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Research Article

The Effects of Microwave Energy to the Drying of Apple (Gala) Slices

Elma (Gala) Dilimlerinin Kurutulmasına Mikrodalga Enerjisinin Etkileri

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Abstract

In this work, the drying behaviors of apple slices with 2, 4, and 6mm thickness were investigated in a microwave conveyor dryer. The effects of different microwave power levels (1050 W, 1500 W and 2100 W) and conveyor speeds (0.175, 0.210 ve 0.245 m/min) on drying time, color changing and energy consumption have been investigated. The results show that drying time and energy consumption decreases considerably with increasing microwave power and with decreasing conveyor speed. Then, the mathematical models were fitted to the experimental data. According to the results, the Page Model was found to best explain thin layer drying behavior of the apple slices as compared to the other models. Fick's diffusion model was applied to calculate the effective diffusivities. The effective diffusivity values were found between 1.1916×10^{-8} m^2/s and 2.7540×10^{-7} m^2/s. The activation energies were calculated as 156.65, 40.18 and 17.90 W/g for samples thickness of 2, 4 and 6 mm, respectively. At the end of the drying process, minimum energy consumption for 2mm at 0.175 m/min conveyor speed and 2100 W power is calculated as 1.34 kWh. From the results of colour quality, the colour criteria nearest the those of apple slices occurred at 1050 W and 0.210 m/min.

Keywords: Activation energy, Conveyor, Diffusion, Mathematical modeling, Microwave drying

Öz

Bu çalışmada 2, 4 ve 6mm olarak dilimlenmiş elmanın mikrodalga kurutucuda kuruma davranışı araştırılmıştır. Mikrodalga gücünün (1050 W, 1500 W ve 2100 W) ve konveyör bant hızının (0.175, 0.210 ve 0.245 m/dk) kuruma zamanına, renk değişimine ve enerji tüketimine etkisi araştırılmıştır. Elde edilen sonuçlara göre kuruma zamanı ve enerji tüketiminin mikrodalga gücü ve konveyör bant hızının artmasıyla azaldığı görülmüştür. Daha sonra deneysel sonuçlar matematiksel modellere uygulanmıştır. Sonuçlara göre Page model diğer modeller ile karşılaştırıldığında en uygun model olarak tespit edilmiştir. Fick difüzyon modeli de difüzyon katsayısının tespitinde kullanılarak 1.1916×10^{-8} m^2/s ve 2.7540×10^{-7} m^2/s aralığında difüzyon katsayılarının değiştiği belirlenmiştir. Aktivasyon enerjisi de 2, 4 ve 6 mm dilimler için sırasıyla 156.65, 40.18 ve 17.90 W/g olarak hesaplanmıştır. Kurutma prosesinin sonucunda 2mm dilim kalınlığındaki elma için 0.175 m/dk konveyör hızında ve 2100 W gücünde minimum enerji tüketimi 1.34 kWh olarak hesaplanmıştır. Renk kalitesine bakıldığında da taze elmaya en yakın değer 1050 W ve 0.210 m/dk değerlerinde görülmüştür.

Anahtar Kelimeler: Aktivasyon enerjisi, Konveyör bant, Difüzyon, Matematiksel model, Mikrodalga kurutma

1. Introduction

Apple is an important raw material for many food products and apple plantations are cultivated in many countries all over the World (Bi et al. 2015; Zarein et al. 2015). 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. Fruits and vegetables are regarded as highly perishable food owing to their high moisture content (Doymaz et al. 2006). 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 food materials. The drying process is intended to remove water from foodstuff in order to prevent microbial spoilage and chemical alterations thus prolonging shelf-life while realizing space and weight saving (Aydogdu et al. 2013).

Apple has a significant share in fruit production both in the World and in Turkey. It is also an important raw material for many food products. Apple is usually dehydrated by hot air convective drying and solar drying. High temperature and long drying times required to remove the water from

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the apple in the hot air convective drying may cause serious damage in flavour, colour and nutrients. Therefore, electromagnetic energy is an important alternative source of energy to the apple drying due to above listed disadvantages of hot air drying (Sarı and Karaaslan, 2014). Several studies have been carried out to investigate the drying characteristics of the apple (Andres et al. 2004, Wang et al. 2007, Aktaş et al. 2009, Toğrul 2005, Zarein et al. 2015).

