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MODELING FOAM-MAT DRYING CHARACTERISTICS OF BANANA UNDER MICROWAVE CONDITIONS

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ABSTRACT
In this study, it was aimed to dry banana using microwave-assisted foam-mat drying and to identify the drying behavior. Foam-mat drying of banana foam was made using a microwave oven at output power of 100, 180, 300, 450 and 600 W. Effective moisture diffusivities were obtained in the range of 5.9536 x 10^{-9} and 3.5692 x 10^{-8} m^2 s^{-1}. Activation energy was determined as 10.80 W g^{-1} of microwave dried banana foam. Besides, to find the best model to experimental moisture ratio values, thin layer models of Page, Wang and Singh, Midilli and others, Silva and others, two-term and Peleg were applied. As a result, Midilli and others' model gave a better fit than others with highest value of R^2, lowest values of RMSE, RSS and χ^2.
Keywords: microwave drying, foam-mat drying, banana, modeling, drying kinetic, activation energy

MİKRODALGA KOŞULLARINDA MUZUN KÖPÜK KURUTMA ÖZELLİKLERİNİN MODELLENMESİ

ÖZ
Bu çalışmada, muzun mikrodalga destekli köpük kurutma ile kurutulması ve kurutma davranışının belirlenmesi amaçlanmıştır. Muz köpüğü, 100, 180, 300, 450 ve 600 W mikrodalga güçlerinde köpük kurutma yöntemi ile kurutulmuştur. Aktif nem difüzyon katsayıları, 5.9536 x 10^{-9} ve 3.5692 x 10^{-8} m^2 s^{-1} aralığında bulunmuştur. Mikrodalga ile kurutulan muz köpüğünün aktivasyon enerjisi 10.80 W g^{-1} olarak hesaplanmıştır. Bunun yanında, deneysel nem oranı datalarına en iyi uyan modeli bulabilmek için, ince tabaka kurutma modelleri; Page, Wang ve Singh, Midilli ve diğerleri, Silva ve diğerleri, two-term ve Peleg, uygulanmıştır. Sonuç olarak, Midilli ve diğerleri modeli en yüksek R^2, en düşük RMSE, RSS and χ^2 değerleri ile diğer modellere göre daha iyi uyum sağlamıştır.
Anahtar kelimeler: mikrodalga kurutma, köpük kurutma, muz, modelleme, kurutma kinetiği, aktivasyon enerjisi

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INTRODUCTION

Banana is a fruit that rapidly deteriorating after harvesting. Therefore, preservation methods could be applied to conserve its quality and nutritional value over a longer period of time (Falade and Okocha, 2012). The common method for preservation of foods is air dying. The quality properties such as color, rehydration ratio and texture are usually lower when compared to original material (Ratti, 2001). With air drying method, drying time is usually longer, thus, food materials expose high amount of heat. To overcome this exposure, drying time should be reduced by using other techniques. Drying with microwave ovens is faster and more energy-efficient than hot-air drying methods because of the ability of microwave to produce energy from internal molecular friction.

Foam-mat drying is a drying method that liquid foods are whipped into foams which are more stable. This technique is an inexpensive and simple method and has several advantages such as shorter drying times and lower drying temperatures due to increased surface area to contact with air and obtain rehydratable porous material. Nutritional, quality and sensory properties of food products are also maintained by this method. Foam-mat drying was successfully applied to some fruits: banana (Noordia et al., 2020; Prakotmak et al., 2011; Sankat and Castaigne, 2004), mango (Guimaraes et al., 2017; Lobo et al., 2017), uvaia (Branco et al., 2016), guava (Maciel et al., 2017) and apple juice (Raharitsifa et al., 2006). Dried food materials can be consumed or added as ingredients in baked goods, yogurts, desserts, ice creams, smoothies etc. (Guimaraes et al., 2017).

In this study, it is aimed to determine drying kinetics of banana foam under microwave conditions due to the need of knowledge of drying behavior in design, construction and optimization of drying systems. In addition, foam-mat drying method was also used and assisted with microwave and mathematical modeling was made to identify the drying behavior of banana foams. This drying method can be called as microwave-assisted foam-mat drying.

