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DRYING OF GREEN BEAN AND OKRA UNDER SOLAR ENERGY

In this study, sun drying characteristics of green bean and okra were investigated. Drying experiments were conducted in Iskenderun-Hatay, Turkey. The drying study showed that the times taken for drying of green bean and okra from the initial moisture contents of 89.5% and 88.7% (w.b.) to final moisture content of around 15±0.5% (w.b.) were 60 and 100 h in open sun drying, respectively. The constant rate period is absent in drying curves. The drying process took place in the falling rate period. The drying data were fitted to thirteen thin-layer drying models. The performance of these models was investigated by comparing the determination of coefficient (R^2), reduced chi-square (χ^2) and root mean square error (RMSE) between the observed and predicted moisture ratios. Estimations by Approximation of diffusion (for green bean) and Midilli et al. models (for okra) were in good agreement with the experimental data obtained.

Key words: sun drying; green bean and okra; thin-layer drying models; non-linear regression, effective diffusivity.

Drying of fruit and vegetables is one of the oldest forms of food preservation method known to man and is the most important process to preserve food since it has great effect on the quality of the dried products. The major objective in drying agricultural products is the reduction of the moisture content to a level, which allows safe storage over an extended period. Also, it brings about substantial reduction in weight and volume, minimising packaging, storage and transporttation costs [1-3]. In spite of many disadvantages, sun drying is still practiced in many places throughout the world. Solar energy is an important alternative source of energy and preferred to other energy sources because it is abundant, inexhaustible, renewable, cheap and non-pollutant [4-6].

Okra (*Abelmoschus esculentus* L.), a flowering plant in the mallow family Malvaceae, is a tropical perennial crop growing 3 to 6 feet tall. It is grown throughout the tropical and sub-tropical countries. According to FAO data for 2007, okra production all over the world was about 5,941 million tones. The major producer countries include India, Nigeria, Sudan, Pakistan, Iraq and Ghana [7]. Okra can be consumed as a fresh vegetable, cooked vegetable or an additive for soups, salads and stews [8].

Green bean (*Phaselus vulgaris* L.) is one of the most widely grown fruit crops throughout the world. According to FAO data for 2007, green bean production all over the world was about 6,605 million t. The major producer countries include China, Indonesia, Turkey, India and Egypt [7]. Green bean is cultivated widely in Turkey, where 519,968 t had been produced in 2007. Okra and green bean, like most other fruits and vegetables, are susceptible to rapid deterioration because of their high moisture content. They are preserved in some forms, such as frozen, canned and dried.

Drying is a complex thermal process in which unsteady heat and moisture transfer occur simultaneously [9]. From an engineering point of view, it is important to develop a better understanding of the controlling parameters of this complex process. Mathematical models of the drying processes are used for designing new or improving existing drying systems or even for the control of the drying process. Many mathematical models have been proposed to describe the drying process, of which thin-layer drying models have been widely in use. These models can be categorized as theoretical, semi-theoretical, and empirical [10,11]. Recently, there has been a lot of research in mathematical modelling and experimental studies of the dry-

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ing characteristics of various vegetables and fruits, such as carrot [2], onion [3], ciku [6], sweet potato [12], okra [8,13], green bean [14], potato, apple and pumpkin slices [15], and peach [16]. Studies on the sun drying of green bean and okra are scarce in the literature. Therefore, the present study was undertaken to study the drying kinetics of green bean and okra in direct exposure to the sun, to evaluate a suitable drying model for describing the drying process, and the compute effective moisture diffusivity.

EXPERIMENTAL

Material

Fresh green bean (*Phaselus vulgaris* L.) and okra (*Abelmoschus esculetus* L.) from Iskenderun region, Hatay, were used for the drying tests. Hatay is a province of southern Turkey, situated between the Mediterranean Sea to the west and Syria to the South-East. Its geographic coordinates are 35° 52' to 37° 04' North, 35° 40' to 36° 35' West and is hot and dry in summer. For ensuring the uniformity of the physical characteristics of the green bean and okra dried. The average diameters of green bean and okra were kept at 1.56±0.2 cm and 1.64±0.2 cm, respectively. Green bean samples cut in the form of slices of 4±0.1 cm length with a knife.

