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Effects of Hot Air and Vacuum Drying Methods on Drying Kinetics and Some Quality Characteristics of Traditionally Produced Couscous in Turkey

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Drying kinetics and changes in some quality properties of couscous were studied to determine optimal drying method and drying temperature. Drying methods using hot air drying (HAD) and vacuum drying (VD) were applied and couscous samples were dried as thin layer at 55, 65 and 75 °C. Pressure was set at 0.98 bar for vacuum drying. Quality parameters of color values (L*, a*, b*, chroma) and water activity values were measured. Drying periods for VD and HAD at 65 °C were found to be similar. Lower color deviation (ΔE) and water activity values were also determined for vacuum-dried samples. The Midilli et al. model was found to be the most appropriate thin layer model for both HAD and VD methods.

Key Words: couscous, vacuum drying, hot air drying, color, water activity, modelling

Abbreviations: HAD – hot air drying, m – moisture content (g water/g wet matter), me – equilibrium moisture content (g water/g wet matter), mo – initial moisture content (g water/g wet matter), MR – dimensionless moisture ratio, t – time (min), VD – vacuum drying, ΔE – total color deviation, ΔL – changes in brightness

INTRODUCTION

Couscous is an important traditional food that has gained worldwide preference recently due to its flavor and good nutritional properties. It is a major nutriment especially in North African, Arabian and Turkish cuisine in addition to its use as a side dish (Çelik et al. 2004). Couscous is prepared using durum wheat; it is second to pasta in popularity and consumption worldwide (D'Egidio and Pagani 2010).

As a highly perishable product, couscous should be consumed rapidly or dried (Modou et al. 2015). It is manufactured commercially using different technologies in addition to its traditional production by women in Turkey using bulgur or semolina. Traditionally couscous is generally dried under the sun and/or shadow in open air conditions. Traditional couscous drying methods result in very long drying periods and undesirable color. Open air drying methods are dependent on weather conditions that account for the production of home-made couscous prepared using traditional methods during summer (Kaup and Walker 1986). Depending on the climate, the drying process takes at least 10 d, a rather long period. Other disadvantages of open air drying for couscous are the long final cooking procedure and the development of rancidity during its storage (Pagani et al. 2009). These reasons make it necessary to study alternative drying methods for couscous.

Hot air drying is the mostly commonly used method to obtain dry agricultural and food materials. In this method, the required higher drying temperatures or longer drying periods for lower temperatures may severely harm the color, flavor, and nutrients of the products (Izli et al. 2017).

Vacuum drying is a method used for drying different materials, retaining especially their color, nutrients and vitamin content. Application of vacuum increases the mass transfer due to increase in the pressure gradient inside and outside the material and maintains a low temperature level necessary for thermolabile materials. However, the most important disadvantage of vacuum drying is its higher cost (Alibas 2010).

Thin layer drying is the process of drying one layer of product particles or slices. It includes simultaneous heat and mass transfers. The most important aspects of this drying method are the mathematical modeling of the drying process and the design of equipment that make it possible to determine the most suitable process conditions (Onwude et al. 2016). A lot of mathematical models are used to define the thin layer drying process. Mathematical modeling of this drying process is also important in improving the performance of drying equipment (Alibas 2010).

This study was conducted primarily to search the drying kinetics of couscous that were dried using hot air and vacuum drying methods, to determine the optimum drying conditions depending on drying time and product quality, to compare the several empirical and semi-empirical mathematical models of the drying process, to predict the constants of these models, and finally to determine the best fit by nonlinear regression analysis.

MATERIALS AND METHODS

Preparation of Couscous

Traditional preparation of couscous was done by mixing semolina, milk, egg, salt and water in a large wooden dish. According to the formulation of traditional couscous, blending ratios of 16.1%, 22.9%, 3.3% and 57.7% were selected for the ingredients semolina, milk, egg, and flour, respectively (Çelik et al. 2004). The agglomerates were sieved to obtain uniform round granules. Drying was finished in 3 d and fresh couscous samples were stored at 4°C to prevent loss of nutritional and physical properties until the drying experiments.

