the drying. Considering slab geometry of thickness L drying from both sides and in absence of any external resistances (Rao and Rizvi, 1986):

$$\frac{C - C_e}{C_0 - C_e} = \frac{8}{\pi^2} \sum_{n=1}^{\infty} \frac{1}{(2n-1)^2} \exp[-(2n-1)^2 \frac{\pi^2 D_e t}{L^2}] \tag{3}$$

Moisture transport in a sample during drying is a complicated process, which combines many mechanisms. Generally, an effective diffusivity (D_e) is used to describe the moisture transport. In equation 2, it is assumed that the sample temperature and thickness are constant during drying.

In order to take into account the volume shrinkage, the moisture content in the above equation can be written in the form of Y=C/V, then the equation becomes,

$$Y^* = \frac{Y - Y_e}{Y_0 - Y_e} = \frac{8}{\pi^2} \sum_{n=1}^{\infty} \frac{1}{(2n-1)^2} \exp[-(2n-1)^2 \frac{\pi^2 D_e t}{L^2}] \tag{4}$$

Since the equilibrium moisture content for the conditions of drying in the present study is considered negligible (Uddin et al., 1990), also for conditions where L is small and t is large, the terms in the summation series in the above corresponding to n>1 are small. Under these conditions the following approximation can be made:

$$\ln \frac{Y}{Y_0} = \ln(\frac{8}{\pi^2}) - \frac{\pi^2 D_e t}{L^2} \tag{5}$$

Sample shrinkage is incorporated in the equation 4. Thus, the volume and thickness changes are taken into account in the above equation by combining equations 2 and 6:

$$\ln \frac{\frac{C}{C_0}}{p\frac{C}{C_0} + q} = \ln(\frac{8}{\pi^2}) - \frac{\pi^2 D_e t}{L_0^2 (\frac{C}{C_0})^{2\eta}} \tag{6}$$

Plotting $\ln(Y/Y_0)$ versus t/L^2 (i.e. $\ln \frac{\frac{C}{C_0}}{p\frac{C}{C_0} + q}$ versus $\frac{t}{L_0^2 (\frac{C}{C_0})^{2\eta}}$), the diffusion coefficient for the falling rate period, the effective diffusivity (D_e), can be obtained.

Color change

Color change is resulted from the non-enzymatic browning and destruction of natural fruit pigments. Non-enzymatic browning is usually assumed to follow zero-order kinetics (Toribio and Lozano, 1986; Singh et al., 1983) while destruction of natural fruit pigments follows the first-order reaction kinetics (Abers and Wrolstad, 1979; Skrede, 1985).

Zero-order reaction: $$\frac{C}{C_0} = -kt \tag{7}$$

First-order reaction: $$\frac{C}{C_0} = \exp(-kt) \tag{8}$$

Either the zero-order or the first-order kinetic model may be used to analyze the color results of the present study.

RESULTS AND DISCUSSION

Drying of three tropical fruits (guava, honeydew and mango) were studied in the heat pump, microwave and freeze dryers under different experimental conditions [temperature: (30 -50)^oC; relative humidity: (21 – 43)%; air velocity: (1.2 – 3.3) m/s; sample thickness: (2 -10) mm]. The experimental data on sample weight loss, sample dimensions (thickness and volume) and color index as function of drying time are analyzed to determine drying rate, volume and thickness shrinkage, moisture diffusivity and rate constants for color change. To overcome experimental uncertainties, large number of experiments was conducted and high R^2 values (greater than 0.92 in most of the cases) were obtained in data analysis. The details of the experimental results could be found in the thesis of Xiang Hui (2001).

Drying Rate

The calculated drying rates for guava under typical conditions in heat pump, microwave and freeze drying are shown in Figures 1-3. Individual experimental conditions are written as T, Rh and L for temperature, relative humidity and sample thickness respectively.