Drying is a complicated process which involves simultaneous heat and mass transfer. Water molecule transport has a close relationship with the drying process, including molecular diffusion, such as capillary motion, liquid diffusion, vapor diffusion and hydrodynamic. In microwave drying, the heat is resulted from the conversion of microwave energy into thermal energy within the moist materials and provides desired heat and pressure in order to dry material quickly. In order to overcome these problems and reduce the drying time to achieve an efficient and rapid heat transfer process, the use of microwaves for drying food has been developed. Microwave is a rapid method for drying food (Mohammadi et al. 2014). The application of microwave heating for food materials is recently of special interest. Therefore, it has been the subject of investigations and several recent researchers have demonstrated the significant advantages of microwave drying (Çelen and Kahveci 2013a). Microwave drying process is a relatively inexpensive method that has attracted the attention of many investigators. Many studies have been done on microwave drying or microwave assisted drying for a great variety of food products. The references and the subjects for some of these studies are: (Ozbek and Dadali 2007) – mint drying, (Erdem 2006)– red pepper drying, (Kassem et al. 2011) – grape drying, (Alibas 2007) – pumpkin drying, (Worknech et al. 2011)– tomato drying, (Maskan 2000) – banana drying, (Evin 2012) – roseships drying, (Işık et al. 2011)– lentil drying, (Albanese et al. 2006) – potatoes drying.

In this study, the effect of microwave power and conveyor speed on some drying characteristics (slice thickness, drying time, moisture content, effective diffusivity, activation energy) of apple was investigated experimentally for various values of microwave power and conveyor speed in a microwave dryer. The suitability of some empirical and semi-empirical models was also specified for drying simulation of apple slices. Furthermore, a colour analysis was conducted to investigate the effects of microwave drying on the product colour quality. Moreover, another purpose in this study is to generate a control system that will decrease the energy cost of the drying period, increase the product quality and reduce the total drying period.

2. Material And Methods

Apple (Gala) shown in Figure 1. was obtained from the store of a local market (Tekirdağ/Turkey) where they had been stored at 4 °C.

Experiments were performed in a microwave conveyor dryer (Figure 2). The microwave cavity was a rectangular shape with a cross-sectional area of 500 mm x 400 mm x 3500 mm. The microwave power was generated by means of 3 magnetrons of 700 W at 2.45 GHz. The conveyor speed and the speed of rotation can be set by the invertor that controls the electric motor, and which is located in the control panel. The conveyor speed is adjustable and can be set by the potentiometer of control unit.

The weight of the apple slices was specified with a digital scale (Presica XB 620 M; Precisa Instruments AG, Dietikon,

Figure 1. Apple samples used in the experiments (2 mm, 4 mm and 6 mm).

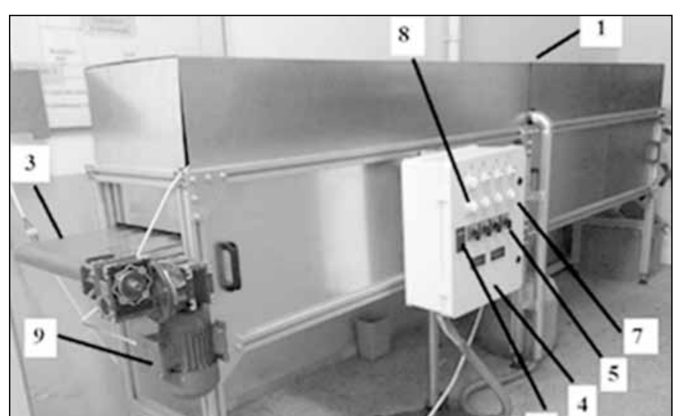

Figure 2. The experimental setup of microwave conveyor dryer.

Switzerland) of ± 0.001 g precision and a capacity of 620 g. The energy consumption was measured by an energy meter (Enda, Turkey). The colour analysis of the product was conducted by a Spec HP-200 (Jiangsu, China) colorimeter.