Drying Processes

A laboratory type dryer (Fig. 1) was used for hot air drying (Hasturk Sahin et al. 2011). Couscous samples were placed on a perforated tray to provide adequate ventilation in the drying chamber. An electronic balance was placed outside the drying cabinet and connected to a computer. The sample tray was connected to the electronic balance. Thus, samples were weighed automatically and weights were recorded on the computer periodically. Hot air drying (HAD) experiments were done at various drying temperatures (55°C, 65°C, and 75°C) at 2 m/s air velocity based on recommended data in the literature (Çelen et al. 2016).

Vacuum drying (VD) experiments were carried out using a 23-L capacity vacuum dryer (Vacucell brand) (Fig. 2). Drying temperatures (55°C, 65°C, and 75°C) were tested and vacuum chamber pressure was set at 0.98 bar during the experiments.

All drying processes were continued until the equilibrium moisture content values were reached, and a constant weight of the samples was obtained.

Color Analysis

Color properties were evaluated as quality parameters of fresh, hot-air-dried and vacuum-dried couscous samples. Color measurements for the samples were taken according to the L*a*b* color system with the use of a colorimeter (Spec HP-200). Color values of the dried samples were compared with those of the fresh samples. L*, a*, b* and chroma (C) values were measured using this colorimeter. L*, a*, and b* are the lightness, redness, and yellowness of the samples, respectively. The L* value changes between 0 (an indicator of whiteness and 100 (an indicator of blackness). Positive a* values define redness while negative a* values define greenness. The positive b* values define yellow while the negative b* values

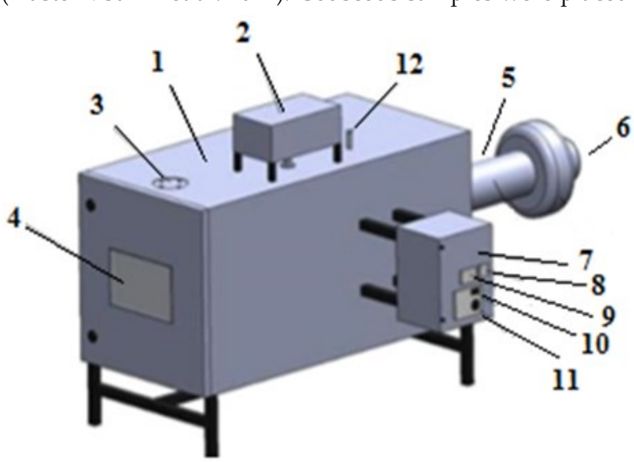

Fig. 1. Hot air dryer (1: Drying cabinet, 2: Electronic balance, 3: Moist air outlet, 4: Sample transfer door, 5: Heater, 6: Fan; 7: Control panel, 8: Heater switch, 9: Temperature control unit, 10: Power switch, 11: Air velocity switch, 12: Temperature sensor).

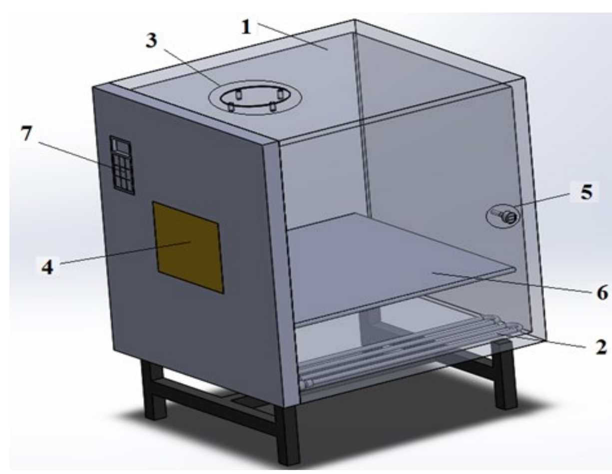

Fig. 2. Vacuum dryer (1: Drying oven, 2: Heater, 3: Moist air outlet, 4: Sample transfer door, 5: Temperature sensor, 6: Tray, 7: Control panel).

define blue color. The closeness of these values to measured values for the fresh sample is accepted as a quality indicator (Aktas et al. 2013; Çelen et al. 2016).

