Sorption Isotherms, Drying Kinetics and Qualities of Osmotically Pretreated Fruits Undergoing Forced Convection Solar Drying

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Abstract

Solar energy, a form of sustainable energy, has a great potential for a wide variety of applications because it is abundant and accessible, especially for countries located in the tropical region. Drying process is one of the prominent techniques for utilization of solar energy. This research was aimed at studying and investigating forced convection solar drying of osmotically pretreated fruits viz. mango, guava, and pineapple. The fruit cubes with a dimension of 1cm x 1cm x 1cm were immersed in 35% w/w sucrose solution prior to the drying process. Drying kinetics, color and hardness of the final products obtained from solar drying were investigated and compared with those obtained from open air-sun drying. Desorption isotherms of the osmosed fruits were also examined and five mathematical models were used to fit the desorption curves. Experimental results revealed that solar drying provided higher drying rate than natural sun drying. Color of glac fruit processed by solar drying was more intense, indicated by lower value of lightness and higher value of yellowness, than that processed by natural sun drying. Hardness of the products dehydrated by both drying methods, however, was not significantly different ($p>0.05$). Validation of the mathematical models developed showed that the GAB model was the most effective for describing desorption isotherms of osmotically pretreated mango and pineapple whereas Peleg's model was the most effective for describing desorption isotherm of osmotically pretreated guava.

Keywords: Forced convection solar drying; Osmotic dehydration; Osmotic pretreatment

INTRODUCTION

Osmotic pretreatment is a dehydration technique by immersing target materials, mostly fruits and vegetables, in a hypertonic aqueous solution i.e., sugar and salt solutions. A driving force for water removal is set up due to a difference in osmotic pressure between the food product and its surrounding solution. During osmotic processing, water flows from the product into the osmotic solution, whereas osmotic solute is transferred from the solution into the product (Rastogi & Raghavarao, 1997). Osmotic dehydration removes water from the foods up to a certain level, which is still high for preservation and shelf stability, hence osmosed foods must be further dried to a desired moisture content (Shunkla & Singh, 2007; Silveira et al., 1996; Teles et al., 2006). Due to being operated at mild temperature, open sun drying and forced convection solar drying are practical preservation techniques for heat sensitive products such as fruits and vegetables. Convective drying of osmotically pretreated and non-pretreated food stuffs have been comparatively studied by many authors (El-Aouar et al., 2003; Prothon et al., 2001). It was reported that osmotic pretreatment can shorten drying time, leading to a reduction of energy consumption, and improve product stability, retention of nutrients and product qualities in terms of color, flavor, and texture (Lewicki & Lenart, 1995). Mango, guava, and pineapple are common fruits widely cultivated in South-East Asia. They are excellent sources of vitamin C which is an important antioxidant needed by human body to neutralize free radicals (Quek et al., 2007). This research was aimed to study forced convection solar drying of osmosed mango, guava, and pineapple. Drying kinetics and quality attributes of the products dried by the forced convection solar drying were investigated and compared with those dried by natural sun drying.

MATERIALS AND METHODS

Raw materials

Fresh well-graded mango (*Mangifera indica* cv. Namdokmai), guava (*Psidium guajava* cv. Pansetong), and pineapple (*Ananas comosus* cv. Pattavia) were purchased from a local fruit market in Mahasarakham province, Thailand. The fruits were washed with tap water, manually peeled and cut into cubic shape (1 cm x 1cm x 1 cm) by a stainless steel die.

Osmotic pretreatment

Fruit cubes were osmotically pretreated with 35% w/w sucrose solution at ambient temperature for 24 hours. After removing from the solution, the osmosed fruit cubes were blotted with adsorbent paper to eliminate superficial syrup, and then were transferred to the drying process.

Drying procedure

A force convection solar dryer used in this study was depicted in Figure 1. The solar air collector as shown as label (6) was 60 cm x 100 cm in dimension. It was downward oriented at the angle of 13°. A corrugated black zinc sheet, label (5), was used as an adsorber plate. A 3 mm acrylic sheet was used as a transparent cover to avoid heat losses. The axial fan (label (3)) with ¼ hp motor (label (2)) powered by PV modules (label (1)) sucked the heated air through the 0.0265 m^3 drying cabinet, as labeled (9).