Drying process

The selected samples were cleaned with tap water to make samples free from dust and foreign materials. The samples, about 100 g, were distributed uniformly in a single layer in the sample tray, and then sun dried by direct exposure to solar radiation in August 2007 in the Iskenderun, Hatay. The green bean and okra were exposed to sunlight for 12 h daily. During the night, the moisture loss was not recorded. The samples during the night were packed for reducing the effect on increase in moisture content. Moisture loss was measured at 4-hour intervals during drying by a Mettler balance (model BB3000), which has a 0-3000 g measurement range with an accuracy of ±0.1 g. Drying was continued until the sample reached the desired moisture level (15+0.5%, w.b.). Dried samples were packed in a bag (low density polyethylene, LDPE) and thermally sealed. The experiments were repeated duplicate for obtaining more accurate results, after that average values were used.

Moisture content

The moisture content of the fresh samples was determined by using a vacuum oven at 70 °C for 24 h [17]. Triplicate samples were used for the determination of moisture content and the average values were reported.

Ambient air temperature

Ambient air temperatures were measured by an iron-constantan thermocouple, which was used with a manually controlled 8-channel automatic digital thermometer, with a reading accuracy of ±0.1 °C (Meter Electronic, Turkey).

Mathematical modeling of drying curves

Moisture ratio (MR) of samples was obtained using the equation below:

$$MR = \frac{M_t - M_e}{M_0 - M_e} \tag{1}$$

where M_t, M_0 and M_e are the moisture content at anytime, initial moisture content and equilibrium moisture content of samples (kg water/kg dry matter), respectively. The moisture ratio (MR) was simplified to M_t/M_0 instead of $(M_t - M_e)/(M_0 - M_e)$ by some investigators [12,16] because of the continuous fluctuation of relative humidity of the drying air during sun drying.

The drying rate (DR) is expressed as the amount of the evaporated moisture over time. The drying rates calculated by using Eq. (2):

$$DR = \frac{M_{t1} - M_{t2}}{t_2 - t_1} \tag{2}$$

where t_1 and t_2 are the drying times (h) at different times during drying; M_{t1} and M_{t2} are the moisture content of samples (kg water/kg dry matter) at time t_1 and t_2, respectively.

The experimental moisture ratio data of green bean and okra obtained were fitted to the 13 commonly used thin-layer drying models in Table 1. Non-linear least square regression analysis was performed using Levenberg-Marquardt procedure in Statistica 6.0 computer program. The three criteria of statistic analysis have been used to evaluate the fitted of the experimental data to the different models; the coefficient of determination (R^2), reduced chi-square (χ^2) and root mean square error ($RMSE$). These parameters can be calculated as:

$$\chi^2 = \frac{\sum_{i=1}^{N}\left(MR_{\exp,i} - MR_{\text{pre},i}\right)^2}{N - z} \tag{3}$$

$$RMSE = \left[\frac{1}{N}\sum_{i=1}^{N}(MR_{\text{pre},i} - MR_{\exp,i})^2\right]^{1/2} \tag{4}$$

where $MR_{\exp,i}$ and $MR_{\text{pre},i}$ are experimental and predicted dimensionless moisture ratios, respectively; N is

Table 1. Proposed thin-layer drying models for green bean and okra (a, b, c, g, h, k, k_0 and k_1: empirical constants and coefficients in drying models)

Model name	Model equation	References
Lewis	$MR = \exp(-kt)$	Ayensu [18]
Henderson and Pabis	$MR = a\exp(-kt)$	Henderson and Pabis [19]
Modified Henderson and Pabis	$MR = a\exp(-kt) + b\exp(-gt) + c\exp(-ht)$	Karathanos [20]
Logarithmic	$MR = a\exp(-kt) + c$	Kingsly *et al.* [16]
Two-term	$MR = a\exp(-k_0t) + b\exp(-k_1t)$	Lee and Kim [13]
Two-term exponential	$MR = a\exp(-kt) + (1-a)\exp(-kat)$	Sharaf-Eldeen *et al.* [21]
Approximation of diffusion	$MR = a\exp(-kt) + (1-a)\exp(-kbt)$	Sacilik *et al.* [22]
Verma *et al.*	$MR = a\exp(-kt) + (1-a)\exp(-gt)$	Verma *et al.* [23]
Page	$MR = \exp(-kt^n)$	Yaldiz and Ertekin [24]; Senadeera *et al.* [25]
Midilli *et al.*	$MR = a\exp(-kt^n) + bt$	Akpinar [15]; Ruiz Celma *et al.* [26]
Parabolic	$MR = a + bt + ct^2$	Sharma and Prasad [27]
Weibull	$MR = \exp\left(-\left(\frac{t}{b}\right)^a\right)$	Corzo *et al.* [28]
Wang and Singh	$MR = 1 + at + bt^2$	Wang and Singh [29]

number of observations; z is number of constants in models. For quality fit, R^2 value should be higher, and χ^2 and *RMSE* values should be lower [13,30,31].

