An Experimental Study for Solar Tunnel Drying of Apple

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Abstract : Using solar tunnel dryer, the thin-layer solar drying experiments of apple were carried out under the conditions of Ankara, Turkey. During the experiments, apples were dried to the final moisture content of 11 from 82% w.b. in 1.5 days of drying in the solar tunnel dryer as compared to 2 days of drying in the open sun drying. The experimental drying data of apple slices obtained were used to fit the Page, logarithmic and Wang and Singh models, and constants of drying models tested were determined by non-linear regression analysis. Among the various models tested to represent the solar tunnel drying behaviour of organic apple, one was selected which presented best statistical indicators. Samples dried in the solar tunnel dryer were completely protected from insects, rain and dusts and the dried samples were of high quality in terms of colour and hygienic. Since this system is simple in construction and can be constructed at a low cost with locally obtainable materials, it has been successfully used for drying various agricultural products such as vegetables and fruits by growers in Ankara.

Key Words : apple, solar drying, moisture content, colour

Güneş Enerjili Tünel Tipi Kurutucu ile Elmanın Kuruma Davranışlarının Belirlenmesi İçin Bir Deneysel Çalışma

Öz : Tünel tipi güneş enerjili kurutucu kullanılarak organik olarak yetiştirilen elmanın kurutma denemeleri Ankara koşullarında deneysel olarak yapılmıştır. Denemeler esnasında elma dilimleri, yaklaşık %82 y.b. (yaş baz)'den %11 y.b.'ye tünel tipi kurutucuda 1.5, açık alanda ise 2 günde kurumuştur. Deneysel olarak elde edilen kuruma verileri Page, logarithmic and Wang and Singh modellerinde kullanılmış ve modellerin katsayıları doğrusal olmayan regresyon tekniği ile belirlenmiştir. Organik elmanın kuruma davranışını iyi karakterize edecek model, çeşitli istatistiksel karşılaştırma yöntemleri ile belirlenmiştir. Tünel tipi kurutucuda elde edilen ürünler, tamamen böcek, yağmur ve tozdan korunmuş ve renk ve temizlik bakımından yüksek kaliteli ürün elde edilmiştir. Geliştirilen bu sistemin yapımı kolay ve maliyetinin düşük olmasından dolayı, Ankara'daki yetiştiricilerce çeşitli meyve ve sebzelerin güneş enerjisi ile kurutulmasında başarıyla kullanılmıştır.

Anahtar Kelimeler : elma, güneş enerjili kurutma, nem içeriği, renk

Introduction

Apple is an important raw material for many food products and apple plantations are cultivated all over the world in many countries. Thus, it is very important to define the conditions under which the characteristics of fresh apple can be preserved and to define optimal parameters for their storage and reuse (Velic et al. 2004). Fruits and vegetables are regarded as highly perishable food owing to their high moisture content. Thus, they exhibit relatively high metabolic activity compared with other plant-derived foods such as seeds. This metabolic activity continues after harvesting, thus making most fruits highly perishable commodities. Drying is one of the most common processes used to improve food stability, since it decreases considerably the water activity of the material, reduces microbiological activity and minimises physical and chemical changes during its storage. Apple is usually dehydrated by hot air convective drying, solar drying and microwave drying. High temperature and long drying times required to remove the water from the apple in the hot air convective drying may cause serious damage in flavour, colour and nutrients. Therefore, solar energy is an important alternative source of energy to the apple drying due to above listed disadvantages.

Solar drying is essential for preserving agricultural products, so it is necessary to know the drying process and storage of apple. Using a solar dryer, the drying time can be shortened by about 65% compared to sun drying because, inside the dryer, it is warmer than outside; the quality of the dried products can be improved in terms of hygiene, cleanliness, safe moisture content, colour and taste; the product is also completely protected from rain, dust, insects; and its payback period ranges from 2 to 4 years depending on the rate of utilization. The most important feature of solar dryers is that the product does not include any kind of preservatives or other added chemical stuffs, which allows its use for people suffering from various allergic reactions from chemical preservatives and other added stuffs. Furthermore, the product is not exposed to any kind of harmful electromagnetic radiation or electromagnetic poles (Tiris et al. 1996). Although for agricultural products, solar dryers with solar air heater offer better control of required drying air conditions, solar tunnel dryers based on plastic tunnel greenhouses have a great potential and doesn't require any other energy during operation. Therefore, solar tunnel dryer may become a more convenient alternative for rural sector and other areas in which electricity is scarce and in regular supply. Also, it can reduce crop losses, improve the quality of dried product significantly and is economically beneficial compared to traditional drying methods.