Two hundred grams of osmosed fruit cubes spread on the mesh tray was placed in the drying chamber. Drying experiments were performed in March 2005 during 10 a.m. - 3 p.m. temperature of the drying chamber, outlet air velocity, and solar radiation were monitored and recorded. Water loss from the samples was determined by weighing the sample tray outside the drying chamber, using an electronic balance with ± 0.01 gram resolution. Open sun drying process was carried out by spreading osmosed fruit cubes on the tray and sun dried directly. The experiments were conducted in duplicated.

Physical properties of the final products

Lightness (L), redness (a), and yellowness (b) of the dried fruit cubes were determined by a colorimeter (Mini Scan XE Plus, Hunter Associates Laboratory Inc., Reston - Virginia, USA). Hardness, the maximum force, measured by a texture analyzer (TA.XT.2*i*, Stable Micro Systems, UK) was used to describe textural characteristics of the end products. Texture analyzer was equipped with 33 mm cylindrical probe and the compression tests were conducted at a constant cross head speed of 1 mm/s. Water activities of the final products were determined using an aw meter (WA-360, Shibaura Electronics Co., Ltd., Saitama, Japan).

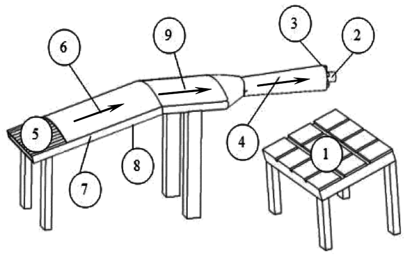
Sorption isotherms

The sorption isotherm, a graphical representation of water activity (or the relative humidity of the surrounding air) against moisture content, is of particular importance in selecting suitable packaging materials, predicting stability and moisture change during storage, and designing drying processes (McLaughlin & Magee, 1998).

The desorption isotherms of osmotically pretreated mango, guava, and pineapple cubes were determined using the standard static gravimetric method. Five air-tight glass jars containing saturated salt solutions (LiCl, $MgCl_26H_2O$, NaBr, $NaNO_3$, and KCl) were prepared to obtain relative humidities ranging from 10 to 82%. Five grams of osmosed fruit cubes were put in sample holders above saturated salt solutions. The jars were then placed in an air oven at a fixed temperature of 40 °C. The samples were periodically weighed until there was no considerable weight change (±0.001g). The equilibrium moisture contents of the samples were determined by AOAC method (AOAC, 1995).

Modeling of sorption isotherms

To predict the moisture sorption behavior of material, several mathematical models have been proposed in the literatures. Some of them are based on theories of the mechanism of the sorption process (BET model, based on a mono-layer and GAB model, based on multi-layer and condensed film), others are semi-empirical (Ferro-Fontan, Henderson and Halsey models), and empirical models, Smith and Oswin models (Al-Muhtaseb et al., 2004). The GAB, modified Henderson, modified Chung-Pfost, and modified Oswin models have been recommended as standard equations by the American Society of Agricultural Engineers to describe sorption isotherms (ASAE, 1996).



1. PV module	2. ¼ hp Motor	3. Axial flow fan
4. Air duct	5. Black zinc plate	6. Solar collector
7. Air duct	8. Insulator	9. Drying chamber

Figure 1. Indirect forced convection solar dryer.

Five selected mathematical models viz. modified Henderson, modified Chung-Pfost, modified Oswin, Peleg, and the GAB model, were used to predict the desorption curves of osmotically pretreated mango, guava, and pineapple cubes. Model expressions were summarized in Table 1.

Statistical analysis

Parameters of the sorption models were determined by nonlinear regression analysis. The goodness of the fit was evaluated through the coefficient of determination (R^2) and root mean square error (RMSE). RMSE is defined as the following equation:

$$\text{RMSE} = \sqrt{\frac{\sum_{i=1}^{n}(M_{exp,i}\ M_{pre,i})^2}{N}}$$

where

$M_{exp,i}$ is the *i*th experimental equilibrium moisture content

$M_{pre,i}$ is the *i*th predicted equilibrium moisture content

N is the number of observation.

