# Design of Hazelnut Drying System Supported By Solar Energy, Investigation of Drying Performance and Determination of Proper Drying Model

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**Abstract-** Rapid and efficient drying process for the hazelnuts is required because of the lack of plain areas for solar drying due to the rough landforms in the Black Sea Region, high amount of cloudy days, causing product deteriorations and rots by instantaneous rain transitions and unexpected sudden rains. In this study, a hazelnut drying system supported by solar energy in order to achieve a rapid and efficient drying process was designed and drying performance was examined. In the designed system, a spiral shaft was used for movements of the hazelnuts in the drying chamber. Besides, the inner temperature of the chamber increased with the help of a sun collector. The process control device was used to keep the inner temperature as constant at 40°C. In the experiments, 20kg weight hazelnut husk was used. The experiment was performed between 09:00 and 17:00 hours in a day with normal sunlight conditions and the total drying process took about 8 hours. The moisture ratios (MR) and drying rates (DR) graphics were obtained by scaling weight losses of the hazelnuts in each hour. As a result, it is observed that the 20kg weight of the hazelnuts decreased to the 17.201kg and therewith the total removed moisture from the hazelnuts was about 2.799kg. In the light of the moisture ratios obtained by experiments, 8 different kinetic drying models were performed with MATLAB software. According to the kinetic model results, the lowest reduced chi-square ($\chi^2$) and root mean square error (RMSE) were about $241 \times 10^{-6}$ and $155 \times 10^{-4}$ respectively. In addition, the coefficient of determination ($R^2$) was calculated as 0.9982 which is the highest result closest to 1. Among the 8 kinetic models, the Page model is given the best results for the drying process.

**Keywords** Hazelnut, drying, moisture ratio, drying rate, solar energy.

## 1. Introduction

The hazelnut (Corylus avellana L.) is a member of the Betulaceae family that is generally known as the birch family [1]. This species is classified into two subgroups as Betulaceae and Corylideae and the hazelnut we know is Corylus L. [2]. The hazelnut which belongs to the Betulaceae family is popular worldwide and it is a tree hazelnut that is commonly eaten by people. Mainly, the hazelnut is cultivated in the Black Sea Region of Turkey and its mass production was about 545.000 tons in annual average between 2012 and 2016 years [3]. Besides, it is produced in Italy, USA, Georgia, and Azerbaijan [3]. Other European countries, such as Spain and France, have a small amount of production capacity, but those are still important hazelnut producers of hazelnut varieties with specific characteristics [4]. In 2017, the leading producer of the hazelnut was Turkey with 675.000 tons of mass production and the second one was Italy with 131.000 tons capacity [5]. The hazelnut consists of 58-64% fat, 11-16% protein, and 15-18% carbohydrates. Besides, it is also a good source of vitamins, minerals, organic acids, phenolic compounds and fat-soluble bioactive compounds [6]. More than 95% of the hazelnut harvest is used in the food industry and the rest of them is eaten directly [7]. The raw hazelnut is commonly used in food and chocolate industries, such as ice cream, cake, and biscuits. In addition, hazelnut oil is preferred in cooking, cosmetic, and pharmaceutical industries [8].

The hazelnut is needed for specific drying or roasting process in order to store and use apart from the harvest period. Otherwise, aflatoxins and fungus are formed in wet hazelnuts. The roasting process changes the taste, color, texture, and appearance of the hazelnut and increases the distinctive properties significantly. Roasted hazelnut is a tastier product than the raw hazelnuts. The roasting process also eliminates clumps of hazelnut seeds, defuses enzyme which speeds up the food damages and wipes out undesirable microorganisms and food pollutants. The drying or roasting process of foods depends on the heat and mass transfer properties of the dried product. The temperature and moisture information of the product is crucial for equipment and process design, choosing the application such as quality control, proper storage and carriage [9].

In order to extend shelf life and prevent food spoilage in the storage process, several drying methods were developed. Many kinds of research have been studied on those developed drying methods in the literature. Alibas experimentally studied the drying methods of microwave, convective, and combined microwave of the leaf beet. Their results showed that the proper drying process for the drying of chard leaves was combined microwave-convective drying method. The optimum combination level for combined microwave-convective drying method consists of 500 W power, 75°C temperature with 0.09 kWh energy consumption and 4.5 min drying period [10]. Ceylan et al. investigated the usage of a drying oven with a heat pump for the apple drying process experimentally. Sliced apples with 4mm thick were dried at 40°C in 20% average relative humidity using 2.8m/s airspeed throughout 3.5 hours from 4.8 (g water/g dry substance) to 0.18 (g water/g dry substance) water ratios. Their results showed that the toxin production and the activities of some toxigenic blights because of lower-level water activity were prevented. In addition, it was seen that the heat pump system can be used in order to energy requirement of furnace in environment air with low relative humidity of regions [11]. Variyenli designed and built plane surface and incarcerating surface with absorber-plated drying ovens and performed the performance comparisons of those experimentally as well. In the experiments, kiwi slices with 4-6 mm thickness in 100g weight were dried. The experiments were performed using 2.5, 3.0, and 3.5m/s air velocities. It was determined that the average temperature in the drying chamber for hazelnuts drying process was about 41.6°C and 44.1°C for plane surface and incarcerating surface drying ovens respectively. As a result, it was concluded that the incarcerating surface drying oven carried out the drying process in less than 30 minutes on average when compared with the plane surface drying oven [12].