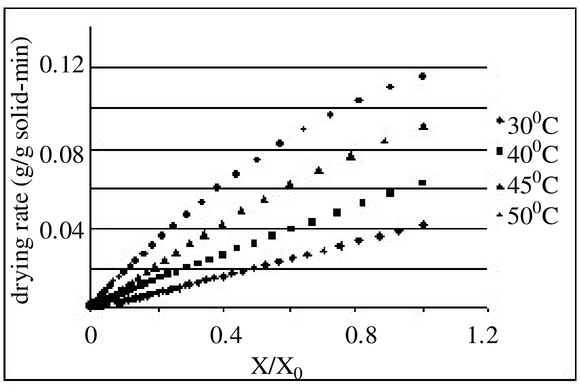

Figure 1- Drying rate of guava as a function of moisture content for different air velocity in heat pump drying (T45Rh21L5)

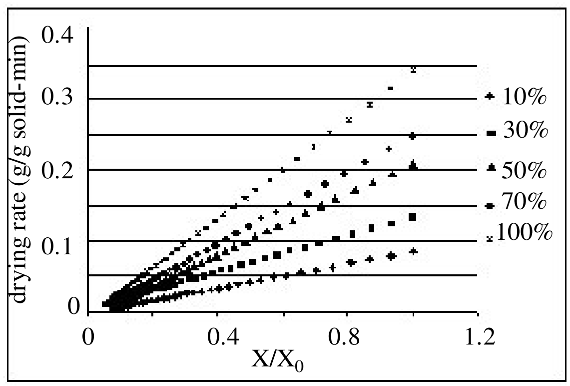

Figure 2- Drying rate of guava as a function of moisture for different power level in microwave drying

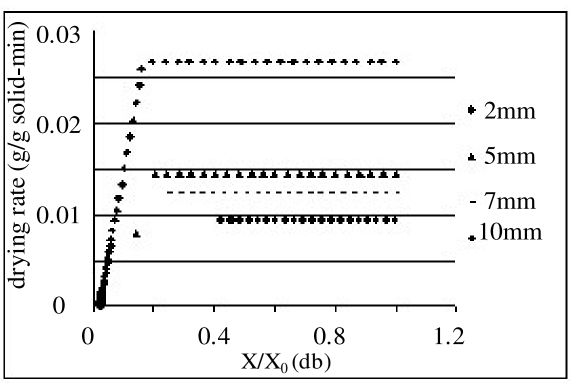

Figure 3- Drying rate of guava as a function of moisture content for different sample thickness in freeze drying

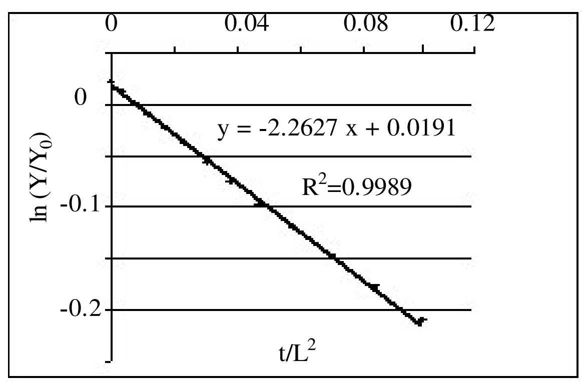

Figure 4 – Plot of $\ln(Y/Y_0)$ versus (t/L^2) for guava (T45Rh21U3L5)

The drying rate results show that guava and mango do not show any constant drying rate period, whereas, honeydew results show a short constant drying rate period under some drying conditions of low air velocity (below 1.2 m/s). It may be attributed to the higher moisture content of honeydew (about 9 g/g solid) compared to guava and mango (about 5 g/g solid). The effect of air velocity on drying rate for three fruits, guava, mango and honeydew, are studied. In general, there is increase in drying rate with the increase of air velocity. However, the effect is more significant in the lower range of air velocity, below 3.0m/s, and higher moisture content of the sample. Zhou (2000) has also obtained the similar results when drying kiwi fruits in heat pump drying.

Shrinkage

Sample shrinkage, both bulk volume and thickness, is measured at different moisture content levels and under different experimental conditions, such as air temperature, velocity, relative humidity and sample thickness. Results show that bulk volume shrinkage data are more accurate and consistent than the value of thickness shrinkage. This is mainly due to measurement accuracy. As the material dries, the sample shape deforms. At low moisture content, sample surface becomes uneven and this results in low accuracy in thickness measurements. For the analysis of thickness shrinkage, data below 15% moisture content (dimensionless) are not considered. Results show that experimental conditions (air temperature, velocity, humidity and sample thickness) do not have significant effect on bulk shrinkage. Hence, for simplicity, the effects of experimental conditions on shrinkage have not been considered in relating shrinkage to the moisture content. The bulk volume shrinkage and thickness shrinkage data for samples studied under different conditions are correlated in the form of equations 1 and 2 respectively. Similar equations have been used by some researcher (Querioz and Nebra, 1996 and Uddin et al., 1990) for apple, banana and pineapple. The constants in equations 1 and 2 for each fruits are listed in Tables1-3.