Independent sample t-test with 95% confidence interval was used to test the difference between quality parameters (color and hardness) obtained from force convection solar drying and open sun drying.

Table 1. Estimated and statistical parameters of the sorption models

Estimated and statistical parameters*	Mango	Guava	Pineapple
Modified Henderson $rh=1-\exp[-A(T+B)M^C]$			
A	0.0031	0.0012	0.0027
B	-312.9930	-312.9970	-312.9970
C	3.6738	9.8005	3.5697
R^2	0.9439	0.9602	0.9757
RMSE	1.1552	1.1725	0.9181
Modified Chung-Pfost $rh=\exp\left[\frac{-A}{T+B}\exp(-CM)\right]$			
A	316.9707	300.6146	11957.49
B	-311.4601	-307.8600	-81.1929
C	0.3347	0.1812	0.1794
R^2	0.9448	0.9696	0.9621
RMSE	2.2879	0.8442	1.5753
Modified Oswin $M=(A+BT)\left(\frac{rh}{1-rh}\right)^C$			
A	-15.3440	-6.2799	0.3551
B	0.1002	0.0981	0.0735
C	0.2044	0.1618	0.1781
R^2	0.9054	0.9796	0.9525
RMSE	1.3398	0.7042	1.1684
Peleg $M= Arh^B+Crh^D$			
A	15.0834	28.9435	-7.1780
B	0.4059	0.2380	0.1000
C	7.5924	23.6279	38.5643
D	0.4055	9.1953	0.2916
R^2	0.9513	0.9907	0.9951
RMSE	0.9609	0.4755	0.3762
GAB $M=\frac{ABCrh}{(1-Brh)(1-Brh+BCrh)}$			
A	18.6142	19.9889	23.7660
B	0.2492	0.4452	0.3046
C	30.7704	83.4811	40.7626
R^2	0.9657	0.9758	0.9977
RMSE	0.8062	0.7672	0.2594

* rh = relative humidity (decimal); M= equilibrium moisture content (%d.b.); T = absolute temperature (K); A, B, C, and D = constants.

RESULTS

Drying kinetics

During the drying process, average temperature of the drying chamber and outlet air velocity were in the range of 34-39 ºC and 4-9 m/s respectively. Solar radiation fluctuated between 550 and 850 W/m^2. Drying characteristics and temperature evolution of osmostically pretreated mango, guava, and pineapple cubes were depicted in Figures 2-4. Moisture decreased rapidly at the early period of drying and then gradually decreased. It was also found from the figures that at the same elapsed time, forced convection solar drying provided glacé fruits with higher temperature and lower moisture content. Higher air velocity caused by blower and higher drying temperature caused by solar collector, in the case of solar drying, induced greater rate of heat transfer from the drying medium to the material and led to the higher moisture transfer rate from the material to the drying medium. These were repetative why at a specific time glacé fruits obtained by solar drying were at higher temperature but contained lower moisture content than those obtained by open sun drying. Water activity values of mango, guava, and pineapple glacé processed by solar drying were 0.53, 0.35, and 0.66 respectively and those processed by natural sun drying were 0.61, 0.44, and 0.78 respectively.

Physical properties of glacé fruits

Color and hardness of glacé fruits obtained by forced convection solar drying and natural sun drying were tabulated in Table 2. Color parameters of the final products were found to be affected by drying method. Products produced by force convection solar drying appeared darker and yellower than those produced by natural sun drying. However, redness values of all osmosed fruit cubes dried by both techniques were not significantly different. Hue angles ($\tan^{-1}$ b/a) of the fruit cubes dried by natural sun drying were therefore greater than those dried by solar drying. Hue angles of the dried mango, guava, and pineapple were in the range of 78.61-79.74, 86.21-86.99, and 79.45-82.38, respectively. More intense in color for the case of solar drying might be attributed to the non-enzymatic browning reaction which was accelerated by high temperature. Since the fruits contained amino compounds and reducing sugar the possible browning reaction that can be occurred was Maillard reaction. However, hardness values of all kinds of osmosed fruits dried by both drying techniques were not significantly different.