Determination of effective moisture diffusivity

Fick's second law of diffusion equation, symbolized as a mass-diffusion equation for drying of agricultural products drying in a falling rate period, is shown in the following equation:

$$\frac{\partial M}{\partial t} = D_{\text{eff}}\nabla^2 M \quad (5)$$

The analytical solutions of Fick's second law (Eq. 5) for different geometrics can be given as Eqs. (6) and (7)) with the assumption that neglecting shrinkage, constant temperature and diffusion coefficients and uniform initial moisture distribution.

Infinite slab:

$$MR = \frac{8}{\pi^2}\sum_{n=0}^{\infty}\frac{1}{(2n+1)^2}\exp\left(-\frac{(2n+1)^2\pi^2 D_{\text{eff}}\, t}{4L^2}\right) \quad (6)$$

Sphere:

$$MR = \frac{6}{\pi^2}\sum_{n=1}^{\infty}\frac{1}{n^2}\exp\left(-n^2\pi^2\frac{D_{\text{eff}}t}{r^2}\right) \quad (7)$$

where, D_{eff} is the effective moisture diffusivity in m^2/s, t is the time (s), n is a positive integer, L and r are the half-thickness and radius of samples (m), respectively. For long drying periods, Eqs. (6) and (7) can be further simplified to only the first term of the series. Eqs. (6) and (7) are written in a logarithmic form as follows:

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

$$\ln MR = \ln\left(\frac{6}{\pi^2}\right) - \left(\frac{\pi^2 D_{\text{eff}}t}{r^2}\right) \quad (9)$$

The effective moisture diffusivity was calculated from a slope of a straight line by plotting data in terms of ln *MR versus* drying time, which gives a straight line with a slope of (K_1 and K_2), in which:

$$K_1 = \frac{\pi^2 D_{\text{eff}}}{4L^2} \quad (10)$$

$$K_2 = \frac{\pi^2 D_{\text{eff}}}{r^2} \quad (11)$$

RESULTS AND DISCUSSION

Ambient temperature

The experiments were performed in August 2007, in Iskenderun, Hatay, Turkey. The variation of ambient air temperatures during sun drying of green bean and okra samples under natural convection in a typical day is shown in Figure 1. During the drying experiments, the temperature of ambient air ranged from 33 to 46 °C. The air temperature reached in its higher figures between 10.00 am and 16.00 pm.

Drying curves

The changes in moisture ratio with drying time of samples in open sun drying are presented in Figure 2. The drying study showed that the times taken for dry-

ing of green bean and okra from the initial moisture contents of 89.5 and 88.7% (w.b.) to final moisture content of around 15±0.5% (w.b.) were 60 and 100 h in open sun drying, respectively. The moisture ratios of samples reduced exponentially with drying time evidently, which are typical to ones for foodstuffs such as okra, carrot, onion, tomato and peach [8,13,16,22,32].

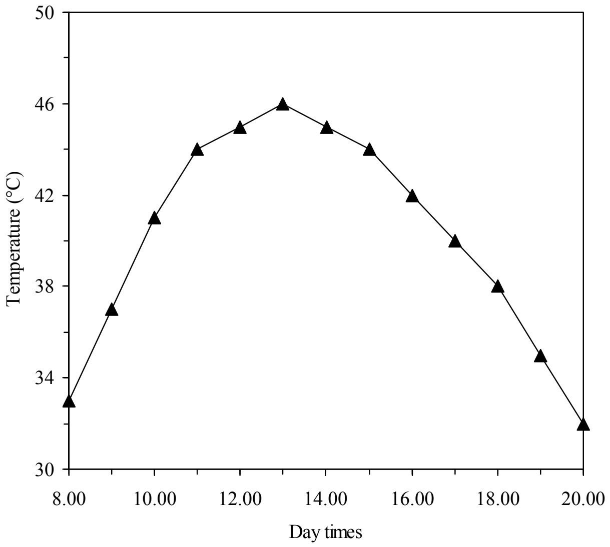

Figure 1. Variation of ambient temperature during sun drying of green bean and okra on a typical day of August 2007 at Iskenderun, Hatay.