Table1: The constants p, q, η and R^2 in heat pump drying.

Fruit	p	q	R^2	η	R^2
Guava	0.9103	0.067	0.9902	0.3124	0.9206
Mango	0.8245	0.1468	0.9677	0.3697	0.9319
Honeydew	0.9173	0.0567	0.9904	0.4693	0.9688

Table 2: The constants p, q, η and R^2 in microwave drying.

Fruit	p	q	R^2	η	R^2
Guava	0.9286	0.0431	0.9749	0.3298	0.9644
Mango	0.9034	0.0657	0.9776	0.4084	0.9410
Honeydew	0.9522	0.0371	0.9951	0.5159	0.9788

Table 3: The constants p, q η and R^2 in freeze drying

Fruit	p	q	R^2	η	R^2
Guava	0.8163	0.1743	0.9406	0.3070	0.7508
Mango	0.8170	0.1497	0.9575	0.3471	0.9179
Honeydew	0.8366	0.1803	0.9771	0.3942	0.9449

Effective Diffusivity coefficient

Equation 6 is used to calculate diffusion coefficient. The equation takes into account shrinkage of sample bulk volume and thickness. Diffusivity is calculated from the slope of the plot. Good linear fit is obtained confirming that drying took place under falling rate period. During microwave drying under certain drying conditions a second falling rate period appeared. This particularly happened for sample thickness greater than 7mm. For such case a second diffusivity is calculated. Typical data fit for guava is shown in Figure 4. All the diffusivity values for heat pump and microwave drying are listed in Tables 4 and 5.

Table 4: Diffusivity values of water as function of drying conditions for HP drying.

Experimental conditions	Guava		Mango		Honeydew	
	Slope	$D_e(m^2/s)$	Slope	$D_e(m^2/s)$	Slope	$D_e(m^2/s)$
T45Rh21U3L2	1.1699	1.98E-11	1.2486	2.11E-11	0.5637	9.52E-12
T45Rh21U3L5	2.2627	3.82E-11	3.3227	5.61E-11	1.4640	2.47E-11
T45Rh21U3L7	3.1290	5.28E-11	5.2498	8.87E-11	2.0867	3.52E-11
T45Rh21U3L10	4.3008	7.26E-11	7.0512	1.19E-10	3.9104	6.60E-11
T45Rh21U1.2L5	1.6440	2.78E-11	2.8266	4.77E-11	0.8917	1.51E-11
T45Rh21U1.91L5	2.1165	3.57E-11	3.0870	5.21E-11	1.2584	2.13E-11
T45Rh21U3L5	2.2627	3.82E-11	3.3227	5.61E-11	1.4640	2.47E-11
T45Rh21U3.34L5	2.7500	4.64E-11	3.4629	5.85E-11	1.6990	2.87E-11
T45Rh21U3L5	2.2627	3.82E-11	3.3227	5.61E-11	1.4640	2.47E-11
T45Rh33U3L5	2.1243	3.59E-11	2.7280	4.61E-11	1.2008	2.03E-11
T30Rh41U3L5	1.0416	1.76E-11	1.4807	2.50E-11	0.7362	1.24E-11
T40Rh43U3L5	1.7224	2.91E-11	2.7815	4.70E-11	1.0115	1.71E-11
T45Rh33U3L5	2.1243	3.59E-11	2.7280	4.61E-11	1.2008	2.03E-11
T50Rh30U3L5	2.2456	3.79E-11	3.8157	6.44E-11	1.1952	2.02E-11

Table 5: Diffusivity values of guava as a function of drying conditions for MW drying.

