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THE EFFECT OF DIFFERENT MICROWAVE POWERS ON THE DRYING KINETICS AND POWDER PROPERTIES OF FOAM-MAT DRIED EGG WHITE POWDER

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ABSTRACT

The aim of this study is to determine the effect of different microwave powers on the drying kinetics and powder properties of foam mat dried egg white powder. For this purpose, the egg white foam was obtained by using kitchen blender (1000W, 5min) and dried in a domestic microwave oven at five different microwave powers (120-720W). According to the results, the drying time decreased from 360s to 80s according to increasing microwave power (P <0.05). In order to determine the drying kinetic of egg white foam, the experimental data was fitted to various semitheoretical models and one empirical model. Page model which showed the highest R^2 values (0.983-0.994) was chosen as the most suitable model for determining the drying behavior of egg white foam. In addition, the average effective moisture diffusivity and activation energy values were calculated and ranged between 3.3389E-08 to 1.4139E-07 m^2/s and 28.0640 W/g, respectively.
Keywords: Egg white, foam mat drying, drying kinetic, thin-layer modeling, powder properties

FARKLI MİKRODALGA GÜÇLERİNİN KÖPÜK KURUTMA YÖNTEMİ İLE KURUTULMUŞ YUMURTA BEYAZI TOZLARININ KURUMA KİNETİĞİ VE TOZ ÜRÜN ÖZELLİKLERİ ÜZERİNE ETKİSİ

ÖZ

Bu çalışmanın amacı, farklı mikrodalga güçlerinin köpük kurutma yöntemi ile kurutulmuş yumurta beyazı köpüğünün kuruma kinetiği ve toz özellikleri üzerine etkisinin belirlenmesidir. Bu amaç doğrultusuna, yumurta beyazı köpüğü blender kullanılarak (100W, 5dk.) elde edilmiş ve mikrodalga fırında beş farklı mikrodalga gücünde (120-720W) kurutulmuştur. Artan mikrodalga gücü ile kuruma süresi 360s'den 80s'ye azalmıştır (P <0.05). Yumurta beyazı tozunun kuruma kinetiğini belirlemek için, deneysel veriler çeşitli yarı teorik modeller ve bir empirik model kullanılarak modellenmiştir. Yüksek R^2 değeriyle (0.983-0.994) Page model yumurta beyazı köpüğünün kuruma davranışının belirlenmesi için en uygun model olarak seçilmiştir. Ayrıca, ortalama etkin nem difüzyon katsayısı ve ortalama aktivasyon enerjisi hesaplanmış ve sırasıyla 3.3389E-08- 1.4139E-07 m^2/s ve 28.0640 W/g olarak bulunmuştur.
Anahtar kelimeler: Yumurta beyazı, köpük kurutma, kuruma kinetiği, ince tabaka modelleme, toz özellikler

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INTRODUCTION

Foam mat drying is a process in which liquids or semi-liquid/solid foods are transformed into stable foam by using foaming agent and stabilizer and to subsequently be dried (oven, tray dryer, microwave dryer, freeze dryer etc.) under thin-layer conditions (Abbasi and Azizpour, 2016; Venkatachalam et al., 2014; Rajkumar et al., 2007). The drying rate of foam mat drying is comparatively high compared to other drying techniques due to an enormous increase in the liquid-gas interface, in spite of the fact that the heat transfer is impeded by a large volume of gas present in the foamed mass (Sharada, 2013). A high-quality food powder can be obtained by the proper selection of the foaming method, agent, stabilizers, and time and also selected drying method and temperature (Venkatachalam et al., 2014). The advantages of foam mat drying process compared to the other drying techniques are suitability for all types of liquids, rapid drying at a lower drying temperature, high retention of nutritional value, easy reconstitution, and being cost-effective (Kudra and Ratti, 2006).

Egg white (albumen) powder which is rich in protein commonly used as a food ingredient especially in the bakery industry for its foaming and gelling properties (Muthukumaran et al. 2008a). Egg white contains 56% of whole egg's total proteins (Ovalbumin, Ovotransferrin, Ovomucoid, Ovomucin, Lysozyme, G2 and G3 globulin, avidin) along with the majority of the minerals such as chlorine, magnesium, potassium, sodium, and sulfur (Solval, 2011). Egg white powder was used as a foaming agent and stabilizer at several studies such as foam mat freeze-drying of apple juice (Raharitsifa and Ratti 2010), foam mat convective drying of cantaloupe (Salahi et al., 2015) etc.. In addition, the egg white powder can be used as an encapsulating agent in the food industry (Solval, 2011).

There are several studies on the drying of egg white by using different drying techniques such as spray drying (Ayadi et al. 2008; Ma et al., 2013), pulse-spouted bed microwave freeze drying (Wang et al., 2013), and foam mat freeze drying (Muthukumaran et al., 2008a and b). However, from the authors' knowledge, there is a paucity of literature investigating the effect of foam mat microwave oven drying technique on the drying behavior, drying rate, effective moisture diffusivity, and powder properties of foam mat dried egg white powder. Foam mat microwave drying method is one of the promising methods which combines the advantages of microwave and foam mat drying such as short drying time, higher drying rate, effective moisture diffusivity, surface area, and higher quality of the end product etc. (Alibas, 2006; Kudra and Ratti, 2006; Mathukumaran et al., 2008b). For this reason, the aim of this study was to determine the effect of different microwave powers on the drying kinetics and powder properties of the foam mat dried egg white powder.