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Sun shines in Ankara, situated in Middle Anatolian Region in Turkey, over an average 2466 h per year, delivering about 1525 kWh/m^2–year of solar radiation on the horizontal surface (Ankara Meteorological Station 2004). Hours of sunshine and solar radiation between June and September, namely drying period in Ankara, make up about 46.59 and 49.64% of these values, respectively. These data show that abundantly available solar energy can be used for the drying of the agricultural products.

Recently, there has been an increasing demand for organic fruits and vegetables due to human health benefits. The development of new, consumer attractive, high quality, dried fruit products is desirable so as to widen product availability and diversify their market, particularly as nowadays fruit consumption is so highly recommended in the consumer's diet. Organic and dried agricultural products are of growing importance in the world. Parallel with these changes in human consumption, organic agriculture in Turkey has developed very rapidly and organic agriculture production was about 292 000 tonnes in 2003 in Turkey (Anonim 2004).

Dried apples can be consumed directly or treated as a secondary raw material (Velic et al. 2004). Despite extensive search, no published work seems to have been carried out on the solar drying behaviour of organic agricultural products. Therefore, this experimental study was carried out to study the drying kinetics of organic apple in a solar tunnel dryer under climatic conditions of Ankara, and to fit the drying curves with mathematical models available in literature. Also, this research has been prepared to make the solar drying of various agricultural products with the help of solar tunnel dryer more common in Ankara, which has an important share in Turkish agriculture.

Material and Methods

The apples (*cv. Starking*) used in this study were obtained from the Department of Plant Protection, Faculty of Agriculture, Ankara University, during the summer season of 2003. Since they were grown in accordance with organic agriculture methods, no chemical substances such as synthetic fertiliser and pesticide were used. Ripe and sound apples were harvested by hand one day before experiments. Test samples having between 105-110 g were washed with tap water and not peeled but the core was taken out with a cylindrical 10 mm diameter core borer. Then, the apples were cut into 5±2 mm thick slices with the help of a hand operated slicer. Apple slices weren't treated any chemical solution in any way. About 2.5 kg samples of apple slices were used for drying measurement. The initial moisture content of apple slices was determined using the vacuum oven method at 70 °C for 24 h (AOAC 1990). These experiments were replicated thrice to obtain a reasonable average. The sample was found to have a moisture content of about 82% w.b. (wet basis).

A schematic view of the experimental solar tunnel is shown in Figure 1. The experimental solar tunnel, having dimensions of 1.8 m by 2.5 m by 8 m was located in the Department of Agriculture Machinery, Ankara (39º57' N, 32º53' E). It was oriented in an east-west direction to make the solar radiation incident more efficient on the solar tunnel dryer. Tunnel was covered with a plastic film of semi-transparent polyethylene, 150 microns in thickness in order to incorporate UV and far infrared protection. To prevent insects and birds from entering the dryer, wire mesh was fixed at the inlet and outlet side of the solar dryer. Two wire mesh trays, having dimensions of 1 m by 2.5 m, were used to accommodate apple slices to be dried as thin layer solar drying. The temperature and relative humidity in tunnel was measured using SHT11 relative humidity and temperature sensors. These sensors were installed in inlet, middle and outlet points of the solar tunnel dryer in order to monitor continuously the temperature and relative humidity of drying air. During the drying process, the temperature and relative humidity in solar tunnel dryer were continuously recorded at 1 min intervals throughout runs by a suitable software connected to a personal computer.
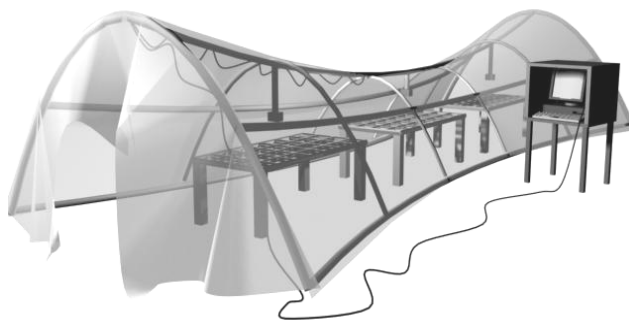