Expt. conditions	Slope1	Slope2	$D_{e1}(m^2/s)$	$D_{e2}(m^2/s)$
L2D15P100	1.1633		1.96E-11	
L5D15P100	3.5070		5.92E-11	
L7D15P100	6.6693		1.13E-10	
L10D15P100	31.459	12.6970	5.31E-10	2.14E-10
L5D15P10	1.1120		1.88E-11	
L5D15P30	1.5443		2.61E-11	
L5D15P50	2.3887		4.03E-11	
TL5D15P70	2.4262		4.10E-11	
L5D15P100	3.5070		5.92E-11	

Colour Change

Colour change of fruits is studied by drying six different fruits (apple, pear, papaya, mango, honeydew and guava) in the heat pump drier and microwave drier under different conditions. Total color changes for mango under different drying methods are shown in Figure 5. Weight and colour index (L*, a*, b*, and ΔE*ab) of samples were measured by withdrawing the samples from the dryer periodically. The results are analyzed ΔE*ab is calculated as $\Delta E*ab = \sqrt{\Delta a*^2 + \Delta b*^2 + \Delta L*^2}$. In the freeze-drying, the measurement of colour index during the drying process is not possible as the ice on the sample surface will melt, giving a false reading in the colour index. Thus, only the colors of fresh and dried sample were measured. The rate constant of colour change of different fruits in heat pump drying and microwave drying are listed in Tables 6 and 7.

Microwave drying provides high drying rate at the initial stage of drying due to high moisture content of fruits and also at the final stage of drying when water transport is mainly controlled by vapor diffusion. On the other hand, heat pump drying produces better quality (appearance, nutrients retention) products. An integration of microwave and heat pump drying (microwave-heat pump-microwave) can optimize product quality and drying cost.

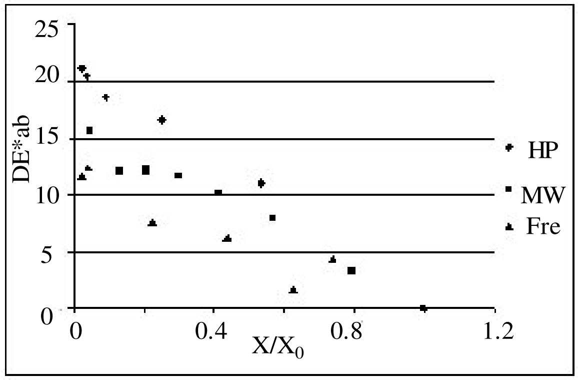

Figure 5 – Comparison of total color change for mango among different drying methods.

Table 6: Rate constant of colour change of fruits in heat pump drying

Fruit	a*		b*		ΔE*ab	
	k (min^{-1})	R^2	k (min^{-1})	R^2	k (min^{-1})	R^2
Guava	-0.0066	0.9977	0.0516	0.9944	0.1133	0.9076
Mango	0.0115	0.9999	0.1482	0.9839	0.1732	0.9356
Apple	0.0208	0.9886	0.0826	0.9845	0.1933	0.9917
Pear	0.0214	0.9534	0.076	0.9728	0.0733	0.9691
Papaya	0.0570	0.9933	0.0634	0.9771	0.0892	0.9862
Honeydew	-0.0153	0.9833	0.1106	0.9968	0.2106	0.9872

Table 7: Rate constant of colour change of fruits in microwave drying

Fruit	a*		b*		ΔE*ab	
	k (min^{-1})	R^2	k (min^{-1})	R^2	k (min^{-1})	R^2
Guava	-0.0388	0.8009	-0.1082	0.9513	0.2246	0.9165
Mango	-0.0140	0.6368	0.2682	0.9833	0.4305	0.9519
Apple	0.1558	0.9774	0.3509	0.9990	0.3759	0.9981
Pear	0.0468	0.9675	0.1227	0.9799	0.1271	0.8517
Papaya	0.1863	0.9716	0.1803	0.9852	0.2493	0.9776
Honeydew	-0.0087	0.9846	0.1700	0.9484	0.1136	0.9586

CONCLUSIONS

In the present work, drying kinetics, shrinkage and colour change of different fruits are studied and the following conclusions are drawn:

It appears from the above results that freeze-drying leads to a minimum shrinkage, better colour retention, but long drying time, resulting in higher cost. While microwave drying may be suitable in the early stage of drying, when the moisture content is higher, or towards the end of drying, when the moisture transport to the surface is purely diffusion control. It is likely to perform better in combination with another drying method, for example, microwave-heat pump drying. Heat pump appears to provide better control of drying conditions. It enables drying to be performed at low temperature and low relative humidity, leading to a better retention of appearance. A combination of microwave and heat pump may provide the desire condition of drying to achieve fast drying rate, lower shrinkage, better appearance of the product and least cost.