MATERIAL AND METHODS

Material

The commercial pasteurized liquid egg whites (15.0±0.0°Brix, 9.3±0.2 pH, foam capacity 1066.0±0.0, *Salmonella* absent in 25 g, *Staph. Aureus*. <100 CFU/ml, Enterobacteriaceae <10 CFU/ml) were obtained from Anako Yumurta ve Ürünleri Gıda San. İhr. İth. ve Tic. A.Ş., Ankara, Turkey. Egg whites were kept under refrigeration (4°C) conditions until the next step of the experiment.

Foam Preparation

In order to obtain egg white foam, the method described by Mathukumaran et al. (2008a and 2008b) was used. Before the foaming process, the egg white was removed from the refrigerator and kept outside until reaching room temperature (+24±2°C). Fifty milliliters of egg white was added to the glass beaker (500ml) to make the egg white foam. A kitchen blender (1000W power, SHB 3107, Sinbo, Turkey) was used to make foam and three different whipping periods as 1.5, 3, and 5min were used. According to visual inspection, the most stable foam was chosen as the foam which was whipped for 5 min.

Microwave Drying

The egg white foams were dried in a domestic microwave oven (Arçelik MD574, Turkey) at 5 different microwave power (120W, 350W, 460W, 600W, and 720W). The egg white foam of approximately 6.00±0.20g was placed in a glass dish (10.8cm diameter, 2mm side thickness) which was put on the rotating glass of microwave. The thickness of egg white foam was measured by using the caliper. Samples were removed periodically (at 10s intervals) from the microwave oven and weighed. The experiments were completed when the change in the mass of the samples dropped to 0.01 (g) between the two measurements. The drying processes were repeated two times under the same conditions and the average value of the results was taken into consideration for calculations. The egg white foam powder was obtained by grinding the dried material (flakes) with a mortar and packaged in aluminum polythene bags for further analysis.

Mathematical modeling of drying curves and calculations of drying rate

The dried mass of the egg white was determined after drying in the vacuum oven (Nuve Laboratory and Sterilization Tech, EV018, Turkey) at 70±5°C in order to calculate the moisture content (AOAC, 2000). The moisture ratio (MR) of egg white foam during microwave oven drying was calculated using the Eq. (1);

$$MR=\frac{M_t-M_e}{M_0-M_e} \quad (1)$$

Where M_t, M_0, and M_e are the moisture content at any time, initial, and equilibrium moisture contents (kg water (H_2O)/ kg dry matter (DM)), respectively.

Drying curves were fitted to seven well-known semi theoretical thin layer drying models (Lewis ($MR=exp(-kt)$), Page ($MR=exp(-kt^n)$), Henderson and Pabis ($MR=a*exp(-kt)$), Logarithmic ($MR=a*exp(-kt)+c$), Two-Term ($MR=a*exp(-k_0t)+b*exp(-k_1t)$), Two-Term Exponential ($MR=a*exp(-kt)+(1-a)*exp(-kat)$), and Approximate Diffusion models ($MR=a*exp(-kt)+(1-a)*exp(-kbt)$)) and one empirical model (Wang and Singh ($MR=1+at+bt^2$)) (Onwude et al., 2016). Nonlinear regression analysis was used to evaluate the parameters of the selected model by using statistical software SPSS 16.0 (SPSS Inc., Chicago, IL, U.S.A). The goodness of fit was determined using the coefficient of correlation (R^2) that can be described by the equations given by Erbay and Icier (2009).

The assumptions for thin-layer drying models which were also reported by Erbay and Icier (2009) are;

-Moisture was initially uniformly distributed throughout the mass of the product.

-The surface moisture content of the sample instantaneously reached equilibrium with the condition of the surroundings.

-Resistance to mass transfer at the liquid-gas interface was negligible.

-The product characteristics (diffusion coefficient etc.) were constant and the shrinkage was negligible.

Drying rate was defined as:

$$Drying\ Rate\ (DR)=\frac{\Delta X}{\Delta t * S} \quad (2)$$

where X is moisture content (kg H_2O/kg DM), t is the time (s), S is the total surface area of all egg white foam in one container (m^2) and DR is the drying rate (kg H_2O/kg DM.s.m^2) (Tekin and Baslar, 2018).