Modeling of desorption isotherms

As expected, the desorption isotherms of all osmosed fruit cubes showed an increase in equilibrium moisture content with increasing water activity (Figures 5-7). This was a consequence of an inability of the foodstuff to maintain vapor pressure with decreasing moisture content. As moisture content decreases, moisture in the food tends to show a lower vapor pressure, acting as if in solution, changing with atmospheric humidity which results in the characteristic sigmoid shape of water sorption isotherms (Caurie, 1970).

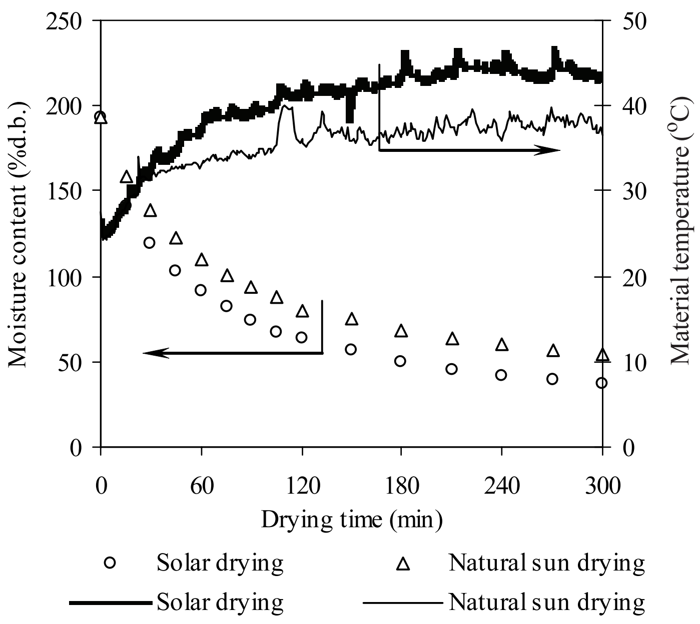


Figure 2. Influence of drying method on drying kinetics and temperature evolution of osmosed mango.

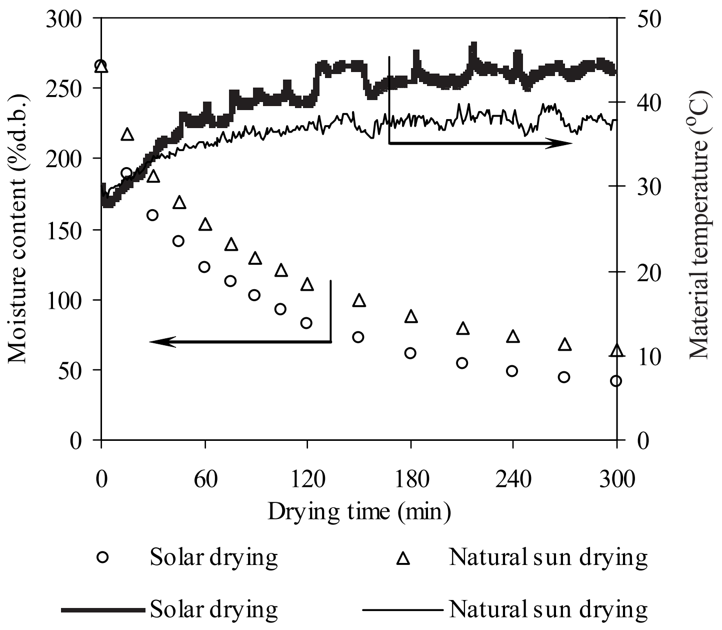


Figure 3. Influence of drying method on drying kinetics and temperature evolution of osmosed guava.

