Research Paper / Araştırma Makalesi

Rehydration Kinetics of Sun-Dried Eggplants (*Solanum melongena* L.) at Different Temperatures

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ABSTRACT

In this study, sun-dried eggplant samples were rehydrated at three different rehydration water temperatures (25, 35 and 45°C) and the effect of rehydration kinetics were determined. Four different models were used to model the rehydration behaviors of sun-dried eggplants, and non-linear regression analysis were performed to obtain the model that gives the best fit to experimental data. The coefficients of models were calculated. According to regression analysis, Peleg model gave a better fit for all rehydration conditions applied. Additionally, the effective diffusivities were between 3.21×10^{-8} and 4.06×10^{-8} m^2 s^{-1}. Rehydration water temperature influenced rehydration rates, and moisture uptake of samples was faster at high temperatures.

Keywords: Eggplant, Sun drying, Rehydration, Kinetics, Peleg model

Güneşte Kurutulmuş Patlıcanların (*Solanum melongena* L.) Farklı Sıcaklıklardaki Rehidrasyon Kinetiği

ÖZ

Çalışmada, güneşte kurutulmuş patlıcan örneklerinin rehidrasyonunda, üç farklı rehidrasyon suyu sıcaklığının (25, 35 ve 45°C) rehidrasyon kinetiğine etkisi incelenmiştir. Dört farklı modelle, rehidrasyonda elde edilen deneysel sonuçların uygunluğu doğrusal olmayan regresyon analizi uygulanarak karşılaştırılmış ve modellere ait katsayılar hesaplanmıştır. Deneysel sonuçlara en iyi uyum gösteren modelin Peleg modeli olduğu belirlenmiştir. Çalışmada ayrıca efektif difüzivite katsayıları da belirlenmiş ve 3.21×10^{-8}- 4.06×10^{-8} m^2 s^{-1} değerleri arasında hesaplanmıştır. Yüksek sıcaklıkta yapılan rehidrasyon işleminde nem kazanımının daha hızlı olduğu belirlenmiştir.

Anahtar Kelimeler: Patlıcan, Güneşte kurutma, Rehidrasyon, Kinetik, Peleg modeli

INTRODUCTION

Eggplant (*Solanum melongena* L.) is a member of the Solanaceae family. Eggplant is an economically and nutritionally important crop like other solanceous vegetables such as tomato, potato and pepper. The three cultivated species are annuals and perennials in temperate and humid tropic conditions, respectively, and have wide environmental adaptation. Eggplant is mostly produced and widely used in Asia and Africa; in addition, it is also produced and used in Europe and America [1]. Eggplant is a good source of minerals and vitamins and can be compared with tomato in terms of total nutritional value [2, 3]. Eggplants have many ingredients such as fat, water, carbohydrate, water soluble sugar, amid protein and phenolic compounds that are beneficial for human health. Its fresh weight consists of 92.7% moisture, 4% carbohydrates and vitamins, 1.4% protein, 1.3% fiber, 0.3% fat, and 0.3% minerals [4]. It provides relevant quantities of P, K, and

Cu to the diet, with global mean values of 26.6 mg, 198.5 mg, and 0.062 mg per 100 g of fresh weight of these minerals, respectively [5]. Eggplant has a very limited shelf life for freshness, and loses water and quality when field heat is not removed quickly. Therefore, it can be preserved in some ways to extend its shelf life such as refrigeration, modified atmosphere and freezing [6, 7]. Drying is a possible method of processing eggplant, avoiding further deterioration. Dried eggplant is a valuable ingredient in different kinds of meals.

Drying is one of the oldest methods of food preservation. It is also a classical method of food preservation, which provides longer shelf-life, lighter weight for transportation and smaller space for storage [8]. Sun-drying is still one of the most widely used method but also so many types of drying systems and dryers have been developed to increase quality and energy efficiency [9, 10].