Calculation of Effective Moisture Diffusivity and Activation Energy

The effective moisture diffusivity (D_{eff}) values of egg white foams were calculated by Fick's diffusion model as given in (Eq. 3).

$$MR=\frac{M_t-M_e}{M_0-M_e}=\frac{8}{\pi^2}\sum_{n=1}^{\infty}\frac{1}{(2n-1)^2}exp\left[-(2n-1)^2\pi^2\frac{D_{eff}}{4L^2}t\right] \quad (3)$$

Where t is the time (s), D_{eff} is the effective moisture diffusivity (m^2/s) and L (m) is the thickness of samples. For sufficiently long drying times (n=1) (Crank, 1975), the change in MR value becomes linear, a limiting case of Eq. (3) is obtained, that allows the calculation of D_{eff} value from the slope of the natural logarithm of MR versus drying time curve by using the only first terms (n = 1) of Eq. (4)

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

D_{eff} is typically calculated by plotting experimental MR in logarithmic form versus drying time. From the Eq. (3), a plot of lnMR versus drying time gives a straight line with a slope of (Eq. 5):

$$\text{Slope}=\frac{\pi^2 D_{eff}}{4L^2} \quad (5)$$

The relation between D_{eff} and microwave power is assumed to be an Arrhenius function (Eq. 6) (Dadali et al., 2007).

$$D_{eff} = D_0 exp\left(-E_a \frac{m}{P}\right) \quad (6)$$

where D_{eff} is the effective moisture diffusivity (m^2/s), D_0 is the pre-exponential factor (m^2/s), E_a is the activation energy (W/g), P is the microwave power (W) and m is the mass of the sample (g).

Powder Properties

For the determination of bulk density, the modified procedure described by Jinapong et al. (2008) was used. For this purpose, one gram (m) of egg white powder was loaded into a 10 ml graduated cylinder. The directly measured volume (V_1) was used to calculate the bulk density (ϱ_{bulk}) according to the ratio of mass to volume. The tapped density (ϱ_{tapped}) was calculated after tapping the cylinder on a soft surface for 80 times (V_2). Flowability and cohesiveness values of the powders were calculated by using the relationship between the bulk and tapped densities and evaluated in terms of Carr index (CI) and Hausner ratio (HR), respectively (Jinapong et al., 2008). The wettability times of powders were determined by measuring the time for completely wetting 1 g of sample placed around a beaker of 100 ml containing 10 ml of distilled water at room temperature (Goula and Adamopoulos, 2008).

Statistical Analysis

The data was analyzed using statistical software SPSS 16.0 (analysis of variance (ANOVA), (α = 0.05), SPSS Inc., Chicago, IL, U.S.A.). All drying experiments were replicated and all analyses were triplicated.

RESULTS AND DISCUSSION

The drying behavior of egg white foam was determined from the mass loss in the samples of the known initial moisture content of 87.8 ± 0.05% (wet basis, wb). The result was consistent with the result of Mathukumaran et al. (2008b, 88% wb). The drying time of the egg white foam ranged between 80s and 360s and an increase in the microwave power resulted in a significant decrease in the drying time except for 600W microwave power (P <0.05). This situation may be due to higher water evaporation rate at the high microwave power which causes higher generation in the sample (higher vapor pressure differences between the center and surface of the product) (Moradi et al., 2013). The drying time of foam mat freeze-drying (25g sample, -40ºC condenser temperature, +20ºC heating plate temperature) of egg white foam was found to be as 20-24h by Mathukumaran et al. (2008b). By using microwave drying technique, the drying time of egg white foam could be significantly decreased compared to the freeze-drying technique. In addition to the selected drying methods, equipment, drying conditions, amount, thickness, moisture content, and foam structure and stability of egg white foam may cause different drying times.

The drying behavior of egg white foam was described by using seven well-known semitheoretical thin layer drying models and one empirical model. The model parameters and correlation coefficients (R^2) are given in Table 1. The highest coefficient of correlation was one of the primary criteria for selecting the best model to define the drying behavior of egg white foam (Erbay and Icier, 2009). Drying behavior of egg white foam can be adequately described by the selected models due to higher R^2 values of models which were found to be higher than 0.800. However, Page model which showed the highest R^2 value was chosen as the most suitable model for determining the drying behavior of egg white foam. In addition, Arabhosseini et al. (2009) reported that fewer numbers of the model parameters are preferable to find a relationship between the parameter and the drying conditions which are valid for Page model. Several researchers reported that Page model was chosen to determine the microwave drying behavior of corn husk (Akdoğan et al., 2017), onion (Demiray et al., 2017), spinach (Ozkan et al., 2007), and apple pomace (Wang et al., 2007). The calculated drying rate constant (k) of Page equation (1/s) significantly increased according to the increasing microwave power from 120W to 350W (P <0.05), however, further increase did not cause a significant change in the k values ($P > 0.05$). According to the drying rate constant, it can be said that the higher moisture removal rate and drying rate occurred during drying experiments which performed in the 350-720W microwave powers.