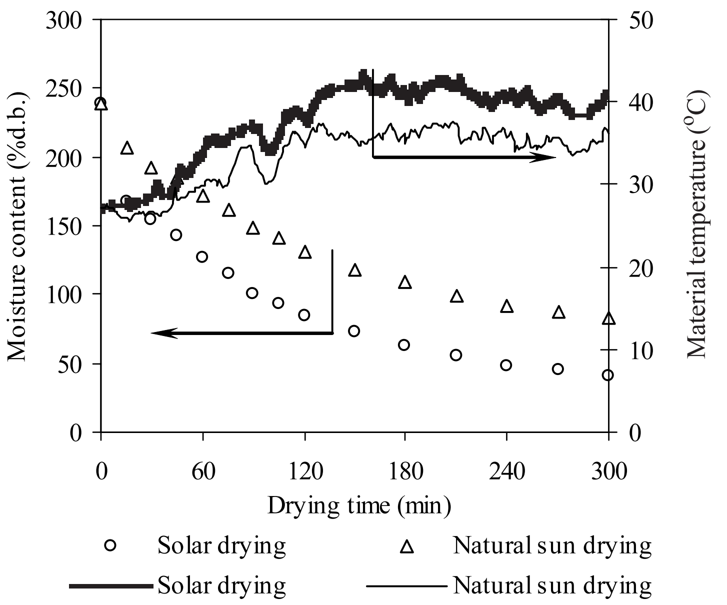


Figure 4. Influence of drying method on drying kinetics and temperature evolution of osmosed pineapple.

Table 2. Estimated and statistical parameters of the sorption models

Material	Drying process	Lightness	Redness	Yellowness	Hardness (N)
Mango	Open sun drying	50.74 ± 1.34^b	9.18 ± 0.61^a	22.47 ± 0.82^a	0.09 ± 0.02^a
	Solar drying	47.30 ± 1.46^a	9.53 ± 0.52^a	23.44 ± 0.37^b	0.11 ± 0.02^a
Guava	Open sun drying	59.04 ± 1.26^b	3.10 ± 0.44^a	19.79 ± 0.22^a	0.12 ± 0.03^a
	Solar drying	55.94 ± 1.52^a	3.71 ± 0.41^a	20.08 ± 0.44^a	0.10 ± 0.02^a
Pineapple	Open sun drying	50.15 ± 1.39^b	6.71 ± 0.22^a	21.88 ± 0.76^a	0.10 ± 0.03^a
	Solar drying	40.66 ± 1.25^a	7.57 ± 0.75^b	23.40 ± 0.90^b	0.12 ± 0.01^a

Different superscripts indicate that the values between open sun and solar drying of the same fruit material are significantly different ($p < 0.05$).

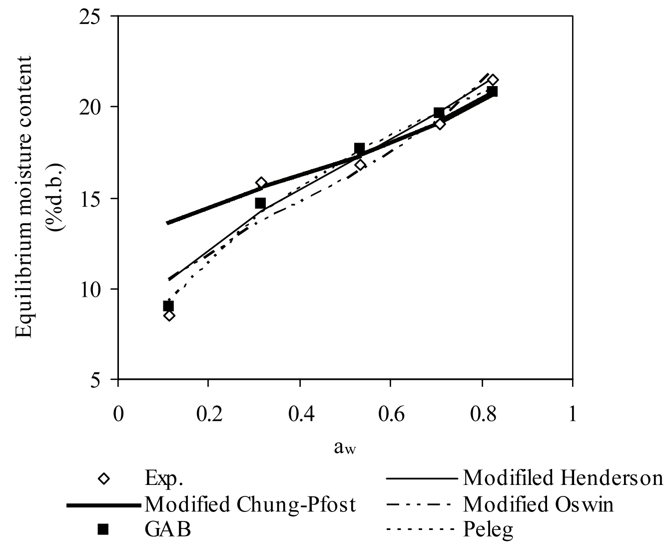


Figure 5. Comparison between experimental and predicted desorption isotherm of osmosed mango.