Figure 1. Schematic representation of the solar tunnel dryer

Three sets of drying experiments were conducted during the periods of August to September 2003 under the climatic conditions of Ankara. Each experiment was done between 08:00 and 18:00. During the drying experiments, the weather was generally sunny and no rain appeared. For all drying experiments, apple slices were spread on the wire mesh tray inside the drying tunnel as 2.5 kg and single layer having about 6 mm. To determine the moisture loss of drying apples during experiments, apple slices were taken from 3 points, namely inlet, middle and outlet of the solar tunnel dryer and weighed at various time intervals, ranging from 30 min at the beginning of the drying to 1 h during the last stage of the process. The moisture loss of samples was determined by means of a digital electronic balance having an accuracy of 0.01 g. After 18:00, the apple slices in the solar tunnel dryer were collected and placed in plastic boxes in order to induce diffusion of moisture within the drying samples. These were again spread in the dryer in the next morning and the drying process was continued until no further changes in their mass were observed. Afterwards, the dried products were packed in low-density polyethylene bags until the beginning of colour experiments within one week after drying. Also, to compare the performance of the solar tunnel dryer with that of open sun drying, control samples of apple were put on a tray near the dryer and dried simultaneously under the same weather conditions.

The appearance of the both raw and dried apple slices was evaluated by a colour-difference meter technique using a Minolta CR-300 Chromameter with an aperture size 8 mm. In the International Commission on Illumination (CIE) L^*, a^* and b^* uniform colour space, the L^* indicates lightness, a^* chromaticity on a green (-) to red (+) axis and b^* chromaticity on a blue (-) to yellow (+) axis. The colorimeter was calibrated each time with a standard white plate having L^*, a^* and b^* values for 97.38, 0.02 and 1.55, respectively. Measurements were individually taken for five raw and dried apple slices, and the average of five readings was calculated. Colour difference ΔE and hue angle $H°$ were determined using the following equations:

$$\Delta E = \sqrt{(L_0 - L_f)^2 + (a_0 - a_f)^2 + (b_0 - b_f)^2} \qquad (1)$$

$$H° = \tan^{-1}\left(\frac{b^*}{a^*}\right) \qquad (2)$$

where ΔE is the colour difference, $H°$ is the hue angle, L_0, a_0 and b_0 are the L^*, a^* and b^* colour values of raw apple and L_f, a_f and bf are the L^*, a^* and b^* colour values of dried apple slices, respectively.

The raw apple slices were used as the reference and a higher ΔE stand for greater colour change from the reference material. $H°$ values of 0, 90, 180 and 270° represent red, yellow, green and blue, respectively.

Solar tunnel drying curves obtained were fitted to the following drying models namely, the Page, logarithmic and Wang and Singh model, respectively:

$M_R = \exp(-kt^m)$ $\qquad (3)$
$M_R = a \exp(-kt) + c$ $\qquad (4)$
$M_R = 1 + at + bt^2$ $\qquad (5)$
Moisture ratio (M_R) is given as follows:

$$M_R = \frac{M - M_e}{M_0 - M_e} \qquad (6)$$

where M_R is the dimensionless moisture ratio; M is the moisture content at any time in % w.b.; M_e is the equilibrium moisture content in % w.b.; M_0 is the initial moisture content in % w.b.

However, M_R is the simplified to M/M_0 in place of equation 6 since the relative humidity of the drying air fluctuated continuously under the sun drying (Diamente and Munro 1993).

The constants of models tested were determined by non-linear regression analysis. The estimation method was Quasi-Newton and the adequacy of models was evaluated and compared by means of the coefficient of determination R^2, mean relative percent deviation E_{MD} and root mean square error E_{RMS} using the following equations:

$$E_{MD} = \frac{100}{N} \sum_{i=1}^{N} \frac{\left|M_{R,ex} - M_{R,pre}\right|}{M_{R,ex}} \qquad (7)$$

$$E_{RMS} = \left[\frac{1}{N} \sum_{i=1}^{N} \left(M_{R,ex} - M_{R,pre}\right)^2\right]^{1/2} \qquad (8)$$

where $M_{R,ex}$ is the experimental moisture ratio, $M_{R,pre}$ is the predicted moisture ratio and N is the number of observations.

R^2 was used as the primary comparison criteria for selecting the best model to fit the models tested to the experimental data. Also, a model is considered acceptable if the values for E_{MD} are below 10%.

Results and Discussion

During the drying experiments, the daily mean values of ambient air temperature, relative humidity and solar radiation changed from 21.6 to 39.7 °C, 12.1 to 51.5%, 205.1 to 796.2 W/m², respectively. The ambient air temperature and solar radiation were reached the highest figures between 12:00 and 15:00, whereas the relative humidity was reached the lowest figures during this time.