Table 1. The model parameters, and statistical results (R^2) (n=3)

	MODELS	MODEL PARAMETERS							R^2
		a	b	c	k (s^{-1})	k_0	k_1	n	
120	Newton	-	-	-	0.050±0.000	-	-	-	0.848±0.040
	Page	-	-	-	1.629E-005±0.00	-	-	2.710±0.002	0.994±0.005
	Henderson and Pabis	1.166±0.022	-	-	0.006±0.000	-	-	-	0.880±0.044
	Logarithmic	5.808±1.584	-	-4.761±1.566	0.001±0.000	-	-	-	0.950±0.051
	Two-Term	0.584±0.011	0.582±0.011	-	-	0.006±0.000	0.006±0.000	-	0.880±0.044
	Two-Term Exponential	0.000±0.000	-	-	20.369±1.359	-	-	-	0.848±0.036
	Approximation of Diffusion	-92.449±12.75	0.987±0.001	-	0.012±0.00	-	-	-	0.932±0.054
	Wang and Singh	-0.003±0.000	5.26E-007±0.000	-	-	-	-	-	0.975±0.014
350	Newton	-	-	-	0.018±0.001	-	-	-	0.885±0.006
	Page	-	-	-	0.001	-	-	1.705±0.003	0.990±0.006
	Henderson and Pabis	1.127±0.016	-	-	0.020±	-	-	-	0.904±0.001
	Logarithmic	2.320±0.435	-	1.271±0.425	0.006±0.002	-	-	-	0.969±0.005
	Two-Term	0.563±0.080	0.565±0.084	-	-	0.020±0.001	0.020±0.001	-	0.904±0.002
	Two-Term Exponential	0.000±0.000	-	-	59.037±4.790	-	-	-	0.885±0.006
	Approximation of Diffusion	-116.597±5.484	0.990±0.000	-	0.042±0.001	-	-	-	0.965±0.004
	Wang and Singh	-0.012±0.002	2.226E-005±0.179E-005	-	-	-	-	-	0.967±0.003
460	Newton	-	-	-	0.022±0.001	-	-	-	0.872±0.015
	Page	-	-	-	0.001	-	-	1.904±0.003	0.983±0.011
	Henderson and Pabis	1.134±0.009	-	-	0.025±0.002	-	-	-	0.895±0.117
	Logarithmic	2.752±0.723	-	1.696±0.723	0.007±0.002	-	-	-	0.978±0.011
	Two-Term	0.557±0.007	0.577±0.006	-	-	0.025±0.002	0.025±0.002	-	0.895±0.012
	Two-Term Exponential	0.000±0.000	-	-	87.906±3.256	-	-	-	0.872±0.015
	Approximation of Diffusion	-120.911±15.597	0.989±0.01	-	0.054±0.002	-	-	-	0.966±0.003
	Wang and Singh	-0.014±0.001	2.478E-005±0.608E-005	-	-	-	-	-	0.968±0.002
600	Newton	-	-	-	0.029±0.002	-	-	-	0.894±0.007
	Page	-	-	-	0.001	-	-	2.076±0.005	0.993±0.007
	Henderson and Pabis	1.117±0.009	-	-	0.032±0.002	-	-	-	0.911±0.005
	Logarithmic	2.175±0.285	-	1.119±0.290	0.010±0.002	-	-	-	0.973±0.004
	Two-Term	0.559±0.005	0.559±0.005	-	-	0.032±0.002	0.032±0.002	-	0.914±0.001
	Two-Term Exponential	0.000±0.000	-	-	101.527±4.974	-	-	-	0.894±0.007
	Approximation of Diffusion	-127.542±9.155	0.990±0.001	-	0.068±0.003	-	-	-	0.977±0.002
	Wang and Singh	-0.018±0.001	5.551E-005±1.348E-005	-	-	-	-	-	0.971±0.004
720	Newton	-	-	-	0.030±0.000	-	-	-	0.894±0.002
	Page	-	-	-	0.001	-	-	2.000±0.001	0.990±0.01
	Henderson and Pabis	1.126±0.001	-	-	0.033±0.001	-	-	-	0.912±0.002
	Logarithmic	1.662±0.044	-	0.599±0.039	0.015±0.001	-	-	-	0.963±0.001
	Two-Term	0.555±0.013	0.571±0.014	-	-	0.033±0.001	0.033±0.001	-	0.912±0.001
	Two-Term Exponential	0.000±0.000	-	-	100.540±4.487	-	-	-	0.893±0.002
	Approximation of Diffusion	-123.099±3.284	0.989±0.000	-	0.073±0.001	-	-	-	0.979±0.001
	Wang and Singh	-0.021±0.001	8.999E-005±0.490E-005	-	-	-	-	-	0.962±0.000

The change in the experimental (MR_{exp}) and predicted ($MR_{pre,}$ Page Model) moisture ratio values of egg white foam versus drying time results are shown in Figure 1. The curves of egg white foam showed an exponential tendency and it was also observed that the drying kinetic of egg foam at 120W microwave power had a different trend compared to other microwave powers. The drying kinetics of egg white foam at 350-720W microwave powers showed a similar trend. As expected, the moisture removal rate was high during the initial stage of drying and then slowed down due to a reduced moisture content of the egg white foam. Mathukumaran et al. (2008b) reported that the moisture removal rate of egg white foam during foam mat freeze-drying was higher during the initial stage of drying due to the higher surface area of egg white foam which helped in faster removal of moisture from the sample. In addition, the higher moisture content of the egg white foam may be the reason of higher moisture rate at the initial stages of the drying.