2.1. Drying Procedure

In order to specify the moisture content, the apples were initially dried in an oven at 105 °C for 24 hours and the dry mass was measured. The moisture content of the apples with respect to the wet basis was 86±0.6% (w.b). Apple slices were washed with tap water and hand peeled, cored with a knife and then cut vertical to their axis into cylindrical slices of 2, 4 and 6 mm thickness using a hand operated slicer (Meisami-asl et al. 2010). About 8±0.2 g, 10±0.3 g and14±0.3 g samples of apple slices were used for each slice of drying, respectively. After that, the apple slices were placed on wooden bars. No pre-treatment was applied to the samples before the experimental study. The drying was controlled by the speed of conveyor and microwave power. The microwave power was generated by four magnetrons. Drying experiments were carried out for microwave powers of 1050 W, 1500 W and 2100 W at the frequency of 2.45 GHz, conveyor speed of 0.175 m/min, 0.210 m/min and 0.245 m/min and for each thickness. Drying tests were repeated three times for each experimental condition in order to minimize the uncertainties in the results. The progress of the drying process was followed by weighing the bars containing apple at regular intervals of time on a digital scale of accuracy ±0.001 g. The drying stage continued until the moisture content reached around 12%±0.5 (wet basis). After each test, the energy consumption during drying and the colour parameters of the dried product were measured and recorded.

2.2. Modeling of the thin-layer drying

The least squares method is used to simulate the drying behavior of apple by the models in Table 1 taken into consideration. In this method, the coefficients in the models are determined by minimizing the sum of the squared differences between the experimental moisture ratios and the theoretical ones. The better the suitability between the model results and the empirical data, the closer the corelation coefficient will be to 1 and the closer the standard error and the chi-square will be to 0. These parameters are defined as Eq. 1-3 (Bi et al. 2015). In these models, MR represents the dimensionless moisture ratio, namely, MR = (m-me)/ (m_0-me), where m is the moisture content of the product at each moment, m_0 is the initial moisture content of the product and me is the equilibrium moisture content. The values of me are relatively small compared with m or m_0 for long drying time. Thus, MR = (m-me)/ (m_0 me) can be simplified as MR = m/m_0 (Çelen and Kahveci 2013a).

$$r=\frac{n_0\sum_{i=1}^{n_0}MR_{pre,i}MR_{\exp,i}-\sum_{i=1}^{n_0}MR_{pre,i}\sum_{i=1}^{n_0}MR_{\exp,i}}{\sqrt{n_0\sum_{i=1}^{n_0}(MR_{pre,i})^2-\left(\sum_{i=1}^{n_0}MR_{pre,i}\right)^2}\sqrt{n_0\sum_{i=1}^{n_0}(MR_{\exp,i})^2-\left(\sum_{i=1}^{n_0}MR_{\exp,i}\right)^2}} \quad (1)$$

$$e_s=\sqrt{\frac{\sum_{i=1}^{n_0}(MR_{pre,i}-MR_{\exp,i})^2}{n_0}} \quad (2)$$

$$\chi^2=\frac{\sum_{i=1}^{n_0}(MR_{pre,i}-MR_{\exp,i})^2}{n_0-n_c} \quad (3)$$

where $MR_{pre,i}$ is the i*th* predicted moisture ratio, $MR_{exp,i}$ is the i*th* experimental moisture ratio, n_o is the number of observations and n_c is the number of coefficients in the drying model.

2.3. Diffusion Model

The method of slopes was used to estimate the effective moisture diffusivity of apple slices under different drying conditions. With decreasing moisture content, the drying characteristics may change during the drying process. This may be controlled by a diffusion mechanism which can be described by Ficks' second law (Bi et al. 2015).

In this study, apple slices were assumed to be infinite plates, according to Ficks' second law, and the effective moisture diffusivity (D_{eff}) within infinite plates can be estimated from the following Equation (4). In the case of symmetric

Table 1. Various mathematical models used in modeling of drying (Akyol et al. 2012).

Model name	Model equation	Model name	Model equation
Newton	mr=exp(-kt)	Geometric	mr=at^{-n}
Page	mr=exp(-kt^n)	Wang and Singh	mr=1+at+bt^2
Henderson and Pabis	mr=a exp(-kt)	Verma et al	mr=aexp(-kt)+(1-a)exp(gt)

boundary conditions, neglecting of material shrinkage and assumption the water distribution in the material is homogeneous, the moisture ratio can be determined as in Eq. (5) (Darvishi et al. 2014).

$$MR = \frac{8}{\pi^2} exp\left(-\frac{\pi^2 D_{eff}}{4L^2} t\right) \tag{4}$$

where MR is the moisture ratio (dimensionless); t is the time (s); D_{eff} is the effective moisture diffusivity (m^2/s); L is the half thickness of the apple slices (m).