Dried fruits and vegetables are generally rehydrated before being consumed. Especially many of dried vegetables are consumed after rehydration process. Rehydration is the process of regaining water to the dried products. With rehydration, water is absorbed into the tissue and consequently the product mass is increased. But also a mass is transferred from the product into the water used for rehydration. During rehydration of the dried fruits and vegetables, while the product gains water from the rehydration medium, also components such as sugar, acid, vitamins and minerals may be transferred into the rehydration medium. Factors such as the drying method and conditions applied on the product, chemical and physical structure of the product, temperature of the water used for rehydration affect the properties of rehydration [11]. While water gaining in the dried product takes place quickly at the beginning of the rehydration, the rehydration rate decreases as the moisture content value of the product gets close to the equilibrium moisture content value [12].

Mathematical models are important in the design and optimization of drying and rehydration processes. With the mathematical model, optimal conditions for drying or rehydrating the food can be determined. Geometrical shape and structure of the food should be considered while modeling. By using mathematical models in design of the drying and rehydration processes, a significant energy saving is provided and loss of time is prevented [13]. Fick's II Law is used for creation of mathematical models. Peleg model, Weibull model, the first order model and exponential model are widely used in the literature for modeling the rehydration process [14, 15].

In this study, sun-dried eggplants were rehydrated at different temperatures and rehydration kinetics were determined by testing four different rehydration models (Peleg model, Weibull model, Exponential model and the first order model). Also, effective diffusivities for each rehydration temperature are calculated.

MATERIAL and METHODS

Material

Sun-dried eggplant samples to be rehydrated in the study were obtained from an herbalist in Denizli province. Dried eggplant samples were brought to the department lab in polyethylene bags and stored in such bags at room temperature until the rehydration process. Before beginning the rehydration process, moisture content of dried eggplant samples was determined according to AOAC method by being dried in a vacuum oven (JSR, JSVO-60T, South Korea) at 70°C for 24 hours [16]. Average moisture content of the samples was calculated as 0.073 kg water per kg dry matter.

Methods

Rehydration

Rehydration processes were performed at three different water temperatures including 25, 35 and 45°C. A water bath was used for rehydration process. 30 minutes before beginning the rehydration process, temperature of water bath (WB-11 Model, Wisd Laboratory Instruments, Wertheim, Germany) was set to the rehydration temperature. Then, 150 mL distilled water was added into a 250 mL glass container and temperature of the water in the glass container was checked by a thermometer to be at the required operating temperature. After rehydration water reached the desired temperature value, the stringed dried eggplant samples were removed from the string, weighted to be 5±0.11 g and placed in a glass container in the water bath. Rehydration processes continued for 24 hours and during this process, samples were taken out from the glass container per every 30 minutes in the first 6 hours and the increase in the weight was measured with a digital balance with 0.01 g precision (TP-3002 model, Denver Instruments, Gottingen, Germany). Before weighing operation, excess water on sample surfaces was wiped with filter paper. Rehydration processes were performed in triplicates.

Rehydration Kinetics Modeling

During rehydration of sun-dried eggplants at different temperatures, rehydration models widely used in literature and given in Table 1 were used depending on the time, in order to determine the model that best expresses the moisture content.

Among these models, Peleg model has two parameters and used in rehydration of many dried foods [18, 20, 21]. In the equation of Peleg model, M_0 is the initial moisture content of non-rehydrated sample (kg water per kg dry matter), M represents the moisture content of sample in the t time of rehydration (kg water per kg dry matter), t is the rehydration time (min.), k_1 is the Peleg rate constant (min. (kg water per kg dry matter)) and k_2 is the Peleg capacity constant (kg water per kg dry matter).

Table 1. Rehydration models used in the study

Models	Model Equations	References
Peleg	$M = M_0 + \dfrac{t}{k_1 + k_2 t}$	[17]
Weibull	$M = M_e + (M_0 - M_e)\exp\left[-\left(\dfrac{t}{\beta}\right)^\alpha\right]$	[18]
Exponential	$M = M_e[1 - \exp(-Ht)]$	[19]
First-order	$M = M_e + (M_0 - M_e)\exp(-Kt)$	[15]

Examining the studies in literature, many researchers stated that the model describing rehydration curves of the foods dried in various ways is the Weibull model [22, 23]. In the equation for Weibull model given in Table 1, M_0 represents the initial moisture content of non-rehydrated sample, M is the moisture content of sample in the t time of rehydration, M_e is the equilibrium moisture content is given by equation 5. t is the rehydration time, α is the shape parameter of Weibull model and β is the speed parameter of Weibull model.

$$M_e = M_0 + \frac{1}{k_2} \tag{5}$$

H value in the equation of Exponential model is the rehydration kinetics constant (min^{-1}) for the model and K value in the equation of First-order model is the rehydration kinetics constant (min^{-1}) for the model.