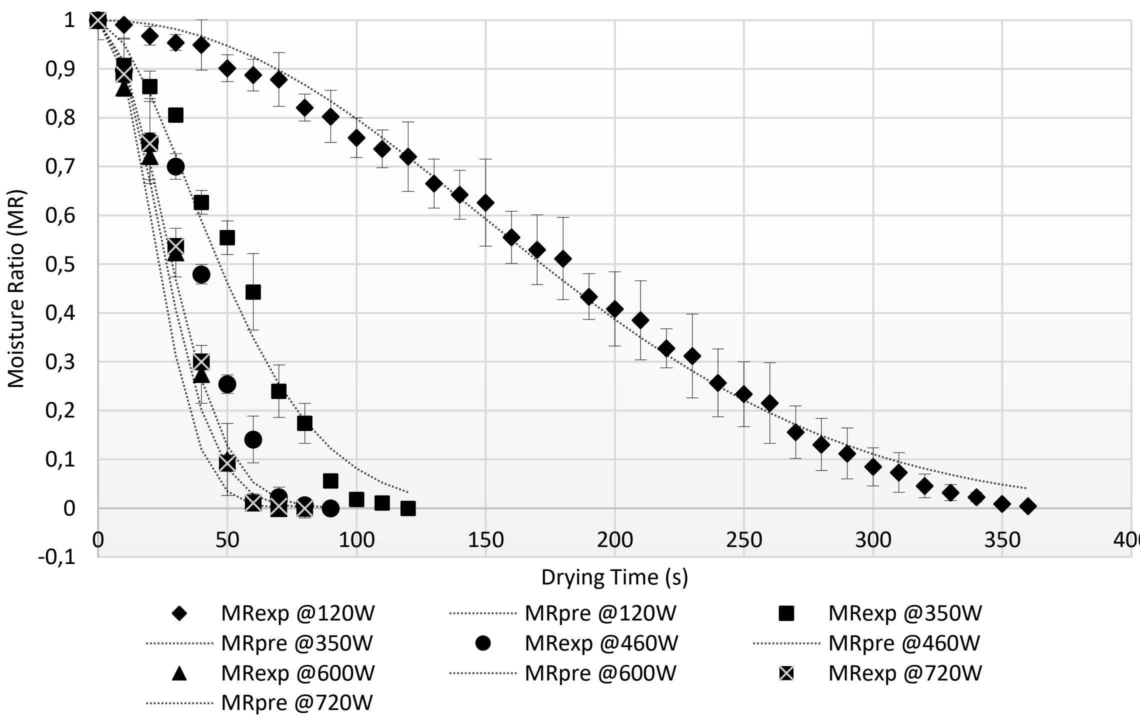

Figure 1. The experimental and predicted moisture ratio values of egg white foam during microwave drying.

The drying rates of egg white foam were calculated (kg H_2O /kg DM.s.m^2) and plotted against the free moisture content (X_f, kg H_2O /kg DM) as shown in Figure 2. The drying rate accelerated with an increase in the microwave power and the highest values of drying rate were obtained during the drying experiment at 720W microwave power. Marzec et al. (2010) reported that higher microwave powers resulted in a higher evaporation rate which is related to the drying rate. In the microwave drying, the water molecules directly absorb and transmit the energy which resulted in homogeneous heat generation and fast boiling of water (Baysal et al., 2003). As a result, at the higher microwave power, the higher drying rate of egg white foam was observed due to higher heat generation and faster evaporating rate of water. As the drying progressed, the lower moisture content of egg white foam resulted in a decrease in the absorption of microwave power and drying rate. Similar results were also obtained by Moradi et al. (2013). According to Figure 2, it can be stated that although the initial moisture contents of the egg white foam were high, the overall drying process takes place in the falling rate periods for all drying experiments except for 120W microwave drying experiments.