MATERIALS AND METHODS

Foaming process

Fully ripened (yellow) but firm bananas of the Cavendish variety and fresh eggs which were obtained from local market used in the drying processes. Bananas were cut into small pieces and pureed by home type kitchen blender (Harmony 550, Fakir Hausgerate, Germany, power consumption: 550 W) for 1 min at maximum speed. Then, 200 g of puree was put into mixing bowl and fresh egg albumin, which is used as a foaming agent, was added at 5 % (weight/weight, w/w, on a wet puree basis). Banana foam was obtained by mixing with a home type mixer (Harmony 550, Fakir Hausgerate, Germany, power consumption: 550 W) for 3 min at maximum speed.

Drying procedure

The drying process was performed by a domestic microwave oven (GW73E, Samsung, South Korea) at power intensities of 100, 180, 300, 450 and 600W. The total amount of banana foam was 20.00±0.20g for each drying experiment. Samples were placed flat as a slab 11 cm (diameter) x 0.2 cm (thickness) so drying occurred from one side. Banana foam was removed periodically (30s intervals) from the microwave oven and weighed (Radwag PS 6000.R1, Polonya). All experiments were completed when the change in the mass of the samples dropped to 0.01 (g) between the two measurements.

Mathematical modeling of drying data

The moisture ratio (MR) was calculated as $(m_t-m_e)/(m_i-m_e)$ where m_t was the moisture content at the time t, m_i and m_e were the initial and equilibrium moisture content (g g^{-1} dry solid), respectively. Drying rate (R) was calculated as $(-L_s/A)*((X_{t+1}-X_t)/(t_{t+1}-t_t))$ where R was the drying rate (g m^{-2} s^{-1}); L_s was the weight of dry solid (g); A was the drying area (m^2); X_t was the moisture content at specific time (g g^{-1} dry solid) and t was time (s).

Six thin-layer drying models: Page (Togrul and Pehlivan, 2003; Vega-Galvez et al., 2010), Midilli and others (Midilli et al., 2002), Two-term, Silva and others (Onwude et al., 2016), Wang and Singh (Omolola et al., 2014; Vega-Galvez et al., 2010) and Peleg (da Silva et al., 2015) were used to fit the experimental data (Table 1).

Table 1. Thin-layer drying models

Model Name	Model	Reference
Page	$MR = \exp(-k \cdot t^n)$	Togrul and Pehlivan (2003); Vega-Galvez et al. (2010)
Midilli and others	$MR = a \cdot \exp(-k \cdot t^n) + b \cdot t$	Midilli et al. (2002)
Silva and others	$MR = \exp(-a \cdot t - b\sqrt{t})$	Onwude et al. (2016)
Wang and Singh	$MR = 1 + a \cdot t + b \cdot t^2$	Omolola et al. (2014); Vega-Galvez et al. (2010)
Two-term	$MR = a \cdot \exp(-k_1 \cdot t) + b \cdot \exp(-k_2 \cdot t)$	Onwude et al. (2016)
Peleg	$MR = 1 - t/(a + bt)$	da Silva et al. (2015)

k is the drying constant, a, b and n are the parameters.

Drying models were fitted to the experimental drying data and the equation parameters were determined using regression analysis by using SigmaPlot software (Systat Software Inc., USA). The goodness of fit of each model were evaluated according to the four criteria; correlation coefficient (R^2), the reduced chi-square (χ^2) (Eq. (1)), root mean square error (RMSE) (Eq. (2)) and residual sum of squares (RSS) (Eq. (3)) (McMinn, 2006):

$$\chi^2 = \frac{\sum_{i=1}^{N}(MR_{exp,i} - MR_{pred,i})^2}{N - n_p} \quad (1)$$

$$RMSE = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(MR_{exp,i} - MR_{pred,i})^2} \quad (2)$$

$$RSS = \sum_{i=1}^{N}(MR_{exp,i} - MR_{pred,i})^2 \quad (3)$$

where $MR_{exp,i}$ is the experimental moisture ratio; $MR_{pred,i}$ is the predicted moisture ratio; N is the number of experimental data points and n_p is the number of parameters in model.