Measurements were done in three replicates and the arithmetic mean of the obtained values were calculated and evaluated. For evaluation, indexes of total color deviation (ΔE), color brightness deviation (ΔL), red color deviation (Δa), and yellow color deviation (Δb) were calculated to determine changes in color due to the drying process. The following equations were used to calculate these values.

$$\Delta L = L_{fresh} - L^* \quad \text{(Eq. 1)}$$

$$\Delta a = a_{fresh} - a^* \quad \text{(Eq. 2)}$$

$$\Delta b = b_{fresh} - b^* \quad \text{(Eq. 3)}$$

$$\Delta E = \sqrt{\Delta L^2 + \Delta a^2 + \Delta b^2} \quad \text{(Eq. 4)}$$

Measurements of Water Activity

Water activity values of fresh and dried couscous samples were detemined using a probe assembly with measurement container by combining Testo 650 data logger. The couscous sample was placed in a measurement container and the water in the air was determined after equilibration occurred in the container. The basics of determining water activity are explained in the Official Methods of Analysis of AOAC International (1995) (Aktas et al. 2013).

Mathematical Modeling

Five different drying models were selected to define the most appropriate model for the drying of couscous (Table 1). These models are semi-theoretical and empirical models also tested in the literature. A semi-theoretical model is derived from a theoretical model (Fick's second law), but it can be simplified in some cases and added with empirical coefficients to improve the fit of the curve. In empirical models, a direct relationship between moisture content and drying time is derived, and the parameters associated with it do not have any physical meaning (Hii et al. 2008). The moisture ratio (MR) in the model equation was determined as follows (Çelen et al. 2016; Delgado et al. 2016):

$$MR = \frac{m - m_e}{m_o - m_e} \quad \text{(Eq. 5)}$$

where m is the moisture content (g water/g dry matter), MR is the dimensionless moisture ratio, mo is the initial moisture content (g water/g dry matter), and me is the equilibrium moisture content.

In these models, a, a_1, a_2, b, n, k, k_1, k_2, g are the model coefficients and t is time (min). The coefficients are determined by nonlinear regression analysis. They were defined by minimizing the sum of the squared differences between the experimental and theoretical moisture ratios. In the literature, several criteria are used to assess the compatibility of a model for experimetally obtained data. Among the criteria, the correlation coefficient (r^2), the reduced chi-square (χ^2), and root mean square error (e_s) are the most widely used. r^2 is the one of the most important criteria for defining the best fit. In addition to r^2, the standard deviation and the reduced chi-square are used to define compliance (Kutlu et al. 2015). The highest r^2 mean values and the lowest mean values of e_s and χ^2 are taken into account in selecting the most suitable model to study the kinetics of thin layer drying (Mirzaee et al. 2010).

Statistical Analysis

PASW Statistics 18 was used to search for significant differences among mean values of color and water activity results. Differences between means were analyzed by one-way analysis of variance (ANOVA). The *P* value ($P<0.01$) was used to determine significant differences. XLSTAT was used in the regression analysis for mathematical modeling and goodness of fit.

RESULTS AND DISCUSSION

Drying Kinetics

Drying method and drying temperature significantly affected total drying period as shown in the drying curves of couscous samples dried by HAD and VD (Fig. 3). Results showed that increase in drying temperature decreased drying time significantly. Similarly, reduction in the drying period with increase in air temperature has been observed in different kinds of food dried using various drying methods (Wang et al. 2004 for potato, Ertekin and Yaldiz 2004 for eggplant, Meisami-asl and Rafiee 2009 for apple, Çelen et al. 2015 for crude olive cake, and Mghazli et al. 2017 for rosemary leaves).