Diffusivities are determined by plotting the experimental drying data in terms of lnMR versus drying time t in the equation. The plot produces a straight line with the slope as follows:

$$Slope = \frac{\pi^2 D}{4L^2} \tag{5}$$

In this investigation, temperature is not directly measurable in the microwave oven used for drying. Since it is difficult to obtain an accurate value for the temperature in a microwave drying system, the activation energy can be calculated using a modified Arrhenius equation. In this case, the activation energy is related to the effective moisture diffusion coefficient and the ratio of microwave power to sample mass (m/P), as Eq. 8 (Darvishi et al. 2014):

$$D_{eff} = D_0 . e^{-Ea.m/P} \tag{6}$$

where E_a is the activation energy (W/g), m is the mass of raw sample (g), D_0 is the pre-exponential factor (m^2/s) and P is the microwave power (W).

2.4. Color Analysis

Colour is an important quality criteria for food consumers. The color change of apple slices during microwave drying at different microwave powers are also studied by the measuring of color parameters using a Spec HP-200 (Jiangsu, China) colour meter. Three time replicates of each sample were measured to determine the average values of L^* (whiteness/darkness), a^* (redness/greenness) and b^* (yellowness/blueness). The total color change (ΔE) is then calculated from the L^*, a^* and b^* values (Çelen and Kahveci 2013b). These parameters are defined as:

$$\Delta L = L_{fresh} - L^* \tag{7}$$

$$\Delta a = a_{fresh} - a^* \tag{8}$$

$$\Delta b = b_{fresh} - b^* \tag{9}$$

$$\Delta E = \sqrt{\Delta L^2 + \Delta a^2 + \Delta b^2} \tag{10}$$

2.5. Determination of Energy Consumption

The energy consumption during drying was measured by an energy meter (Enda, Turkey). Energy consumption values of microwave dryer were recorded using this device.

3. Results And Discussion

3.1. Modeling Drying Data

Models given in Table 1 are used to express the drying behavior of apple slices. Curve fitting computations were carried out on six drying models relating the drying time and moisture ratio. The best fitted model among models in Table 1 gives the Page model. In addition the drying curves based on the Page model are presented with the experimental moisture ratios in Figures 3-5. The acceptability of the drying model is based on a value for the corelation coefficient r which should be close to one, and low values for the standard error e_s and the mean squared deviation χ^2. The results show that the most appropriate model in describing drying curves of apple is the Page model with r in the range of 0.980–0.998, and with e_s in the range of $2.0x10^{-3}$–$8.5x10^{-2}$ and with χ^2 in the range of $1.0x10^{-2}$–$4.9x10^{-2}$ for dried apple slices.

The Page model is generally seen in the food sector. Several research have been presented in literature about the application of the Page model for apple (Çelen and Kahveci 2013b). Some studies shows that different models are suitable for drying apples. These models are Parabolic model by Zarein et al. (2015), Midilli model by Schössler et al. (2012), Menges and Ertekin. (2006), modified Page II model by Toğrul (2005), Logarithmic model by Wang et al. (2007).

The results of previous research have shown that the internal mass transfer resistance controls the drying time due to presence of a falling rate-drying period (Wang et al. 2007). Therefore, the values of effective diffusivity (D_{eff}) at different output powers could be obtained by using Eq. (6). The determined values of effective moisture diffusivity (D_{eff}) for different microwave powers increased from 8.5114×10^{-8} m^2/s to 1.1235×10^{-7} m^2/s with the increase in microwave output power from 1050 W to 2100 W for different amount of sample. These results were in agreement with the previous investigations that the values of effective diffusivities lie within the general range of 10^{-11} to 10^{-9} m^2s^{-1} for food materials (Arslan and Ozcan 2011). Kutlu and İşçi (2014) reported that the effective diffusivity values were varied in the range of $1.65\text{-}11.05\times10^{-8}$ m^2/s. This might be explained