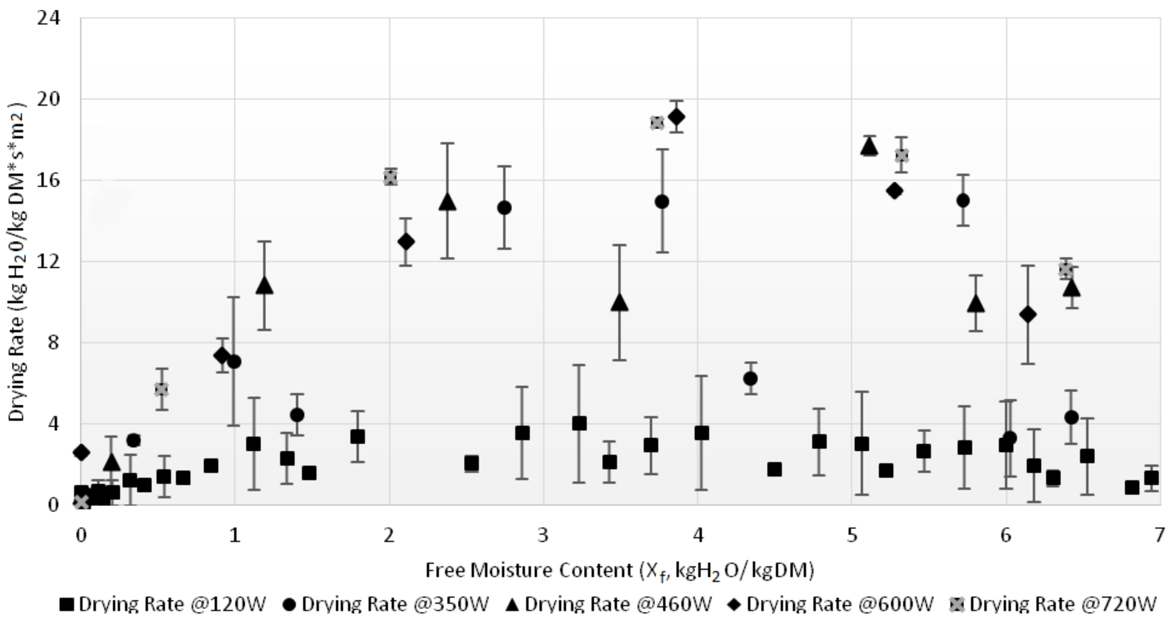

Figure 2. The drying rate (kg H_2O/kg DM*s*m²) of egg white foam

The effective moisture diffusivity values were calculated by plotting the natural logarithm of moisture rate data versus drying time for egg white foam (Figure 3). According to Figure 3, it can be stated that two different kinetics were observed for egg white foam. For this reason, two different D_{eff} values were calculated for all drying experiments and results are given in Table 2. It may be due to the changes in the structure of the egg foam. At the initial stages of the drying experiments, the foam volume and surface area increased due to the porous structure of foam, however, then the volume and surface area of foam decreased. In order to calculate D_{eff} values, it was assumed that the moisture diffusion coefficient is the same in all directions (isotropic material) and shrinkage of the sample is negligible. Similar results were also obtained by Mathukumaran et al. (2008b). Mathukumaran et al. (2008b) reported that the increase in the effective moisture diffusivity values as the drying progress can be attributed to the foaming of egg white. In addition, as drying continues, the development of porous structure reduces the resistance to mass transfer. According to Table 2, it can be stated that the development of porous structure resulted in higher effective moisture diffusivity values (the 2nd D_{eff} values were found to be higher than 1st one). Mathukumaran et al. (2008b) also reported that the egg white foam with 0.125% xanthan gum had three diffusion coefficients (2.677 E-08, 5.962E-08, and 1.247 E-07 m²/s (Average=7.036E-08 m²/s)) where the egg white foam without xanthan gum had only two diffusion coefficients (2.413E-08 and 3.781 E-08 m²/s (Average=3.097E-08 m²/s)). The D_{eff} values of egg white foam were found to be in the same range of the results of Mathukumaran et al. (2008b). In addition, the average D_{eff} values were calculated and as expected, the average D_{eff} values of egg white foam increased with increasing microwave power due to higher moisture removal and drying rate. Demiray et al. (2017) reported that the D_{eff} value and drying rate have a directly proportional relationship. Similar to drying rate values, the higher D_{eff} values were observed for 900W microwave power. In addition, Sadeghi et al. (2013) reported that microwave energy causes rotating bipolar molecules with high frequency into the product. The generated heat inside the product due to the existence of the friction against the bipolar rotation causes moisture to be diffused outside. Because of the high moisture content of the product, employing microwave power during drying considerably improves moisture diffusion.