Calculating the Effective Diffusivities during Rehydration

Diffusion of water during drying of foods and rehydration of dried foods is a complex phenomenon. While a quick mass transfer is concerned at the beginning of rehydration and drying processes, the transfer rate decreases towards the end of the processes. Thereby diffusion of the water decreases [24, 25].

During rehydration, effective diffusivities (D_{eff}) are calculated by 2nd Fick's law, depending on the temperature [25, 26]. While using this law, calculations are made by some assumptions. Assumptions made during rehydration process are as follows; (I) initial moisture content is uniform in dried food material. (ii) Volume and shape changes are negligible during rehydration. (iii) Moisture uptake through food surface begins with immersing food into rehydration water. (iv) external resistances to mass and heat transfer are negligible. (v) Effective diffusivity coefficient is constant during rehydration. (vi) During rehydration, it was accepted that the thickness of samples did not change. [27]. Accordingly, during rehydration of sun-dried eggplant at different temperatures, specified assumptions were made in order to calculate the effective diffusivities and the equation (6) is used because of it is shape similar to a thin plate. Indeed, in the study by Wu et al. [28], the same equation was used for calculation of effective diffusivities by the dimensionless moisture ratio, during drying the eggplants with vacuum drying under 2.5, 5 and 10 kPa absolute pressure and at 30, 40 and 50 °C.

$$\frac{M - M_e}{M_0 - M_e} = \frac{8}{\pi^2}\sum_{n=1}^{\infty}\frac{1}{(2n+1)^2}\exp\left(-\frac{(2n+1)^2}{4}\pi^2\frac{D_{eff}}{L^2}t\right) \tag{6}$$

Where; D_{eff} represents the effective diffusivity (m^2 s^{-1}), M is the moisture content at any time t, (kg water per kg dry matter), M_0 is the initial moisture content of non-rehydrated sample (kg water per kg dry matter), Me is the equilibrium moisture content (kg water per kg dry matter), t is the rehydration time (min) and L is the half of thickness (m) of the food to be rehydrated. The value of the half-thickness (L) is 5 mm.

The graphics for changes in dimensionless moisture values of dried eggplant samples rehydrated in water at three different temperatures were drawn in a way to have semi-logarithmic coordinates and slope (k) values were calculated using the Equation (7).

In the study, effective diffusivities for rehydration process performed at three different temperatures were derived using calculated slopes.

$$k = \frac{\pi^2 D_{eff}}{4L^2} \tag{7}$$

Statistical Analysis

Compatibility of rehydration models used in the study with experimental data was determined by nonlinear regression analysis using Microsoft Excel (Microsoft Office, version 2013). As the compatibility indicators, determination coefficient (R^2) being close to 1 was taken into consideration, and also compatibility was presumed to increase by the root mean square error (*RMSE*) and the low chi-square (χ^2) values. *RMSE* and χ^2 values were calculated using Equation 8 and Equation 9.

$$\text{RMSE} = \left[\frac{1}{N} \sum_{i=1}^{N} \left(M_{exp,i} - M_{c,i} \right)^2 \right]^{1/2} \qquad (8)$$

$$\chi^2 = \frac{\sum_{i=1}^{N} \left(M_{exp,i} - M_{c,i} \right)^2}{N - z} \qquad (9)$$

where, $M_{exp,i}$ experimental moisture content (kg water per kg dry matter), $M_{c,i}$ calculated moisture content (kg water per kg dry matter), N is number of experimental data points and z is number of constant in model. The higher values of R^2 and the lower values of χ^2 and $RMSE$ are chosen as the criteria for goodness of fit.