Hot air drying of the couscous samples lasted about 360 min at 75°C drying temperature and about 660 min for the 75°C vacuum drying temperature to obtain 16.3% moisture content. The samples had an initial moisture content of 35.6%. Moisture content of the hot-air-dried samples changed between 16.4% and 25% while that of the vacuum-dried samples changed between 18.7% and

Table 1. Mathematical models used for drying process modeling (Meisami-asl and Rafiee 2009).

Model	Model Equation
Midilli et al.	$MR = a\exp(-kt^n)+bt$
Two term	$MR = a_1\exp(-k_1t) + a_2\exp(-k_2t)$
Verma et al.	$MR = a\exp(-kt) + (1-a)\exp(-gt)$
Wang and Singh	$MR = 1 + at + bt^2$
Page	$MR = \exp(xkt^n)$

21.9% depending on the drying temperatures after 360 min. A 22.8% (w.b.) moisture content was obtained after 810 min at 55°C while 16.3% (w.b.) moisture content was obtained after 360 min at 75°C drying temperature for HAD. The drying process was finished after 960 min at 55°C, after 920 min at 65°C, and after 600 min at 75°C to obtain a final moisture content of 16.3% (w.b.) for VD. When the vacuum drying temperature was increased from 55°C to 75°C, drying time was reduced at 37.5%. The moisture content curves obtained for vacuum drying at 55°C and 65°C were found close to each other after about 750 min. Similarly, increasing temperature in vacuum drying had an important effect on the reduction of drying time (Alibas and Koksal 2014). As expected, an increase in the drying air temperature decreases the drying period needed to reach a certain moisture level due to increasing heat transfer. In other words, heat and mass transfer, especially water loss, is high at higher temperatures due to water migration as a result of increase in the difference in temperature between the drying air and the product (Taheri-Garavand et al. 2011).

Changes in Color

Table 2 shows the measured and calculated color properties of the dried couscous samples for HAD and VD at different drying temperatures. The color parameters of the fresh samples were compared with those of the dried samples and color losses were calculated. Based on the results of statistical analysis, the effects of drying methods and temperatures on all the measured and calculated color properties were found to be statistically significant (P<0.01). Rather high deviations in the color properties were found after drying of the samples. When the total color deviation values (ΔE) are taken into account for both drying methods, the maximum value (27.36) was calculated for hot-air-dried couscous at 55°C. The minimum ΔE of vacuum-dried samples at 65°C was 16.4. In the vacuum drying experiments, maximum ΔE value was obtained also at the lowest drying temperature of 55°C. The total color deviation in samples dried at 55°C is due to the long drying time, that is, longer exposure to hot air with or without vacuum. Changes in maximum brightness (ΔL*) were observed also at 55°C for both drying methods while ΔL* of the hot-air-dried samples (26.56) was higher than that of the vacuum-dried samples (26) (Table 2). Maximum chroma, redness and yellowness values of dried couscous were observed in samples vacuum dried at 75°C by VD and these values were lower in the vacuum-dried samples at 55°C and 65°C compared with the hot-air-dried samples. These results and the obtained lower color deviation (ΔE) in the vacuum-dried couscous samples can be elucidated by the formation of brown pigments due to enzymatic reaction and non-enzymatic (Maillard) reaction during HAD (Albanese et al. 2013).