Estimation of effective moisture diffusivities and activation energy

The effective moisture diffusivities were calculated by Eq. (4) with Fick's second law for long drying times and infinite slab geometry in one dimension. Assumptions were applied: volume change was negligible; temperature and diffusion coefficients were constant during drying and mass transfer formed in diffusion (Chayjan and Kaveh, 2014; Crank, 1975).

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

where D_{eff} is the diffusion coefficient ($m^2 s^{-1}$); t is the drying time (s) and L is the half thickness of sample (m).

The Arrhenius equation (Ea) was used in modified form to illustrate the relationship between the microwave power intensity with sample amount for estimation of the activation energy (Dadali et al., 2007). Where P is microwave output power (W) and m is the mass of raw sample (g) (Eq. (5)).

$$D_{eff} = D_0 \exp\left(-\frac{Ea\, m}{P}\right) \quad (5)$$

RESULTS AND DISCUSSIONS

Drying kinetics

To investigate the effects of microwave power intensity on moisture ratio, drying rate and drying time, five different microwave power intensity were used to dry banana foam. The drying curves were obtained by plotting the moisture ratio versus drying time shown on Figure 1. It can be seen that as the microwave power level was increased, the drying time of samples was reduced. Drying time was reduced 87.23 % when power intensity increased from 100 to 600W. The drying times and the average drying rates of banana foam were 1410, 720, 390, 240 and 180 s and 1.05, 2.10, 3.92, 6.54 and 8.69 g m^{-2} s^{-1} for 100, 180, 300, 450 and 600W, respectively. Consequently, heat and mass transfers of banana foam were getting faster with increasing power intensity due to the increasing water removal from sample. The drying rate curves of five microwave power intensities had similar trends as it can be seen in Figure 2 and 3. Drying rate was increased 727.62% when increasing power intensity from 100 to 600W. Similar findings were reported by several authors for other foods as foam-mat drying of guava pulp (Qadri and Srivastava, 2017), blue honeysuckle berry (Sun et al., 2020) and papaya (Qadri et al., 2020). The experimental results indicate that there was no constant rate period and drying of banana foam occurred only at falling rate period with internal liquid diffusion.

Effective moisture diffusivities were calculated by using slope method. Hence, the plot of natural logarithm of moisture ratio (lnMR) versus time (t) was drawn. The effective moisture diffusivities were found between 5.9536 x 10^{-9} and 3.5692 x 10^{-8} m^2 s^{-1} (Table 2.). These values are in agreement with the range of effective moisture diffusivity values of foods (Chayjan et al., 2015; Madamba et al., 1996). In the study of Prakotmak et al. (2010), verification was made for moisture diffusion coefficient in banana foam pores which it was in order of 10^{-9} m^2 s^{-1} after use of stochastic pore network in foam densities of 0.21 and 0.26 g cm^{-3}. An increase in microwave power intensity resulted in an increase in effective moisture diffusivity. Similar findings were reported by other authors for foam-mat drying of uvaia pulp (Branco et al., 2016), potato (Chakraborty et al., 2017), banana (Thuwapanichayanan et al., 2008) and cantaloupe (Salahi et al., 2015). The differences in the effective moisture values during drying differs from some factors including physicochemical properties, drying method and conditions, initial and final moisture contents.