RESULTS and DISCUSSION

Effect of Temperature on Rehydration of Sun-Dried Eggplants

Sun-dried eggplant samples were rehydrated in water at 25, 35 and 45°C. The samples gained water during rehydration process. In rehydration process for 24 hours, moisture content of samples increased to an average value of 5.342±0.70 kg water per kg dry matter from the value of 0.073 kg water per kg dry matter. Figure 1 shows the graph indicating changes in weights of samples by time.
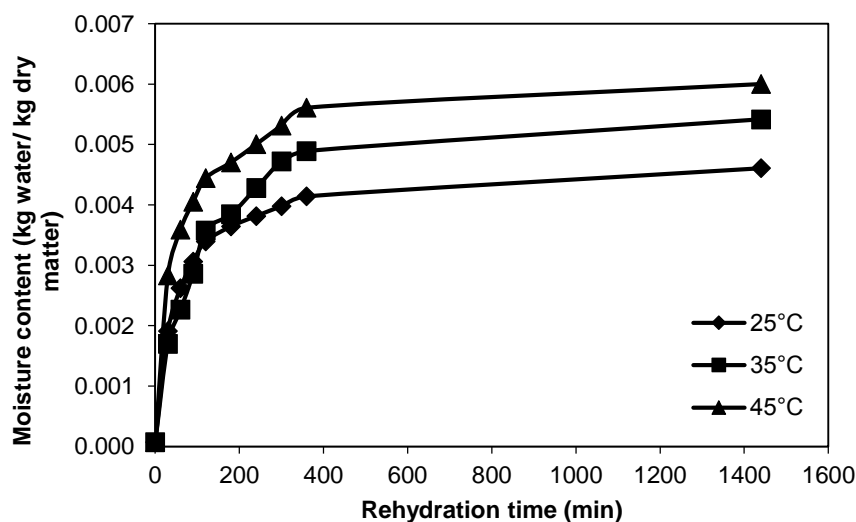

Figure 1. Changes in moisture content of dried eggplants rehydrated at different temperatures by rehydration time

It was determined that the temperature of water used during rehydration affects water gain of samples. Thus, as seen in the Figure 2, it was observed that rehydration rate increased by the increase in temperature of rehydration water. Also, while rehydration rate was higher at the beginning of all the rehydration processes, it is decreases towards the end of the processes. A similar situation can be found in several studies in the literature. For example, Singh et al. [29] sliced sweet potato samples at a thickness of 8±0.3 mm and after some pretreatments, they dried them by convective drying method at 50, 55 and 60°C. Then they rehydrated the dried sweet potato slices in pure water with temperatures of 25, 40 and 80°C. They found that the weight of the samples increased quickly at the beginning of rehydration process. They also determined that the rehydration process performed at 80°C was more rapid than one at 25°C. Doymaz [30] also achieved similar results in his study in which rehydration properties of carrot slices dried with convective method were analyzed.

Modeling for Rehydration Kinetics

Rehydration processes of eggplant samples were continued for 24 hours in each temperature. The weight change data obtained throughout the rehydration was used on the rehydration kinetics modeling given in Table 1.