Water Activity Changes

Water activity values of all couscous samples were lower than 0.62, the critical limit for storage of many foods (Fig. 4). These results are similar to those obtained by Aktas et al. (2013). Mean water activity value for fresh couscous was 93.1 while maximum water activity values of hot-air-dried and vacuum-dried samples were 42.1 and 36.1, respectively. According to statistical analysis results, effects of both drying methods and all temperatures on the decrease of water activity values were statistically significant (P<0.01). Water activity of vacuum-dried samples was lower compared with that of hot-air-dried samples. This is a very important advantage of vacuum

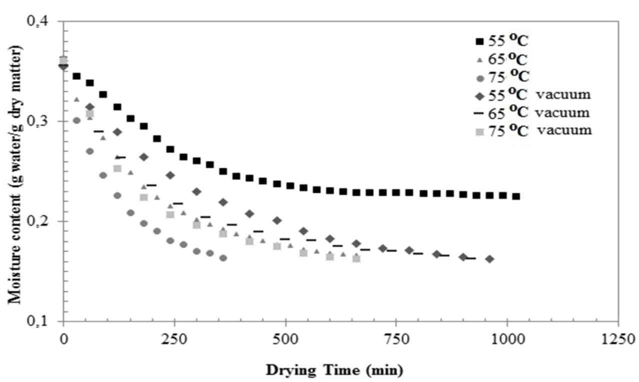

Fig. 3. Changes in drying kinetics of couscous samples depend on drying methods and drying temperatures.

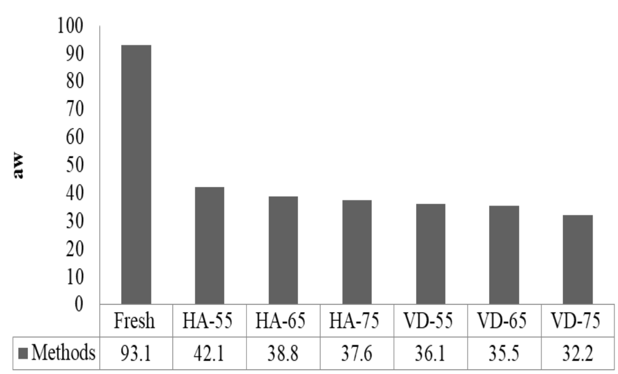

Fig. 4. Change in water activity values with drying methods and temperatures.

Table 2. Color parameter results.

Parameters	L*	a*	b*	C	Δa*	Δb*	ΔL*	ΔE
Fresh couscous	30.04g	2.05g	28.25a	28.33a				
Hot air drying (HA)								
55ºC	56.60a	5.93b	23.15e	23.89e	3.88b	5.10c	26.56a	27.36a
65ºC	54.20c	3.87e	24.69c	24.79c	1.82e	3.54e	24.16c	24.48c
75ºC	53.61d	5.49c	23.89d	24.51d	3.44c	3.82d	23.57d	24.12d
Vacuum drying (VD)								
55ºC	56.04b	3.94d	21.38g	21.74g	1.89d	6.87a	26b	26.96b
65ºC	45.06f	3.59f	21.84f	22.13f	1.54f	6.41b	15.02f	16.4f
75ºC	50.26e	6.86a	24.90b	25.83b	4.81a	3.35f	20.22e	21.05e

Values are means of triplicates. The difference between groups with different letters is significant (P<0.01).
L*, a*, and b* – lightness, redness, and yellowness of the samples, respectively.
C – chroma values; Δa, Δb, ΔL, ΔE – indexes of red color deviation, yellow color deviation, color brightness deviation, and total color deviation, respectively.

drying because a decrease in the water activity of food also reduces the non-enzymatic browning reaction (Krokida et al. 2003; Aktas et al. 2013). Increase in the drying temperature from 55 to 75°C for HAD and VD decreased the water activity values of couscous samples.