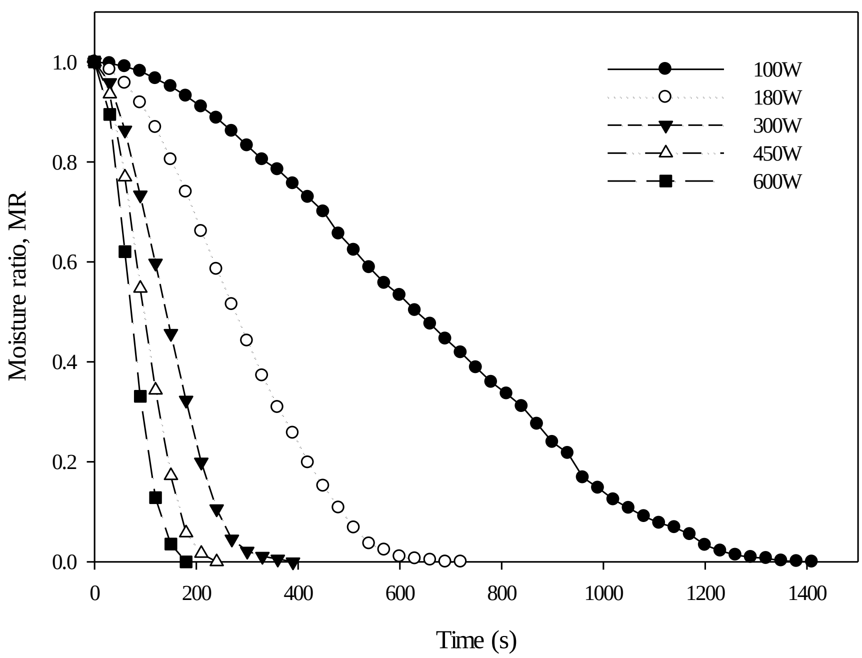

Figure 1. Drying curves of banana foam

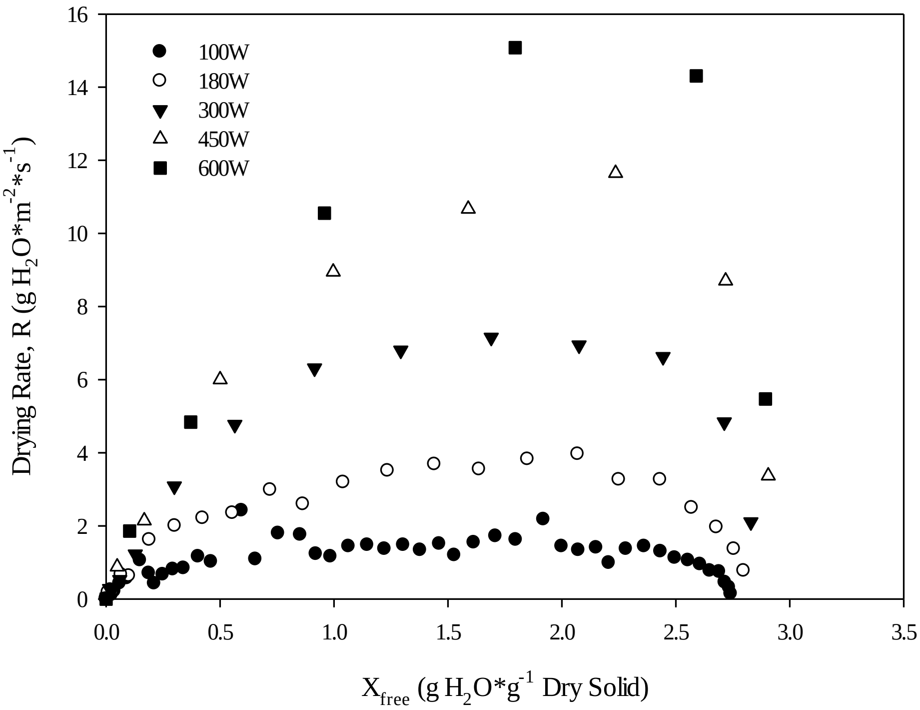

Figure 2. Drying rate of banana foam against free moisture content

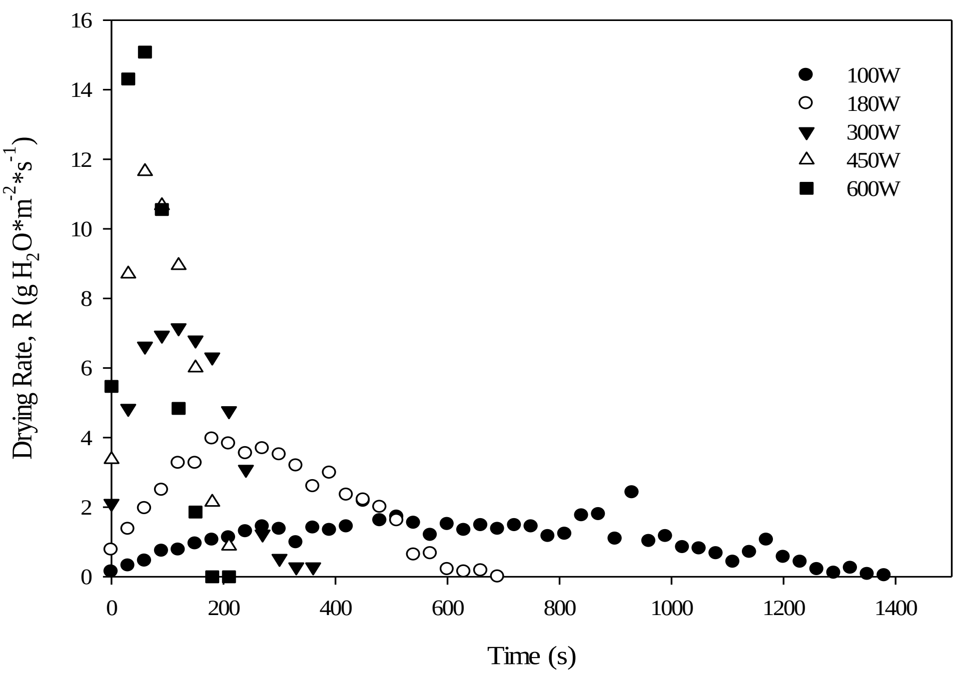

Figure 3. Drying rate of banana foam against time

Table 2. Effective moisture diffusivities and activation energy of banana-foam

Power intensity	Effective Diffusivity ($m^2\ s^{-1}$)	Activation Energy (E_a)
100 W	5.9536×10^{-9}	
180 W	1.2834×10^{-8}	
300 W	2.4044×10^{-8}	10.80 W/g
450 W	3.0566×10^{-8}	
600 W	3.5692×10^{-8}	

Activation energy is defined as the energy needed to begin the diffusion of moisture from the internal regions of the material. In this study, temperature of the drying could not be measured because it was a standard microwave oven used in the drying process. Therefore, the modified Arrhenius equation was used to estimate activation energy of banana foam which indicates the relation between microwave power intensity to sample amount. Ea value of foam-mat drying of banana was estimated as 10.80 W g^{-1} which was similar to value of microwave dried spinach (10.84 W g^{-1}) (Dadali et al., 2007), microwave dried purslane (Demirhan and Ozbek, 2010a) and basil (Demirhan and Ozbek, 2010b).

Model application

Six thin-layer drying models were applied to find the best fitted model to experimental data. The best model describing the thin layer drying characteristics of banana foam was chosen as the one with the highest correlation coefficient (R^2) and the lowest the reduced chi-square (χ^2), root mean square error (RMSE) and residual sum of squares (RSS). The model parameters of thin-layer models fitted to experimental data and statistical results are given in Table 3. R^2 values are generally higher than 0.90. The lowest R^2 values were obtained in two-term model. Both Page and Midilli and others' model might be selected to represent the thin layer drying behavior of banana foam. However, RMSE, RSS and χ^2 values of Midilli and others model were slightly lower than Page model. Therefore, Midilli and others model was chosen as best fitted model to represent the foam-mat drying behavior of banana. Midilli and others' model was also found as the best model to describe the oven drying of sliced lemons (Torki-Harchegani et al., 2016), eggplants (Ertekin and Yaldiz, 2004), microwave drying of purslane (Demirhan and Ozbek, 2010a) and microwave-convective drying of hawthorn fruit (Chayjan et al., 2015).