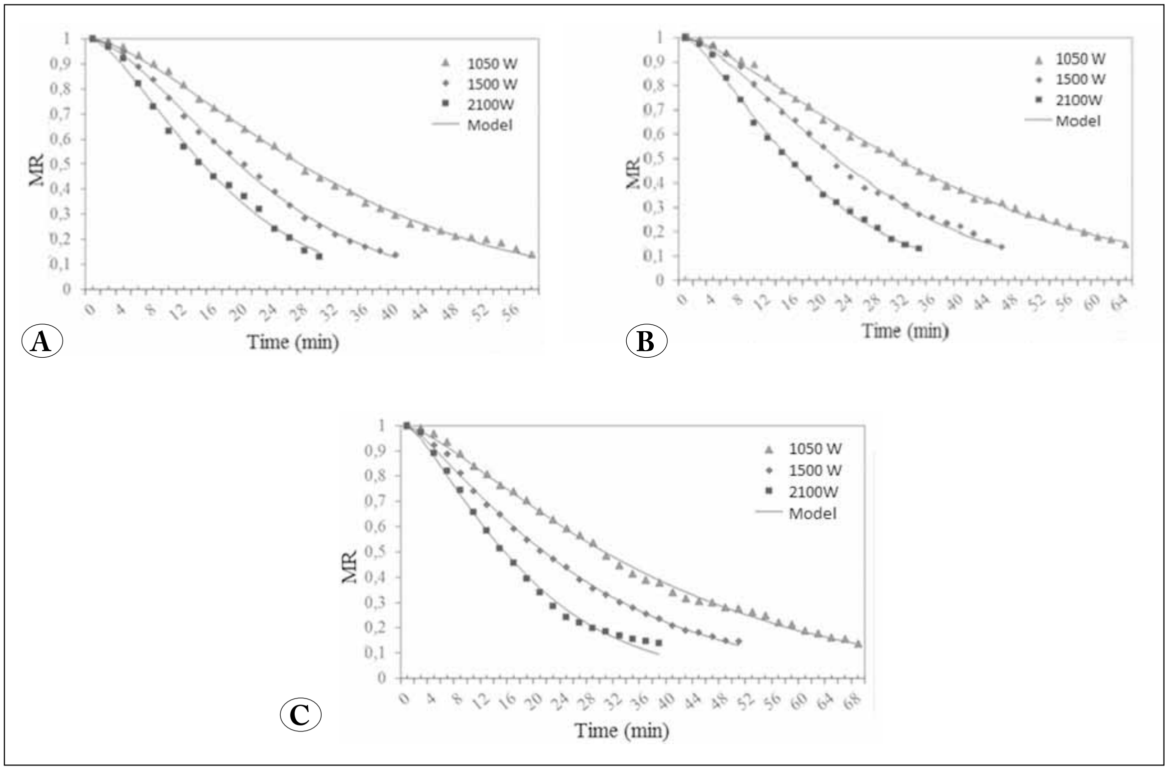

Figure 3. Drying curves based on The Page model of apple with 2 mm layer thickness for different conveyor speeds, **A)** 0.175 m/min, **B)** 0.210 m/min and **C)** 0.245 m/min).