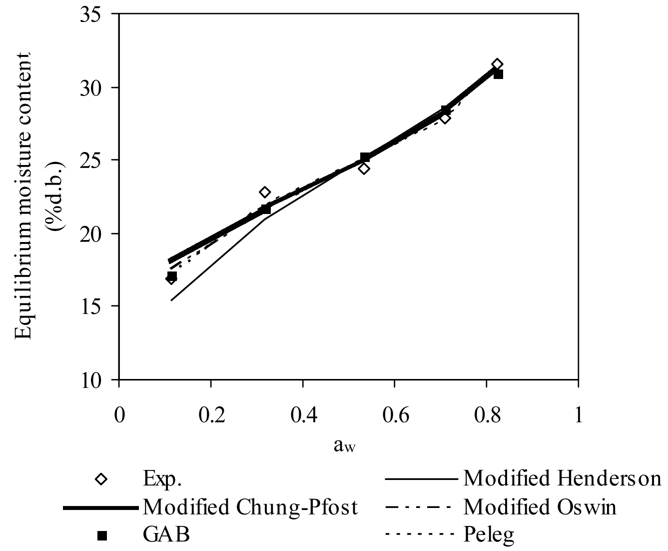


Figure 6. Comparison between experimental and predicted desorption isotherm of osmosed guava.

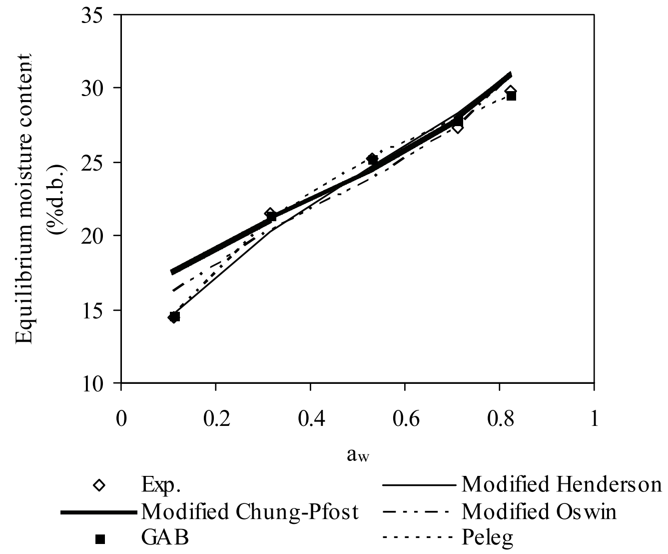


Figure 7. Comparison between experimental and predicted desorption isotherm of osmosed pineapple.

Nonlinear regression analysis was used to fit the sorption models to the experimental data. Estimated and statistical parameters of the models were shown in Table 2. As indicated by highest value of R^2 and lowest value of RMSE, the GAB model was found to be the most satisfactory model for describing desorption isotherms of osmotically pretreated mango and pineapple. While Peleg's model was the most appropriate model for describing desorption isotherm of osmotically pretreated guava. Validation of the models was illustrated in Figures 5-7.

DISCUSSION

Compared to natural sun drying, forced convection solar drying provided the system with higher air velocity and drying temperature. This explained why temperatures of the fruit cubes dried by solar drying were higher than those dried by open sun drying. The higher material temperature in the case of solar drying caused the higher moisture reduction rate and also the more intense color than in the case of sun drying. Color deterioration of fruits during thermal processing is generally attributed to pigment degradation and browning reaction. In this study, a possible browning reaction that can be occurred is Maillard reaction.

CONCLUSIONS

Forced convection solar drying and natural sun drying of osmotically pretreated mango, guava, and pineapple cubes were comparatively investigated in this work. Desorption isotherms of the osmosed fruits were also studied and fitted with five mathematical models such as modified Henderson, modified Chung-Pfost, modified Oswin, Peleg, and the GAB model. The experimental data showed that at a specific drying time, temperatures of the fruits processed by solar drying were higher while moisture contents were lower than those processed by natural sun drying. End products obtained by the solar drying were yellower and darker than those obtained by the sun drying. However, hardness of the final product dried by both drying techniques was not significantly different ($p > 0.05$). Modeling of desorption isotherms of the osmosed fruits showed that the GAB model was the most appropriate model for predicting desorption isotherms of osmosed mango and pineapple. While Peleg model gave the best fit for desorption isotherm of osmosed guava.

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