NOTATION

ΔE^*ab	Total color change	-	p, q	Equation constants	-
b^*	Yellowness	-	Rh	Relative humidity	%
C	Moisture content	kgH_2O/kg dry solid	S_b	Bulk shrinkage ratio	-
C	Color component	-	T	Temperature	^oC, K
D_e	Effective diffusivity	m^2/s	T	Drying time	s, min
k	Rate constant	min^{-1}	X	Moisture content	kg H_2O/kg dry solid
L	Sample thickness	m	V	Sample volume	m^3
L^*	Lightness	-	Y	Moisture content	kg H_2O/m^3

LITERATURE

Konstance, R.P. and C.C. Panzer. Air drying Slices to Reduce aw: An Anti-Clostridial Alternative to Sodium Nitrite. Journal of Food Science. Vol. 50, pp. 862-868. 1985.

Keachaou, N., M.A. Roques and J.F. Lambert. Diffusion in Shrinkage Media: The Case of Drying of Gels. In Physical Properties of Foods, ed by R. Jowitt, F. Escher, M. Kent, B. McKenna, and M. Roques, pp. 55-60. London and New York: Elsevier Applied Science. 1987.

Vagenas, G.K. and D. Marinos-Kouris. Drying Kinetics of Apricots. Drying Technology Vol. 9, no. 3, pp. 735-752. 1991.

Simal, S., C. Rossello, A. Berna and A. Mulet. Heat and Mass Transfer Model for Potato Drying. Chemical Engineering Science. Vol. 49, no. 22, pp. 3739-3744. 1994.

Bowser, T.J. and L.R. Wilhelm. Modeling Simultaneous Shrinkage and Heat and Mass Transfer of a Thin, Nonporous Film during Drying. Journal of Food Science. Vol. 60, no. 4, pp. 753-757. 1996.

Queiroz, M.R. and S.A. Nebra. Theoretical and Experimental Analysis of the Drying Kinetics of Bananas. In Drying '96-Proceedings of the 10th International Drying Symposium, 30 July-2 August 1996, Krakow, Poland, pp. 1045-1052.

Rao, M. A. and S. S. H. Rizvi. Engineering Properties of Food. Marcel Dekker, New York, 1986.

Uddin, M.S., M.N.A. Hawlader and M.S. Rahman. Evaluation of Drying Characteristics of Pineapple in the Production Powder. Journal of Food Processing and Preservation. Vol. 14, pp. 375-391. 1990.

Toribio, J.L. and J.E. Lozano. Heat Induced Browning of Clarified Apple Juice at High Temperatures. Journal of Food Science. Vol. 51, pp. 172-175. 1986.

Singh, R.K., D.B. Lund and F.H. Buelow. Storage Stability of Intermediate Moisture Apples: Kinetics of Quality Change. Journal of Food Science. Vol. 48, pp. 939-944. 1983.

Abers, J.E. and R.E. Wrolstad. Causative Factors of Colour Deterioration in Strawberry Preserves during Processing and Storage. Journal of Food Science. 4, pp.75-78. 1979.

Skrede, G. Colour Quality of Blackcurrant Syrups during Storage Evaluated by Hunter L', a', b' values. Journal of Food Science. Vol. 50, pp. 514-525. 1985.

Zhou, Liwen. Moisture Transfer and Nutrient Retention in Processing and Storage of Fresh Fruit, MEng Thesis, National University of Singapore. 2000.

Queiroz, M.R. and S.A. Nebra. Theoretical and Experimental Analysis of the Drying Kinetics of Bananas. In Drying '96-Proceedings of the 10th International Drying Symposium, 30 July-2 August 1996, Krakow, Poland, pp. 1045-1052.

Xiang Hui. Heat Pump, Microwave and Freeze Drying of Fruits, MEng Thesis, National University of Singapore. 2001.