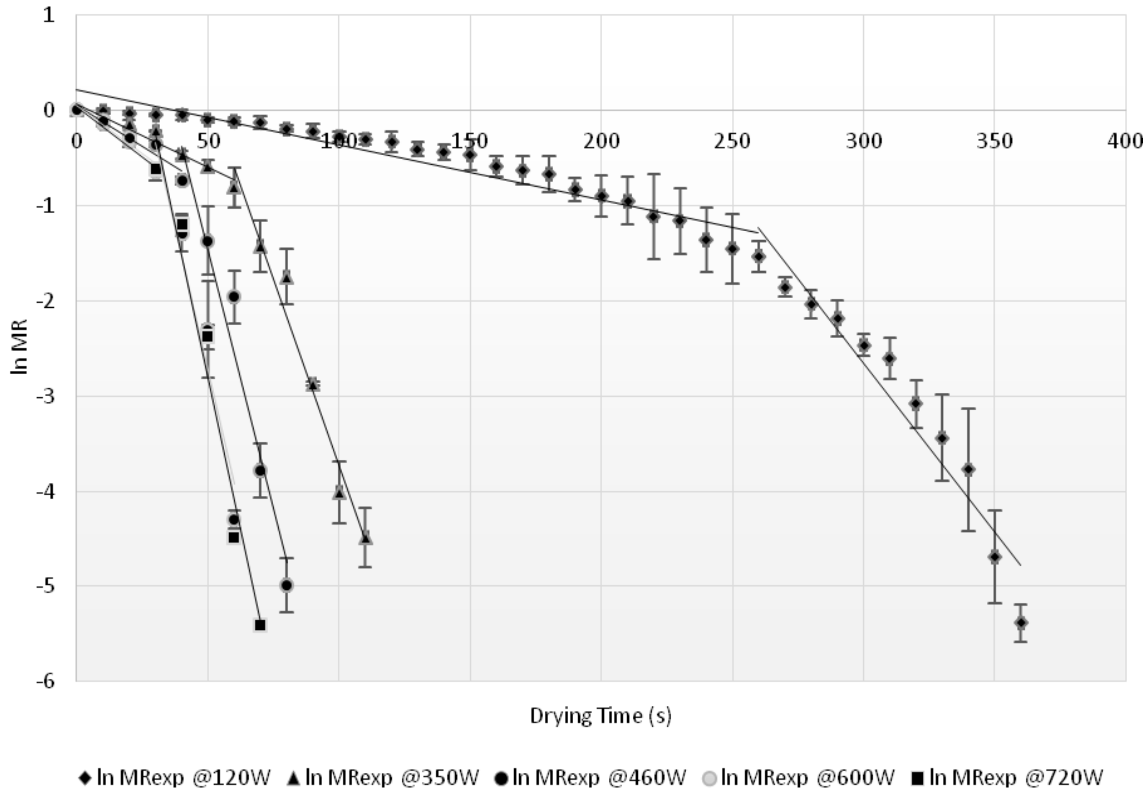

Figure 3. Plots of the natural logarithm of MR (lnMR) against drying time (s) for different microwave powers

Table 2. The effective moisture diffusivity (D_{eff}) (n=3)

Microwave Power (W)	MR	Equation	R^2	Effective Moisture Diffusivity (m^2/s)	Average Effective Moisture Diffusivity (m^2/s)
120	MR≥0.157±0.08[a]	y = -0.0065x + 0.2330	0.8341±0.1281	1.0467E-08±1.4917E-09[a]	3.3389E-08
	MR≤0.157±0.08[a]	y = -0.0347x + 7.2690	0.9557±0.0377	5.6311E-08±1.6065E-09[c]	
350	MR≥0.386±0.08[c]	y = -0.0150x + 0.0740	0.9166±0.0415	2.4342E-08±3.4424E-09[a]	8.5602E-08
	MR≤0.386±0.08[c]	y = -0.0905x + 4.7963	0.9580±0.0036	1.4686E-07±9.6388E-09[d]	
460	MR≥0.494±0.02[d]	y = -0.0164x + 0.0574	0.8903±0.0486	2.6614E-08±1.8360E-09[a]	9.5501E-08
	MR≤0.494±0.02[d]	y = -0.1013x + 3.7585	0.9404±0.0191	1.6439E-07±1.8130E-08[d]	
600	MR≥0.559±0.05[e]	y = -0.0190x + 0.0347	0.9556±0.0146	3.0833E-08±5.0489E-09[ab]	1.1842E-07
	MR≤0.559±0.05[e]	y = -0.1270x + 3.7266	0.9096±0.0405	2.0601E-07±1.6868E-08[e]	
720	MR≥0.289±0.02[b]	y = -0.0301x + 0.1428	0.9044±0.0022	4.8765E-08±2.1802E-09[b]	1.4139E-07
	MR≤0.289±0.02[b]	y = -0.1442x + 4.5563	0.9854±0.0102	2.3401E-07±6.4259E-09[f]	

[a-f] show the significant differences between the samples (*P* <0.05)

The activation energy (E_a) is related to the required energy to facilitate moisture diffusion. Lower E_a values indicate that the lower energy is necessary for moisture diffusion (Tekin and Başlar, 2018). Plots of the natural logarithm of D_{eff} values (ln D_{eff}) against m/P for different microwave powers are shown in Figure 4. The pre-exponential factor and activation energy values were calculated to be as (by using first D_{eff} values) 4.5983E-08m²/s and 30.496W/g, (by using second D_{eff} values), 2.7459E-07m²/s and 32.187W/g, and (by using average D_{eff}) to be as 1.3635E-07m²/s and 28.064W/g, respectively. According to results, it can be stated that the D_{0-1} and E_{a-1} values which were calculated by using 1st D_{eff} values were found to be lower than the D_{0-2} and E_{a-2} values which were calculated by using 2nd D_{eff} values. In addition, the E_a value which was calculated by using average D_{eff} values was found to be lower than both E_{a-1} and E_{a-2} values.