Change in means of the drying temperature and relative humidity at inlet, middle and outlet of solar tunnel is presented Figure 2. The drying temperature and relative humidity at these points in solar tunnel dryer varied continuously from morning to evening. It was observed that the drying temperature in tunnel was greater than the ambient temperature, whereas the relative humidity in tunnel was lower than the ambient relative humidity. Also, there was a significant difference between the values of the temperature and relative humidity. This difference for the temperature and relative humidity was about 13.1° C and 9.2% during the experiment time, respectively. This explicitly indicates that the drying rate in the solar tunnel drying will be higher than open sun drying.

The moisture content of the organic apple as a function of drying time is shown in Figure 3. The interruptions of the lines in this figure represent the night periods of the drying process. As expected, the moisture content decreased considerably with increasing drying time. Apple slice of initial moisture content of around 82% w.b. was dried to the final moisture content of about 11% w.b. until no further changes in their mass were observed. During the experiments, the final drying duration for solar tunnel changed between 26 and 29 h, whereas corresponding value for open sun drying was found to be between 31 and 34 h. Using a solar tunnel dryer, the drying time was reduced to about 14.28% in comparison to open sun drying. Depending on weather conditions, the solar tunnel dryer developed shortened half day the drying time of organic apples. This was expected owing to the values of higher temperature and lower relative humidity obtained in solar tunnel dryer. Similar results have been reported by Schirmer et al. (1996) for banana, Bala and Mondol (2001) for fish and Bala et al. (2003) for pineapple.

Table 1 shows the results of nonlinear regression analysis of fitting the three drying models to the experimental data and evaluation criteria used to compare the statistical validity of the fit *i.e.* R^2, E_{MD} and E_{RMS} for

solar tunnel drying. All models except for Wang and Singh model gave a good fit to the experimental data with a value for R^2 of grater than 0.99. Of all models, the logarithmic model provided the highest R^2 values, followed by the Page model. However, the values for E_{MD} obtained from the Page model were less than 10%, which is in the acceptable range. This model gave a higher value of R^2 and lower values for the E_{MD} and E_{RMS} than the other models. Therefore, the Page model was considered the best model in present study to represent the solar tunnel drying behaviour of apple.

Figure 4 presents the comparison between experimental and predicted values of moisture ratio using the Page model for solar tunnel. It can be seen from this there was a good agreement between experimental and predicted moisture ratios. This indicates the suitability of the Page model in describing solar tunnel drying behaviour of apple.
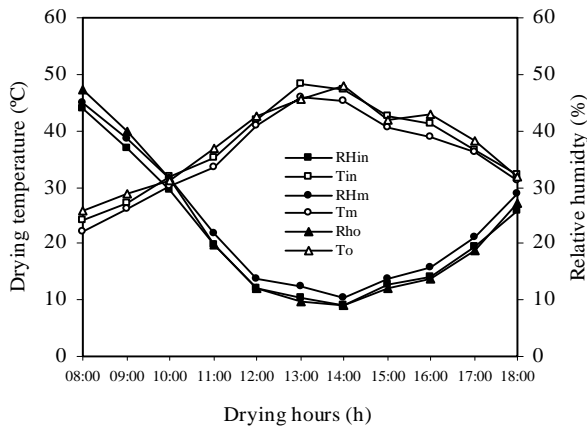
Table 1. Parameter estimation, R^2, E_{MD}, and E_{RMS} of the three drying models fitted to the experimental drying data of apple slices

	Page	Logarithmic	Wang and Singh
k	0.043	0.135	
m	1.559		
a		1.082	-0.0854
b			0.0019
c		0.0012	
R^2	0.9909	0.9940	0.9483
E_{MD}, %	9.43	11.83	25.09
E_{RMS}	7.31×10^{-3}	9.92×10^{-3}	17.42×10^{-3}

Figure 4. Variation of experimental and predicted moisture ratios by the Page model with drying time for solar tunnel drying