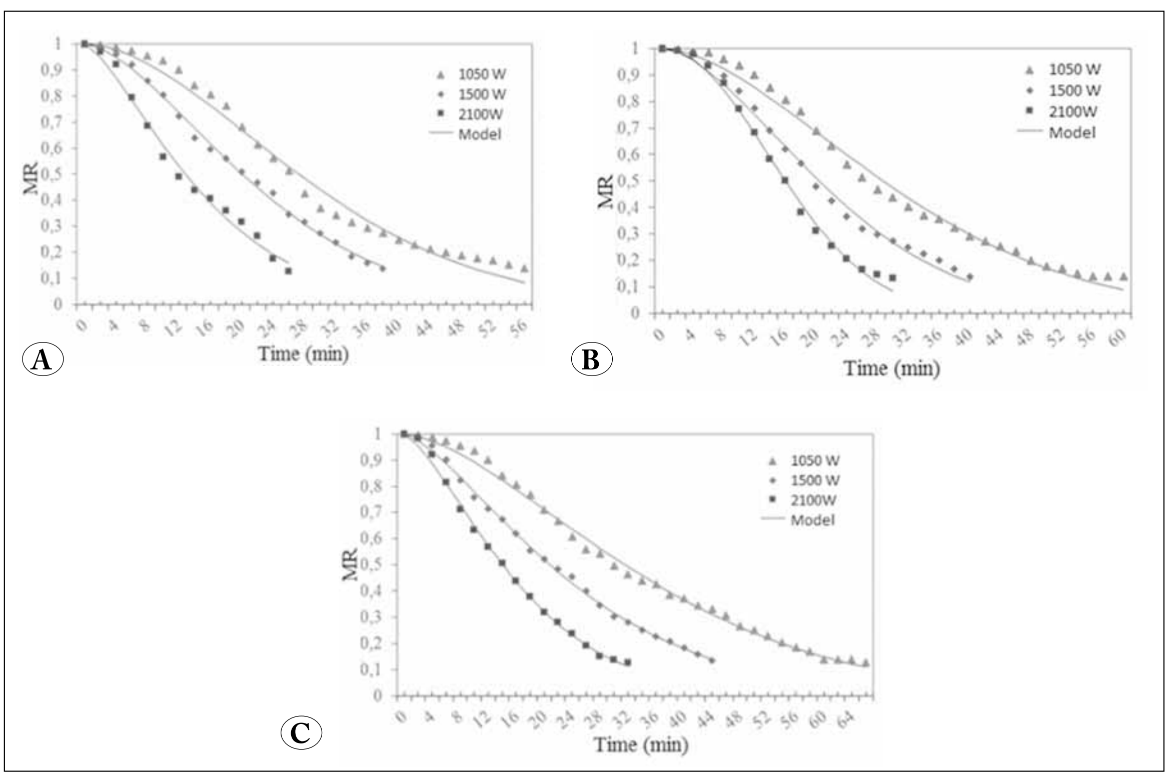

Figure 4. Drying curves based on The Page model of apple with 4 mm layer thickness for different conveyor speeds, **A)** 0.175 m/min, **B)** 0.210 m/min and **C)** 0.245 m/min).