Modeling of Drying Characteristics

The results of statistical analyses for the selected thin layer models are given in Tables 3–6. Drying data complied with the different semi-theoretical and empirical models shown in Tables 3–6 and the drying model results were compared with the experimental values. The model that best describes the thin-layer drying feature is the one with the highest r^2, the lowest χ^2, and e_s values. Statistical analysis results indicated that the Midilli et al. model had the highest value for r^2, χ^2 and e_s, compared with the other models for both VD and HAD. The second best model was the two-term model for HAD. The obtained r^2 values for the models were 0.999 in all cases, indicating a good fit. For VD, χ^2 and e_s values ranged from 0.00002 to 0.000047 and from 0.005 to 0.007, respectively. For HAD, χ^2 and e_s values ranged from 0.000045 to 0.000097 and from 0.007 to 0.010, respectively.

A comparison of the experimental moisture ratio with the predicted moisture ratio by the Midilli et al. model for VD and HAD is given in Fig. 5 and 8, respectively. These figures showed that the predicted values obtained from the Midilli et al. model and the values obtained from the experiments were considerably close to each other. Several studies on drying food have indicated that the Midilli et al. model is the most suitable one (Taheri-Garavand et al. 2011; Darvishi et al. 2012; Meisami-asl and Rafiee 2009; Kutlu et al. 2015; Karaaslan and Erdem 2014; Idlimam et al. 2007; Darvishi 2012).

Experimental and predicted moisture ratios as predicted by the two-term model versus drying time for HAD were also found to be similar (Fig. 7). Therefore, the Midilli et al. and the two-term models were selected as the most appropriate models to determine the thin layer drying characteristics of the couscous samples for HAD. These results concur with those of Lahsasni et al. (2004) and Onwude et al. (2016) on the Midilli et al. and the two-term model models.

CONCLUSION

The effects of HAD and VD methods and temperature on the drying of traditionally produced couscous were determined based on the drying time and moisture ratio. Based on the results, drying periods for HAD were found

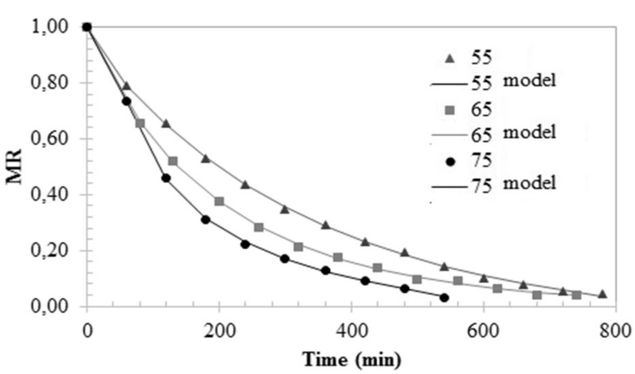

Fig. 5. Predicted and experimental moisture ratios with drying time for vacuum drying (Midilli et al. model).

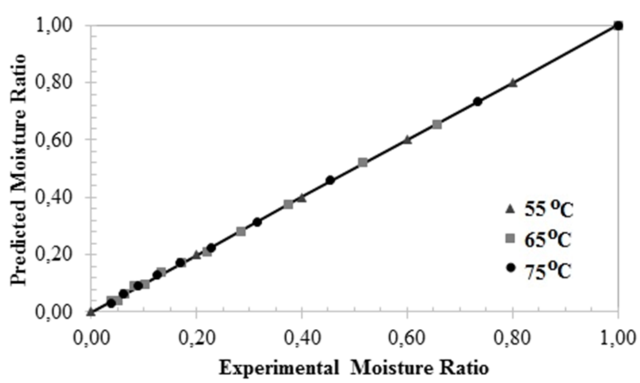

Fig. 6. Comparison of experimental moisture ratio with predicted moisture ratio for vacuum drying.