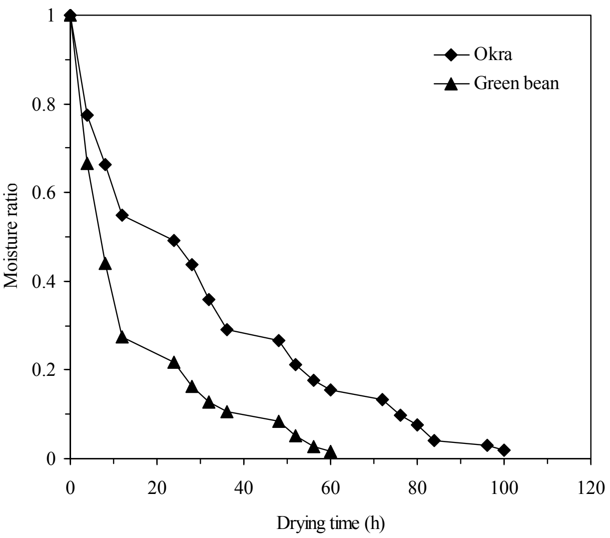

Figure 2. Experimental moisture ratios of green bean and okra versus drying time.

Drying rates of samples was calculated using Eq. (2). The changes in drying rates versus moisture ratio are shown in Figure 3. The drying curves show that drying rate decreased continuously with decreasing moisture ratio. As indicated in these curves, there was no constant rate period in drying of samples. All the drying process occurred in the falling rate period. In the falling rate period, the material surface is no longer saturated with water and drying rate is controlled by diffusion of moisture from the interior of solid to the surface [12]. Similar results have been presented for onion slices [13], green beans, potato and peas [25], okra [8], and carrot [2].

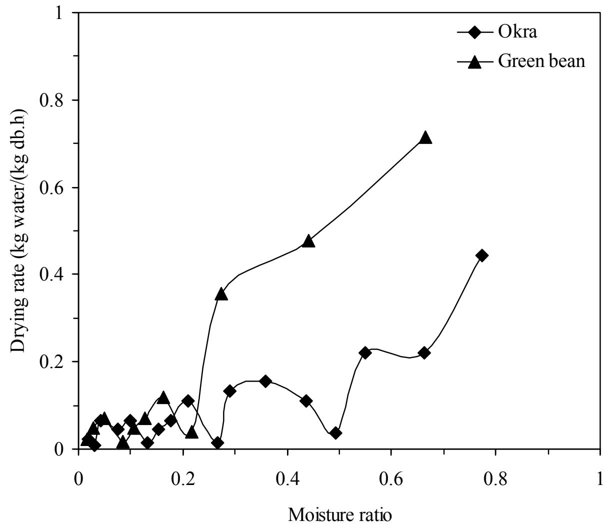

Figure 3. Variation of drying rate with moisture ratio.

Evaluation of the models

The drying data obtained from the experiments were fitted to the selected models mentioned in Table 1. The statistical analysis results are presented in Tables 2 and 3. The best model describing the drying process of the green bean and okra was chosen as the one with the highest R^2 and the least χ^2 and *RMSE*.

From Tables 2 and 3, R^2, χ^2 and *RMSE* values were changed between 0.7226-0.9925, 0.00077--0.02534 and 0.06210-0.38819, respectively. As expected, the approximation of diffusion (for green bean) and Midilli *et al.* models (for okra) give the highest value of R^2 and lowest of χ^2 and *RMSE* values. The R^2, χ^2 and *RMSE* values of the approximation of diffusion and Midilli *et al.* models vary between 0.9842 and 0.9925, 0.00077 and 0.00180, and 0.0210 and 0.09954, respectively. Thus, the approximation of diffusion and Midilli *et al.* models may be assumed to represent the thin layer drying characteristics of green bean and okra. Figures 4 and 5 compare the experimental data with the predicted ones using approximation of diffusion and Midilli *et al.* models for dried green bean and okra. The prediction using the model showed *MR* values banded along a straight line, which proved the suitability of these models in describing the drying characteristics of samples. The Approximation of diffusion

Table 2. Curve fitting criteria for the various models and parameters for drying of green beans