Table 3. Model parameters and statistical results

Model Name		Microwave Power Intensity				
		100W	180W	300 W	450 W	600W
Page	R^2	0.9963	0.9988	0.9989	0.9995	0.9999
	χ^2	0.0005	0.0002	0.0002	0.0001	0.0000
	RMSE	0.0214	0.0124	0.0122	0.0086	0.0035
	RSS	0.0219	0.0039	0.0021	0.0007	0.0001
	k	9.2954×10^{-7}	7.0134×10^{-6}	3.0432×10^{-5}	4.1952×10^{-5}	8.3319×10^{-5}
	n	2.1014	2.0495	2.0359	2.1269	2.1118
Two-term	R^2	0.9201	0.9295	0.9310	0.9181	0.9194
	χ^2	0.0107	0.0110	0.0131	0.0209	0.0274
	RMSE	0.0992	0.0962	0.0968	0.1078	0.1083
	RSS	0.4721	0.2315	0.1313	0.1046	0.0821
	a	0.6063	0.5991	0.5805	0.5688	0.5556
	b	0.6063	0.5991	0.5805	0.5688	0.5556
	k_1	1.6494×10^{-3}	3.7680×10^{-3}	7.2905×10^{-3}	0.0102	0.0134
	k_2	1.6494×10^{-3}	3.7680×10^{-3}	7.2905×10^{-3}	0.0102	0.0134

Midilli and others	R^2	0.9989	0.9995	0.9993	0.9998	1.0000
	χ^2	0.0002	0.0001	0.0001	0.0001	0.0000
	RMSE	0.0118	0.0079	0.0101	0.0057	0.0012
	RSS	0.0066	0.0016	0.0014	0.0003	0.0000
	a	0.9933	0.9913	0.9886	0.9968	1.0005
	k	1.9137×10^{-6}	7.8302×10^{-6}	2.7411×10^{-5}	4.7286×10^{-5}	9.2672×10^{-5}
	n	1.9695	2.0209	2.0492	2.0940	2.0842
	b	-5.1565×10^{-5}	-3.3373×10^{-5}	-3.0136×10^{-5}	-6.8832×10^{-5}	-4.9266×10^{-5}
Peleg	R^2	0.9785	0.9663	0.9608	0.9657	0.9659
	χ^2	0.0028	0.0048	0.0062	0.0062	0.0070
	RMSE	0.0515	0.0665	0.0730	0.0697	0.0705
	RSS	0.1272	0.1106	0.0747	0.0437	0.0348
	a	1274.6375	474.6016	219.9779	169.3259	124.0584
	b	-4.2122×10^{-3}	0.2377	0.3412	0.2142	0.2430
Silva and others	R^2	0.9602	0.9713	0.9777	0.9804	0.9885
	χ^2	0.0051	0.0041	0.0035	0.0036	0.0024
	RMSE	0.0700	0.0614	0.0551	0.0527	0.0410
	RSS	0.2353	0.0942	0.0425	0.0250	0.0118
	a	2.6685×10^{-3}	6.2362×10^{-3}	0.0127	0.0196	0.0279
	b	-0.0341	-0.0539	-0.0797	-0.1086	-0.1405
Wang and Singh	R^2	0.9785	0.9697	0.9690	0.9682	0.9690
	χ^2	0.0028	0.0043	0.0049	0.0058	0.0063
	RMSE	0.0515	0.0631	0.0649	0.0671	0.0672
	RSS	0.1272	0.0995	0.0590	0.0406	0.0316
	a	-7.8402×10^{-4}	-2.1186×10^{-3}	-4.4538×10^{-3}	-5.9709×10^{-3}	-8.1131×10^{-3}
	b	-3.0868×10^{-9}	8.3941×10^{-7}	4.4259×10^{-6}	6.3050×10^{-6}	1.2523×10^{-5}

CONCLUSIONS

Banana foam was obtained by using 5 % of fresh egg albumin and dried under microwave conditions at power intensities of 100, 180, 300, 450 and 600 W. Six thin-layer models were applied and Midilli and others' model was found with a good fit to the experimental data with a high value of correlation coefficient and low values of residual sum of squares, reduced chi-square and root mean square error. In addition, the effective moisture diffusivity and activation energy values (10.80 W/g) were determined for microwave foam-mat drying of banana. Calculated values were similar to those in the literature. Further studies may be carried out to identify the drying behavior of banana foam using microwave-assisted convective drying or the effects of pretreatment during preparation of banana puree may be investigated.

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