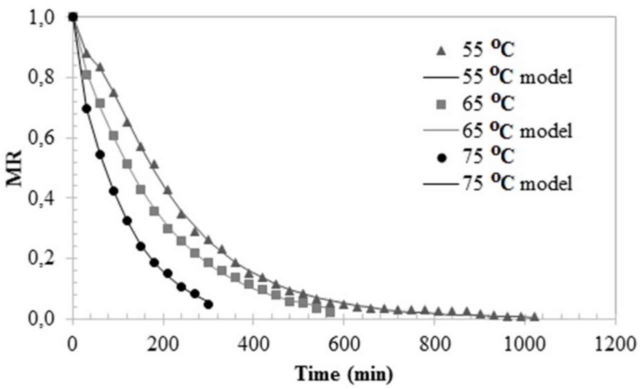

Fig. 7. Predicted and experimental moisture ratios in the two -term model vs. drying time for hot air drying.

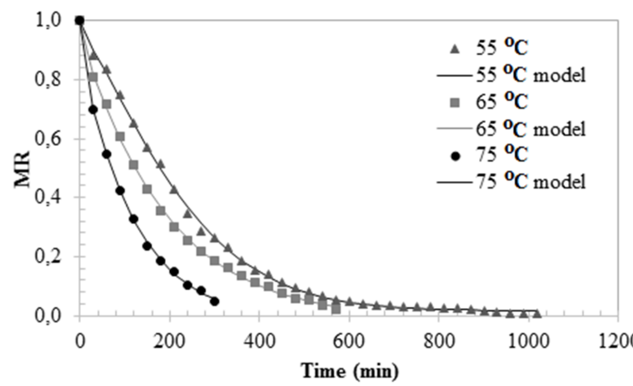

Fig. 8. Predicted and experimental moisture ratios in the Midilli et al. model with drying time for hot air drying.

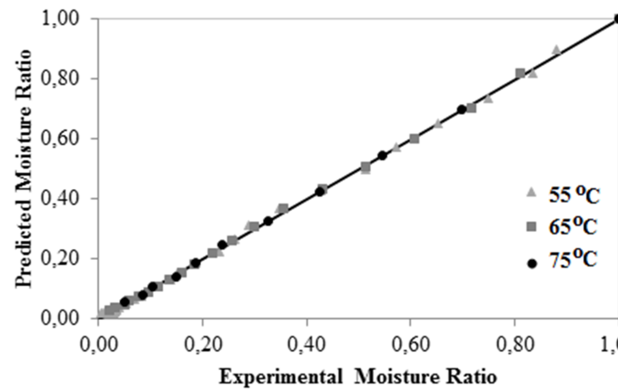

Fig. 9. Comparison of experimental moisture ratio with predicted moisture ratio for hot air drying.

to be shorter compared with drying periods for VD at 75°C while those for HAD at 55°C were longer compared with those for VD. HAD of couscous samples lasted about 360 min at 75°C drying temperature and about 660 min at 75°C vacuum drying temperature to obtain 16.3% moisture content. On the other hand, drying periods for VD and HAD at 65°C were found to be close to each other.

The quality properties of couscous changed depending on the drying methods and drying temperatures. Vacuum-dried couscous samples showed the lowest degree of water activity (32.2) at 75°C. Minimum color deviation (ΔE) that was calculated by considering the ΔL*, Δa* and Δb* values of dried couscous samples was 16.4 for the vacuum-dried sample at 65°C. With respect to drying time, color deviation value, and water activity value, vacuum drying at 65°C may be suggested for drying of couscous.

The five models in the literature were applied to the experimental data to explain the drying behavior of traditionally produced couscous in Turkey. Among these models, the most suitable thin layer model for hot air and vacuum drying of couscous was the Midilli et al. model based on the results of statistical analyses.

Table 3. Statistical analysis results of the models for vacuum drying.