Coefficients for each model were determined by modeling studies performed using Microsoft Excel program. In addition, statistical parameters for the models were calculated and the rehydration model which best fits the experimental data was determined. The coefficients for rehydration models and the statistical parameters were given in Table 2. The determination coefficient (R^2) is an important parameter in determining the most appropriate statistical model. In addition to R^2, the chi-square (χ^2) and $RMSE$ values calculated for each model also helped identification of the most appropriate rehydration model. As a result of the studies, the model with maximum R^2 value and minimum χ^2 and $RMSE$ values was stated as the most appropriate model.
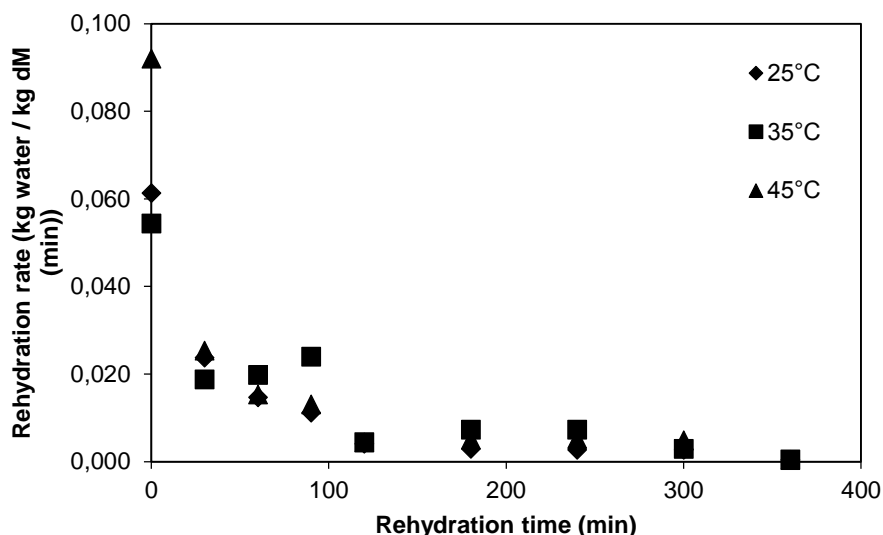
Figure 2. Changes in rehydration rates of dried eggplants rehydrated at different temperatures by rehydration time

Table 2. Estimated parameters and statistical analysis of the models at different rehydration temperatures for sun-dried eggplants

Model	Temperature (°C)	Model Parameters		Statistical Parameters		
Peleg's		k_1	k_2	RMSE	χ^2	R^2
	25	10.177±0.05	0.2206±0.002	0.050913	0.003240	0.9993
	35	16.036±0.07	0.1652±0.005	0.110996	0.015400	0.9924
	45	7.449±0.03	0.1653±0.007	0.057553	0.004141	0.9958
Weibull		β	α	RMSE	χ^2	R^2
	25	0.0118±0.0001	0.5726±0.001	0.012374	0.000204	0.9912
	35	0.0056±0.0002	0.6682±0.003	1.141270	1.736664	0.9897
	45	0.0127±0.0004	0.5305±0.002	0.227688	0.069123	0.9867
First-order rehydration kinetic		K		RMSE	χ^2	R^2
	25	0.0072±0.0006		1.109959	1.368900	0.6593
	35	0.0050±0.0004		1.760756	3.444736	0.8675
	45	0.0074±0.0003		1.648179	3.018327	0.7118
Exponential		H		RMSE	χ^2	R^2
	25	0.0073±0.0008		1.271378	1.271378	0.6418
	35	0.0050±0.0005		1.035911	1.226414	0.8572
	45	0.0074±0.0004		1.707309	3.331320	0.6999

Based on the data obtained by modeling, as seen in Table 2, Peleg model was determined to have the maximum R^2 value and minimum χ^2 and RMSE values. It was determined that Peleg better represents the increase in moisture content values determined experimentally during rehydration process with high prediction ability, in all rehydration conditions. Coherence of the experimentally obtained moisture content values for different temperatures with the moisture content values calculated by Peleg model are shown in the graphs in Figure 3.

Examining the studies on rehydration kinetics in the literature, it is observed that obtained results are similar to the results obtained by our study. Planinic *et al.* [21]