Model	Constants	R^2	χ^2	RMSE
Lewis	*k*: 0.10009	0.9259	0.00615	0.21998
Henderson and Pabis	*a*: 0.91850, *k*: 0.08679	0.9330	0.00611	0.22090
Modified Henderson and Pabis	*a*: 10.98317, *k*: 0.07916, *b*: -5.16652, *g*: 0.07939, *c*: -4.87716, *h*: 0.07915	0.9635	0.00598	0.17033
Logarithmic	*a*: 0.90182, *k*: 013535, *c*: 0.08490	0.9701	0.00302	0.12999
Two-term	*a*: 0.60786, *b*: 0.39973, k_0: 0.25196, k_1: 0.03607	0.9902	0.00111	0.07572
Verma *et al.*	*a*: 0.00000, *b*: 0.1000, *g*: 0.10000	0.9259	0.00752	0.22006
Two-term exponential	*a*: 0.27061, *k*: 0.23240	0.9813	0.00183	0.10592
Approximation of diffusion	*a*: 0.57080, *k*: 0.18924, *b*: 0.20391	0.9925	0.00081	0.06210
Page	*k*: 0.25709, *n*: 0.61006	0.9839	0.00146	0.09465
Midilli *et al.*	*a*: 1.004892, *b*: -0.00031, *k*: 0.27401, *n*: 0.57790	0.9842	0.00180	0.08982
Parabolic	*a*: 0.76545, *b*: - 0.03252, *c*: 0.00035	0.8521	0.01500	0.27482
Weibull	*a*: 0.71058, *b*: 11.18875	0.9886	0.00111	0.07586
Wang and Singh	*a*: -0.04759, *b*: 0.00055	0.7226	0.02534	0.38819

Table 3. Curve fitting criteria for the various models and parameters for drying of okra

Model	Constants	R^2	χ^2	RMSE
Lewis	*k*: 0.032833	0.9638	0.00285	0.15718
Henderson and Pabis	*a*: 0.909820, *k*: 0.02928	0.9775	0.00188	0.13439
Modified Henderson and Pabis	*a*: 11.05235, *k*: 0.03061, *b*: -5.27594, *g*: 0.03070, *c*: -4.86658, *h*: 0.03071	0.9775	0.00251	0.13446
Logarithmic	*a*: 0.92115, *k*: 0.02815, *c*: -0.01702	0.9778	0.00198	0.12813
Two-term	*a*: 8.50014, *b*: -7.59032, k_0: 0.02965, k_1: 0.02965	0.9775	0.00215	0.13439
Two-term exponential	*a*: 0.13344, *k*: 0.21453	0.9826	0.00145	0.11974
Approximation of diffusion	*a*: 1.16677, *k*: 0.51569, *b*: 0.05248	0.9882	0.00105	0.09954
Verma *et al.*	*a*: 0.16675, *k*: 0.51606, *g*: 0.02706	0.9882	0.00105	0.09954
Page	*k*: 0.06870, *n*: 0.79846	0.9806	0.00162	0.13253
Midilli *et al.*	*a*: 0.99841, *b*: -0.00175, *k*: 0.11109, *n*: 0.59501	0.9919	0.00077	0.08020
Parabolic	*a*: 0.85284, *b*: - 0.01761, *c*: 0.00009	0.9650	0.00313	0.15087
Weibull	*a*: 0.79845, *b*: 28.61446	0.9806	0.00162	0.13254
Wang and Singh	*a*: -0.02332, *b*: 0.00014	0.9177	0.00690	0.25488

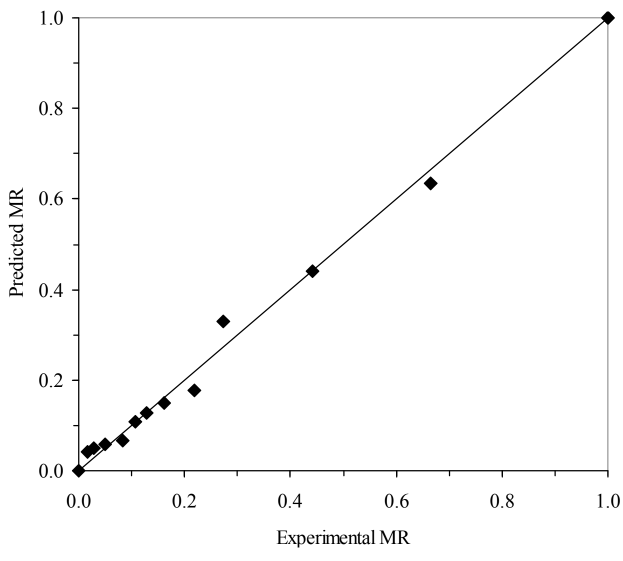

Figure 4. Variation of experimental vs. predicted moisture ratio values using Approximation of diffusion model for green bean drying.