Model	DryingTemp.	Coefficients	r^2	e_s	X^2
Wang and Singh	55ºC	a=-0.003/b= $1.99*10^{-6}$	0.990	0.036	0.001
	65ºC	a=-0,003/b= $2.91*10^{-6}$	0.970	0.063	0.004
	75ºC	a=-0,004/b= $4.94*10^{-6}$	0.966	0.057	0.003
Page	55ºC	k= 0.006/n=1.006	0.992	0.022	0.00046
	65ºC	k= 0.008/n=0.919	0.999	0.006	0.000039
	75ºC	k= 0.003/n=1.023	0.997	0.015	0.000218
Midilli et al.	55ºC	a=0.965/k=0.003 n=0.989/b=-0.000063	0.999	0.007	0.000047
	65ºC	a=1.029/k=0.009 n=0.892/b=$-8.96*10^{-7}$	0.999	0.007	0.000047
	75ºC	a=3.255/k=0.301 n=0.389/b=-0.00011	0.999	0.005	0.00002
Two term	55ºC	a1=5.017/ a2=-4.088 k1=0.005/k2=0.005	0.999	0.011	0.00011
	65ºC	a1=1.521/a2=-0.592 k1=0.004/k2=0.004	0.999	0.009	0.000081
	75ºC	a1=1.512/a2=-0.474 k1=0.006 /k2=0.006	0.994	0.024	0.001
Verma et al.	55ºC	a=210.79/k=0.004/g=0.004	0.997	0.014	0.00021
	65ºC	a=168.154/k=0.005/g=0.005	0.999	0.016	0.00025
	75ºC	a=-0.038/k=53.356/g=0.006	0.994	0.022	0.00048

Table 4. Statistical analysis results and coefficients of the Midilli et al. model for vacuum drying.

Drying Temperature	r^2	e_s	X^2	A	k	n	b
55ºC	0.999	0.007	0.000047	0.965	0.003	0.989	-0.000063
65ºC	0.999	0.007	0.000047	1.029	0.009	0.892	$-8.96*10^{-7}$
75ºC	0.999	0.005	0.00002	3.255	0.301	0.389	-0.00011

Table 5. Statistical analysis results of models for hot air drying.

Model	DryingTemp.	Coefficients	r^2	e_s	X^2
Wang and Singh	55ºC	a=-0.007/b= 0.000014	0.982	0.053	0.003
	65ºC	a=-0.004/b= $4.39*10^{-6}$	0.986	0.046	0.002
	75ºC	a=-0.007/b= 0.000014	0.982	0.053	0.003
Page	55ºC	k= 0.001/n=1.207	0.998	0.016	0.00016
	65ºC	k= 0.006/n=0.994	0.998	0.011	0.00012
	75ºC	k= 0.015/n=0.912	0.997	0.014	0.00018
Midilli et al.	55ºC	a=0.954/k=0.001 n=1.335/b=-0.000016	0.999	0.010	0.000097
	65ºC	a=0.946/k=0.004 n=1.050/b=-0.000016	0.999	0.008	0.000066
	75ºC	a=0.877/k=0.006 n=1.058/b=-0.000031	0.999	0.007	0.000045
Two term	55ºC	a1=1.333/ a2=-0.491 k1=0.005/k2=0.022	0.999	0.008	0.000069
	65ºC	a1=1.296/a2=-0.352 k1=0.006/k2=0.011	0.999	0.009	0.000073
	75ºC	a1=1.592/a2=-0.715 k1=0.010 /k2=0.014	0.999	0.007	0.000048
Verma et al.	55ºC	a=148.641/k=0.007/g=0.007	0.998	0.012	0.00024
	65ºC	a=318.233/k=0.006/g=0.006	0.998	0.011	0.00012
	75ºC	a=2.761/k=0.010/g=0.010	0.997	0.023	0.001

Table 6. Statistical analysis results and coefficients of the Midilli et al. model for hot air drying.

Drying Temperature	r^2	e_s	X^2	A	k	n	b
55ºC	0.999	0.010	0.000097	0.954	0.001	1.335	0.000016
65ºC	0.999	0.008	0.000066	0.946	0.004	1.050	-0.000016
75ºC	0.999	0.007	0.000045	0.877	0.006	1.058	-0.000031

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