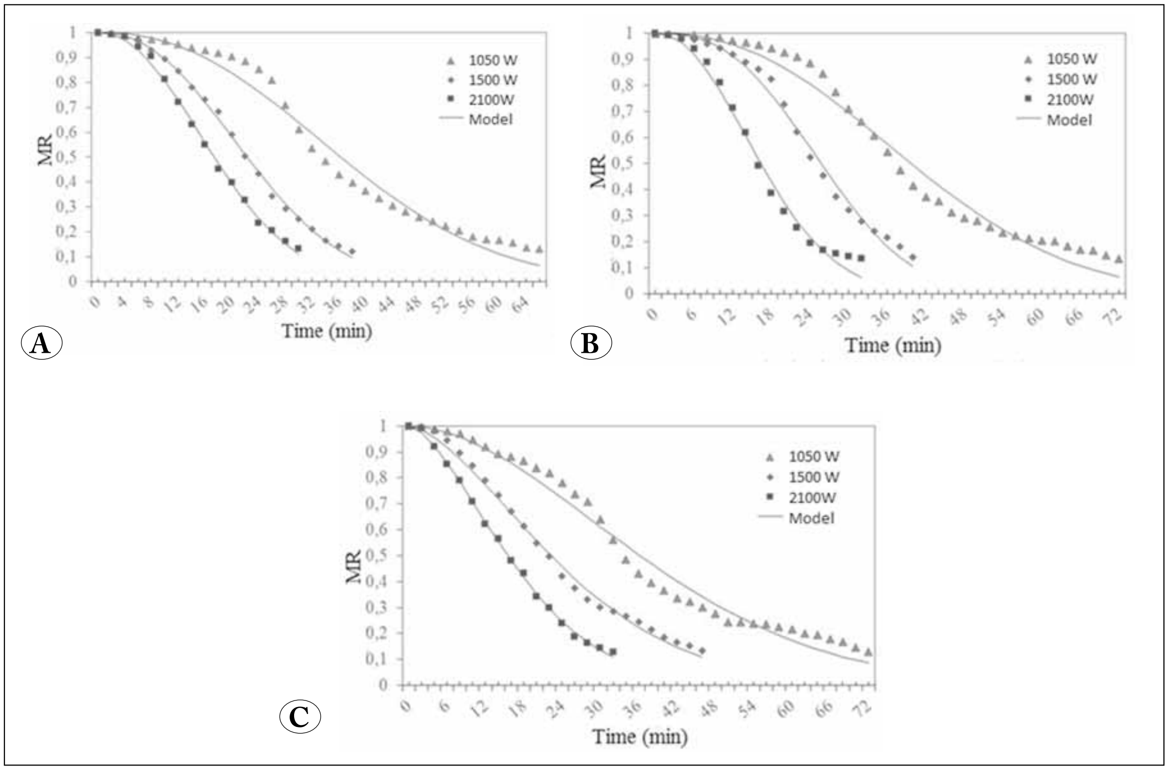

Figure 5. Drying curves based on The Page model of apple with 6 mm layer thickness for different conveyor speeds, **A)** 0.175 m/min, **B)** 0.210 m/min and **C)** 0.245 m/min).

by the increased heating energy, which would increase the activity of the water molecules leading to higher moisture diffusivity when samples were dried at higher microwave power (Wang et al. 2007). The dependence of the effective moisture diffusivity on the microwave power was represented with an Arrhenius-type relationship. The activation energies were calculated as 156.65, 40.18 and 17.90 W/g for samples thickness of 2, 4 and 6 mm, respectively by means of the (LnD_{eff} - m/P) curve. This values are higher than that corresponding to okra (5.54 W/g) (Dadali et al. 2007), mint leaves (12.284 W/g) (Ozbek and Dadali 2007), pandanus leaves (13.6 W/g) (Rayaguru and Routray 2011). The lower activation energy translates to higher moisture diffusivity in the drying process.

The effects of microwave conveyor drying parameters on color change of the apple slices was also evaluated in this study. The color was measured and expressed as the L^*, a^* and b^*. Table 2 showed the effect of drying microwave power and belt speed on the color change of apple slices with the increase of the microwave power and belt speed, apple slices got higher L^* value and higher b^* value. Drying methods exert a significant effect on the colour changes of apple slices. Higher L^* values are desirable in the dried products (Doymaz et al. 2006).

At the microwave drying, luminosity (ΔL) loss at all slices is seen at 0.245 m/min conveyor speed and 2100 W at most. The geometrical structures are distorted and even deformation and darkening have occured at the drying made at 2100 W. Due to over-heating, burning thus darkening are seen on the product. This is an undesirable situation. At low microwave powers, as the product warms slowly, a more uniform drying occurs thus less color and luminosity (L^*) change occurs. As result of color analysis, which is an important quality criteria, working at low power is advantageous regarding the luminosity and color quality protection.

When we consider geometrical structure and luminosity criteria, it can be said that drying made at 1050 W for 2 mm and at 1050 W and 1500 W for 4mm is more convenient. Additionally, the increase in the conveyor speed have increased the luminosity change at the product. It is seen that as conveyor speed increases, color change and deformations also increase.

Fruits and vegetables are generally difficult to dehydrate in hot air, owing to their high water content, which implies long drying times, leading subsequently to serious structural and colour changes, and the inevitable loss of nutrients was reported by Vega-Galvez et al. (2010).

Table 2. Color values of dried apple slices.