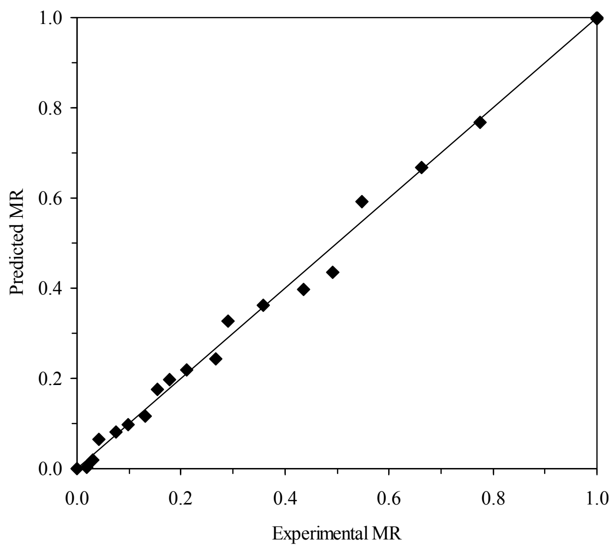

Figure 5. Variation of experimental vs. predicted moisture ratio values using Midilli et al. model for okra drying.

and Midilli *et al.* models have also been suggested by other authors to describe hot air drying of some vegetables and fruits [15], tomato [22] and tomato by-products [26].

Effective moisture diffusivity

The results of effective moisture diffusivity (D_{eff}) of samples and other related products under drying temperatures are presented in Table 4. The values of effective diffusivity of green bean and okra were 1.12×10^{-10} and 1.52×10^{-11} m^2/s, respectively. The values reported herein are within the general range of 10^{-11} to 10^{-9} m^2/s for food materials [33]. However, the values for D_{eff} obtained from this study were lower than those of reported in the Table 4 due to different heating mechanism being applied to the green bean and okra samples.

Table 4. Effective diffusivities of green bean, okra and other vegetables

Product	Drying method	Effective moisture diffusivity, m^2/s	References
Green bean	Sun	1.12×10^{-10}	Present work
Okra	Sun	1.52×10^{-11}	Present work
Okra	Hot-air	1.16×10^{-8}-7.13×10^{-9}	Sobukola [8]
Okra	Hot-air	4.56×10^{-10}-8.05×10^{-10}	Adedeji *et al.* [13]
Green bean	Hot-air	1.6×10^{-10}	Rosselló *et al.* [14]
Green pea	Hot-air	1.5×10^{-10}	Rosselló *et al.* [14]
Garlic	Hot-air	2.0×10^{-10}-4.2×10^{-10}	Madamba *et al.* [33]
Carrot	Hot-air	0.77×10^{-9}-9.33×10^{-9}	Doymaz [32]

CONCLUSIONS

The drying characteristics of green bean and okra were investigated under open sun. The drying process occurred in falling rate period, and no constant rate period of drying was observed. The experimental data were used to fit thirteen thin layer drying models and goodness of fit determined using R^2, χ^2 and *RMSE*. According to the results, the Approximation of diffusion and Midilli *et al.* models could adequately describe the thin layer drying behaviour of green bean and okra, respectively. The effective moisture diffusivity values were estimated from Fick's diffusion model by 1.12×10^{-10} m^2/s and 1.52×10^{-11} m^2/s for green bean and okra, respectively.

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NAUČNI RAD

KARAKTERISTIKE SUŠENJA BORANIJE I BAMIJE SUNČEVOM ENERGIJOM

U ovom radu je ispitivano sušenje boranije i bamije sunčevom energijom. Eksperimenti su obavljeni u Iskenderun-Hatay, Turska. Studija je pokazala da vremena potrebna za sušenje boranije i bamije od početne vlažnosti od 89,5 i 88,7% (mas.), do konačne vlažnosti od oko 15±0,5% (mas.) iznose 60 i 100 h, respektivno. Nema perioda konstantne brzine sušenja. Proces sušenja odvija se uz stalno opadanje brzine sušenja. Eksperimentalni podaci su fitovani prema modelu sušenja 13 tankih slojeva. Ponašanje ovog modela ispitivano je poređenjem koeficijenta determinacije R^2*, redukovanog* χ^2 *i kvadratnog korena srednje kvadratne greške između eksperimentalnih i predskazanih sadržaja vlage RMSE. Procene pomoću aproksimacije difuzije (za boraniju) i modela Midilli-ja i sar. (za bamiju) pokazale su dobro slaganje sa eksperimentalno dobijenim podacima.*

Ključne reči: sušenje sunčevom energijom; zelena boranija; bamija; modeli sušenja u tankom sloju; nelinearna regresija; efektivna difuzivnost.