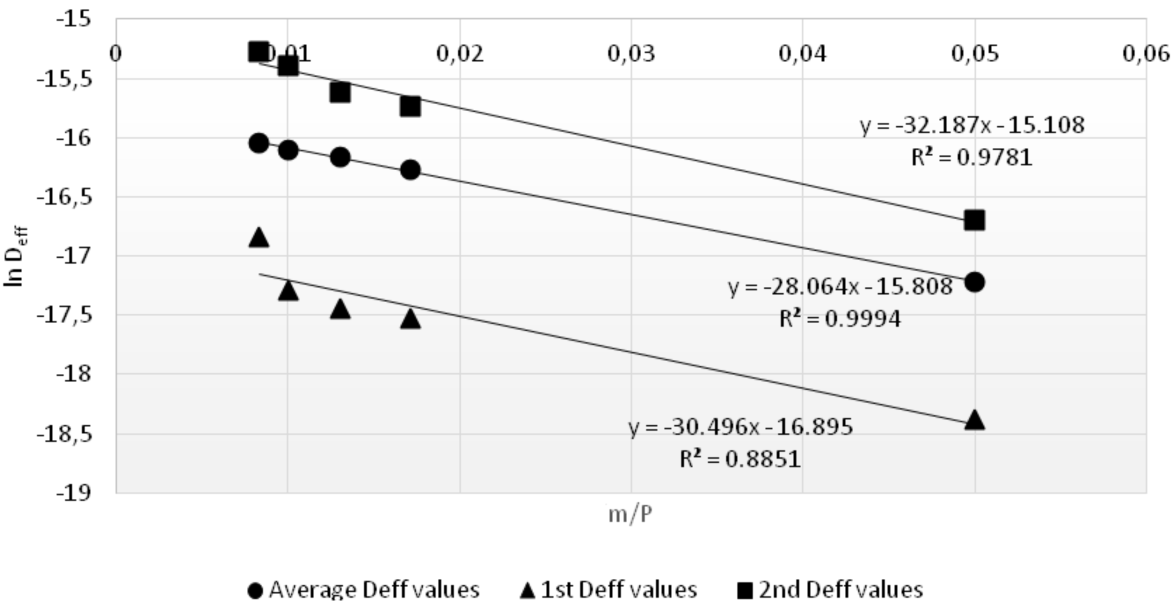

Figure 4. Plots of the natural logarithm of D_{eff} values (ln D_{eff}) against m/P for different microwave powers

Powder properties of egg white powder

The powder properties of egg white powder are given in Table 3. The bulk and tapped density values of egg white powder ranged between 282.33 and 331.35kg/m³ and 416.68 and 514.58 kg/m³, respectively. The bulk density values of egg white powder insignificantly decreased when the microwave power increased from 120W to 350W (*P* >0.05), however, the further increase (350W to 460W) resulted in a significant decrease (*P* <0.05). Beyond 460W microwave power, the bulk density values of egg white powders increased, however, this increase was not found to be significant (*P* >0.05). Similarly, the tapped density values of the samples decreased up to 460W microwave power (*P* <0.05). Lower Carr index reflects better flowability whereas high Hausner ratio shows that the powder is more cohesive and less capable of flowing freely. The egg white powder showed fair flow characteristic and high cohesiveness. In order to improve the flow properties of egg white powder, several food-grade additives such as drying agent and foam stabilizer which improve the flow properties can be added or agglomeration process can be applied to the obtained powders. Opposite to the bulk and tapped density values, the wettability times of the powders firstly increased (120W to 460W, *P*<0.05), however further increase resulted in a decrease in the wettability times of powders (460W to 600W, *P* <0.05).

Table 3. The effect of different microwave powers on the powder properties of the egg white powder (n=3)

Microwave Power (W)	Bulk Density (kg/m^3)	Tapped Density (kg/m^3)	Flowability (Carr Index, CI)	Cohesiveness (Hausner Ratio, HR)	Wettability (s)
120	313.11±16.02^{bc}	495.22±29.82^{cd}	36.74±1.00^{b}	1.58±0.03^{b}	1215.00±0.00^{b}
350	301.86±16.16^{b}	462.45±23.72^{b}	34.61±4.72^{ab}	1.54±0.11^{ab}	1411.80±13.86^{c}
460	282.33±8.59^{a}	416.68±25.46^{a}	32.04±4.91^{ab}	1.48±0.11^{ab}	1721.50±2.12^{d}
600	324.75±9.43^{c}	514.58±20.40^{d}	36.83±2.60^{b}	1.59±0.07^{b}	1034.00±0.00^{a}
720	331.35±6.39^{c}	492.56±6.37^{cd}	32.72±1.45^{ab}	1.49±0.03^{ab}	1042.00±10.11^{a}

$^{a-d}$ show the significant differences between the samples ($P < 0.05$)

CONCLUSION

In this study, it was observed that foam mat-microwave drying is a suitable process to obtain egg white powder. The obtained powder can be used as an encapsulating agent in the drying studies and as a food ingredient, especially in the bakery industry due to its foaming and gelling properties. The moisture removal rate, drying rate, and effective moisture diffusivity values increased with an increase in the microwave power, however, the opposite effect was observed for drying time. Page model (R^2 value>0.983) was chosen as the most suitable model for determining the drying behavior of egg white foam. The average effective moisture diffusivity, average pre-exponential factor, and average activation energy values were calculated to be as 3.3389E-08- 1.4139E-07 m^2/s, 1.3635E-07m^2/s and 28.0640W/g (R^2=0.9994), respectively. The egg white powder showed fair flow characteristic and high cohesiveness. The effect of different storage conditions on the physical, chemical, and powder properties of foam-mat dried egg white powder could be studied in further studies.

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