dried sliced carrot in a fluid bed dryer at different temperatures (60, 70, 80 and 90°C) and rehydrated at room temperature. They have stated that the Peleg model was more successful to represent the rehydration results. Dadali *et al.* [20] dried spinach by microwave method, rehydrated in water at different temperatures and determined that Peleg model was the one appropriate to their working conditions. Moreira *et al.* [31] cut chestnut in dimension of 10×10×15 mm and dried in a convective dryer at 65°C. Then, they rehydrated the chestnuts at four different temperatures (25, 45, 70 and 100°C). They have stated that the results obtained by Peleg rehydration model fit well enough with the experimental data.
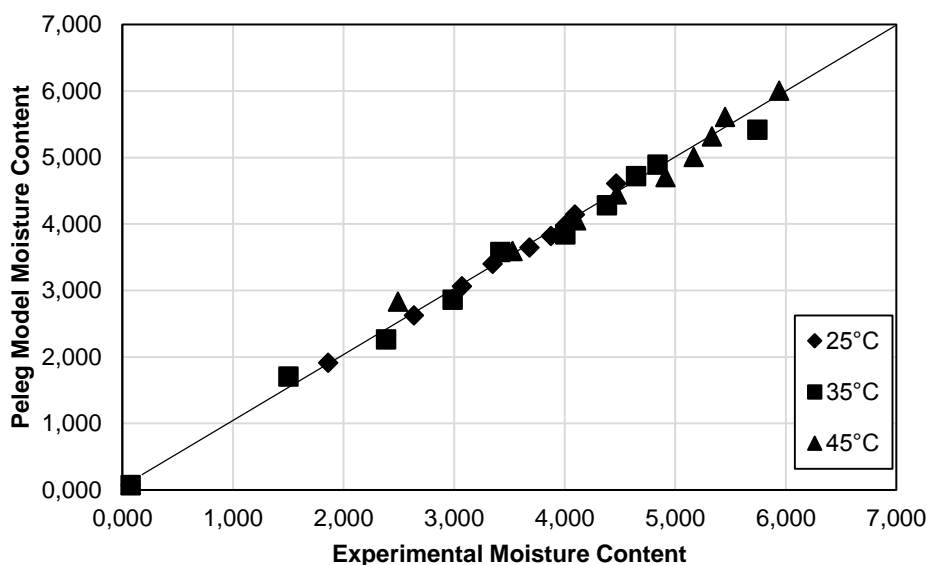
Figure 3. Coherence of experimentally moisture content values with moisture content values by Peleg model

Effective Moisture Diffusivity during Rehydration

In order to calculate the effective moisture diffusivity of sun-dried eggplants during rehydration in water at three different temperatures, changes in dimensionless moisture values by time were drawn in a way to have semi-logarithmic coordinates. Effective diffusivities were calculated by using the obtained slope and shown in Table 3.

Table 3. Calculated effective diffusivities for different rehydration temperatures

Rehydration temperature (°C)	Effective diffusivity (m^2 s^{-1})
25	$3.21×10^{-8}$
35	$3.72×10^{-8}$
45	$4.06×10^{-8}$

According to the results in Table 3, water gaining of samples increased with an increase in the temperature of water used in rehydration process, thus the effective diffusivities also increased. In literature, examining the studies about rehydration of the dried fruits and vegetables, similar results were found. Indeed, Maldonado *et al.* [27] found effective diffusivity values for mango of $1.24×10^{-10}$ m^2 s^{-1} (25°C) and $1.60×10^{-10}$ m^2 s^{-1} (40°C). In another study, Falade and Abbo [32], dried date palm (*Phoenix dactylifera* L.) samples at temperatures between 50-80°C with hot air method and rehydrated the dried date palm samples at three different temperatures (15, 30 and 45°C). At the end of the rehydration process, they have stated that the effective diffusivities increase by the increase in the temperature of rehydration water and calculated the effective diffusivities respectively as $1.80×10^{-10}$ m^2 s^{-1}, $4.74×10^{-10}$ m^2 s^{-1} and $1.15×10^{-9}$ m^2 s^{-1}.

CONCLUSION

Following results were obtained in this study which analyzes the effect of using water at three different temperatures (25, 35 and 45°C) on rehydration kinetics of sun dried eggplants.

• It was determined that dried eggplant samples gained humidity more rapidly with the increase in temperature of the rehydration water. The increase in kinetic energy of the water molecules with the increase in temperature of the rehydration water could be stated as the reason for acceleration in water diffusion into the samples.

• When coherence of the experimental data obtained during the rehydration process with the models in literature, Peleg model had higher R^2 and lower χ^2 and *RMSE* values compared to the other models. Therefore, Peleg model was the best model defining the rehydration kinetics of dried eggplant samples.

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