Figure 2. Change in means of drying temperature and relative humidity at inlet, middle and outlet of solar tunnel (RH_{in}, RH_m and RH_o is the relative humidity at inlet, middle and outlet of the solar tunnel, respectively; T_{in}, T_m and T_o is the air temperature at inlet, middle and outlet of the solar tunnel, respectively)
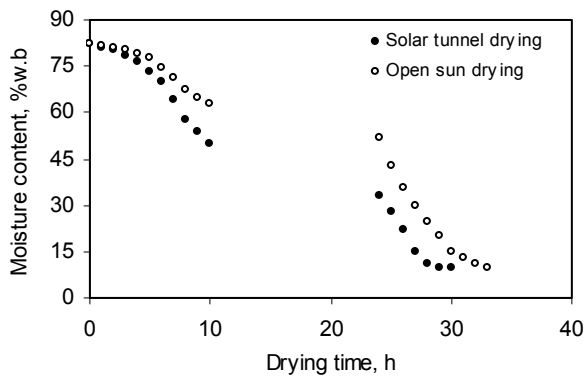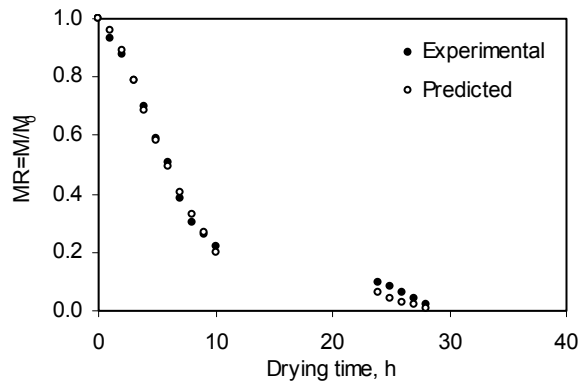
The colour is the most important attributes of the dried product. It reflects a sensation to the human eye and visual examination is the common method of assessing product colour. The effect of solar tunnel and open sun drying on Hunter colour values of apple slices is presented in Table 2. Hunter colour values of apple slices were greatly affected by the drying method. L^*, b^* and $H°$ with the exception of a^* values for samples of open sun drying were lower than those for solar tunnel drying. In terms of desired colour properties for apple slices, a lower value for a^* and higher values for $H°$ and L^* are preferred. The apple dried in the solar tunnel dryer had more yellow colour and brighter as compared to the open sun drying. This darker in the open sun drying process was due to the direct exposure of the apple surfaces to solar radiations for a longer drying time. In addition, natural colours were retained better for the samples dried in the solar tunnel dryer, for the lowest value for ΔE was observed in the samples of solar tunnel dryer. It is clear that the solar tunnel drying maintained the colour quality of fresh apple slices better than open sun drying.

Figure 3. The thin-layer drying curves of apples at indicated drying methods

Table 2. Colour parameters of apple slice for solar tunnel and open sun drying

	Drying method	
Parameter	Open sun drying	Solar tunnel drying
L^*	54.67	65.57
a^*	8.15	5.27
b^*	23.50	34.67
ΔE	26.61	13.46
$H°$	70.87	81.36

Conclusions

The developed solar tunnel dryer is capable of dehydration of the apples as well as most of the agricultural products under the climatic conditions of Ankara. The moisture content was reduced from 82 to 11% w.b. in 32 h for the open sun drying, whereas the solar tunnel dryer took only 28 h. Depending on weather conditions, solar tunnel dryer resulted in a reduction in the drying time to an extent of 14.28% in comparison to open sun drying. In addition, the samples of solar tunnel dryer were completely protected from insects, birds, rain and dusts. The dried apple samples had more yellow colour and brighter when dried by solar tunnel dryer as compared to the open sun drying. The Page, which gave higher the coefficient of determination, lower the root mean square error and mean relative percent error, was considered the best model for explaining the solar tunnel drying behaviour of apple. It is expected that this system will help growers reduce the cost of drying and obtain more quality dried products. Further studies are ongoing.

Acknowledgement

References

Anonim 2004. Statistical database. Republic of Turkey Ministry of Agriculture and Rural Affairs, Ankara, Turkey. http://www.tarim.gov.tr.

AOAC 1990. Official method of analysis. Association of Official Analytical Chemists (No. 934.06), Washington, DC.

Bala, B. K and M. R. A. Mondol. 2001. Experimental investigation on solar drying of fish using solar tunnel dryer. Drying Technology 19 (2): 427-436.

Bala, B. K., M. R. A. Mondol, B. K. Biswas, B. L. Das Chowdury, and S. Janjai. 2003. Solar drying of pineapple using solar tunnel drier. Renewable Energy 28 (2): 183-190.

Diamente, L. M. and P. A. Munro. 1993. Mathematical modeling of the thin layer solar drying of sweet potato slices. Solar Energy 51 (4): 271–276.

Schirmer, P., S. Janjai, A. Esper, R. Smitabhindu and W. Mühlbauer. 1996. Experimental investigation of the performance of the solar tunnel dryer for drying bananas. Renewable Energy 7 (2) : 119-129.

Tiris, C., M. Tiris and İ. Dinçer, 1996. Energy efficiency of a solar drying system. International Journal of Energy Research 20 (9): 767-770.

Velic, D., M. Planinic, S. Tomas and M. Bilic. 2004. Influence of airflow velocity on kinetics of convection apple drying. Journal of Food Engineering 64 (1): 97-102.

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