	L*	a*	b*	Δa	Δb	ΔL	ΔE
Fresh Apple (2 mm)	72.01	-2.09	19.75				
Belt Speed – Power							
0.175 m/min - 1050 W	69.64	5.24	29.54	7.33	9.79	-2.37	12.45
0.175 m/min - 1500 W	64.96	0.02	29.86	2.11	10.11	-7.05	12.50
0.175 m/min - 2100 W	68.53	4.55	34.29	6.64	14.54	-3.48	16.35
0.210 m/min - 1050 W	71.69	4.32	27.89	6.41	8.14	-0.32	10.36
0.210 m/min - 1500 W	70.70	5.49	30.01	7.58	10.26	-1.31	12.82
0.210 m/min - 2100 W	65.31	11.37	34.88	13.4	15.13	-6.70	21.33
0.245 m/min - 1050 W	60.02	4.46	27.52	6.55	7.77	-11.99	15.71
0.245 m/min - 1500 W	58.47	5.33	28.00	7.42	8.25	-13.54	17.50
0.245 m/min - 2100 W	49.36	8.87	25.04	10.9	5.29	-22.65	25.71
Fresh Apple (4 mm)	70.12	-0.62	17.32				
Belt Speed – Power							
0.175 m/min - 1050 W	69.67	7.49	34.06	8.11	16.74	-0.45	18.60
0.175 m/min - 1500 W	66.72	11.45	35.46	12.0	18.14	-3.40	22.05
0.175 m/min - 2100 W	62.97	5.28	34.29	5.9	16.97	-7.15	19.33
0.210 m/min - 1050 W	66.77	8.52	30.11	9.14	12.79	-3.35	16.07
0.210 m/min - 1500 W	64.70	2.49	29.84	3.11	12.52	-5.42	13.99
0.210 m/min - 2100 W	63.35	10.04	30.67	10.6	13.35	-6.77	18.37
0.245 m/min - 1050 W	65.24	6.79	32.18	7.41	14.86	-4.88	17.30
0.245 m/min - 1500 W	64.29	5.85	33.51	6.47	16.19	-5.83	18.38
0.245 m/min - 2100 W	59.16	8.20	29.42	8.82	12.1	-10.96	18.55
Fresh Apple (6 mm)	70.12	-0.62	17.32				
Belt Speed – Power							
0.175 m/min - 1050 W	59.02	14.49	28.58	17.1	9.37	-11.09	22.45
0.175 m/min - 1500 W	58.76	12.73	32.02	15.3	12.81	-11.35	23.00
0.175 m/min - 2100 W	56.26	5.34	33.63	7.98	14.42	-13.85	21.52
0.210 m/min - 1050 W	61.23	8.24	24.62	10.8	5.41	-8.88	15.04
0.210 m/min - 1500 W	57.96	10.65	25.85	13.2	6.64	-12.15	19.19
0.210 m/min - 2100 W	56.88	7.61	26.74	10.2	7.53	-13.23	18.35
0.245 m/min - 1050 W	55.62	13.55	29.17	16.1	9.96	-14.49	23.90
0.245 m/min - 1500 W	54.76	12.51	33.30	15.1	14.09	-15.35	25.76
0.245 m/min - 2100 W	53.46	10.82	24.77	13.4	5.56	-16.65	22.12

The energy consumption during the microwave drying was recorded at the beginning and the end of the test, by the counter on the control panel. The microwave power decreases the energy consumed increases. The reason of that can be explained like that. As the heat produced at low microwave power is low, it requires more time to transfer the produced heat within the biological material and from the material to the environment. Thus, the time required for the water in the material to reach to the evaporation temperature extends and the energy spent for evaporation decreases. This condition prevents the effective drying. Similarly, when the drying periods are considered, at high microwave power the periods are shorter and at low microwave power periods are longer. If a comparison is made in terms of effect of conveyor speed to the drying period; it is measured that at high conveyor speeds, the drying period increase and at low conveyor speed it decreases. As a result, the lowest energy consumption occurs at 0.175 m/min and 2100 W.

4. Conclusion

The concluding remarks are as follows: (1) the most appropriate model in describing drying curves of apple slices is the Page model for microwave drying. (2) Drying time increased with decreasing of microwave power level and this caused to an increase in consumed energy amount. When the belt speed increased, energy consumption increased. The minimum energy consumption values were measured as 1.34 kWh for 2100 W power level, 0.175 belt speed and 2 mm thickness. (3) The values of calculated effective diffusivity for drying at 1050 W and 2100 W ranged from 1.1916×10^{-8} m^2/s to 2.7540×10^{-7} m^2/s. The effective diffusivity increases with decreasing microwave power. Microwave power dependence of the diffusivity coefficients was described by Arrhenius-type relationship. (4) The activation energies were calculated as 156.65, 40.18 and 17.90 W/g for samples thickness of 2, 4 and 6 mm, respectively. (5) Colour analysis is important of foods, especially quality criterion for the production and for the trade. From the results of colour quality, the colour criteria nearest the those of apple slices occurred at 1050 W and 0.210 m/min.

5. Acknowledgements

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