Wang et al. developed a couple of strategies in order to decrease occurred cracks during the hot air-drying process for hazelnuts after the harvest. The physicochemical properties of the nutshells or seeds, moisture adsorption isotherm, nutshell structures and the morphological properties of the inner fibers bonded to the nutshells, and crack ratios were determined for four different hazelnut species experimentally. They used a systematical experimental approach that combines the Taguchi design and gradient drying to decrease the nutshell cracks while the drying efficiency was preserved. Throughout the hot air-drying process, it was seen that the Relative Humidity (RH) is a more effective parameter than the temperature and air velocity factors which effects Jefferson's nutshell cracks. They found out that the crack ratio was about 30% and the drying time was decreased nearly up to 15 hours for Jefferson's hazelnut when the moisture of the nutshell was reached 16g in 100g weight approximately and the RH was increased from 50% to 60 or the temperature was decreased from 38°C to 32°C. As a result, it was determined that Jefferson had the highest cracking ratio because of its lower shell density, larger air gap between shell and kernel. Besides, it was seen that increasing of RH or decreasing the temperature at a critical moisture content of inshells reduced cracking ratio to $< 30\%$ within a drying time of 15 h [13]. Eskandari et al. designed and produced a laboratory-scale dry peeling system using infrared radiation for hazelnuts. The developed system consists of infrared radiation unite to loosen nutshells and an abrasive unite to remove nutshells from hazelnuts. Each performance of those unites was examined individually. Three different infrared powers as 800, 1200, and 1600 Watt and three different radiation times as 2, 3, and 4 minutes, and four different moisture contents as 4, 6, 8, and 10g in 100 g weight were investigated. In general, it was determined that the nutshell crack was about 0.87%, the peeling efficiency was about 81.6% in terms of the performance of the IR dry peeling system [14]. Topuz et al performed an experimental and numerical study on dried hazelnuts in the fluid-bed dryer. In this study, a laboratory-scale fluid-bed dryer system was designed and produced in order to obtain experimental results. They developed a mathematical model for simulation of simultaneous instable heat and mass transfer during the fluid-bed drying process of big parts. Crank-Nicholson finite volume method was performed to solve the system of equations. The results showed that the good agreement between mathematical and experimental results was observed [15]. Ozdemir and Devres defined five semi-theoretical and two empirical thin-film models at 100°C -160°C temperatures range for the thin film properties of hazelnut during the drying process. They observed that effective diffusion ranged from $2.301 \times 10^{-7}$ to $11.759 \times 10^{-7}$ $m^2/s$ and the temperature dependence of diffusion coefficient correlated with Arrhenius type relation. The thin film drying characteristics of the hazelnut drying process were defined using the Thompson model which is an empirical model with linear temperature property [9]. Ceylan and Aktas modeled a hazelnut dryer with heat pump support using artificial neural networks. Artificial Neural Networks (ANN) approach is a general technique to match nonlinear relationships between inputs and outputs without knowing the details of these relationships. In the study, an ANN application was performed for a heat pump dryer controlled by PID. The air velocity was controlled in the PID controlled heat pump dryer and it was changed according to the temperature-controlled by a process control device. The hazelnut drying process was tested at 40°C, 45°C, and 50°C drying air temperatures. Afterward, the total drying times, the moisture ratios of hazelnuts, and the drying air velocities were estimated for four different air temperatures of drying process as 42°C, 44°C, 46°C, and 48°C by applying ANN approach to the experimental results [16]. Aghbashlo et al. presented a mathematical model of the drying process in a semi-industrial conveyor drying system. They used carrot slices for drying experiments. In the experiments, three different air temperatures as 50°C, 60°C, and 70°C, three different air velocities as 0.5, 1.0, and 1.5m/s, and three different kinetic drying models as Lewis, Handerson-Pabis, and Page were used. The coefficients of determination ($R^2$) and Root Mean Square Errors (RMSE) of specimens, squares between experimental and estimated moisture ratios ($\chi^2$) were compared using non-linear regression analysis via MATLAB software. Their results showed that the Page model was the proper mathematical model to define the kinetic drying process [17]. Goncuoğlu et al. examined the serotonin that is a neuroactive compound and tryptophane which is a pioneer in all kinds of nuts in Turkey contents in hazelnuts in two harvest years running. They explained the serotonin content of the hazelnut skins and the effect of the drying process on the serotonin content of the hazelnuts. They determined the serotonin and the free tryptophane concentrations after the water extraction and performed alkaline hydrolysis for bonded tryptophane before UPLC-MS/MS analysis. They found out that the free and bonded tryptophane and serotonin contents changed ($p<0.05$) in most of the hazelnut types according to the harvest year. The average serotonin content of the hazelnut nutshells was 4 times greater than the hazelnuts. Besides, it was seen that the serotonin content of the dried hazelnuts was as valuable as raw hazelnuts, and the essential difference of the serotonin content occurred after the hazelnut was dried at 150°C for 30 minutes [18]. Felbinger et al. studied the experimental control of the 13 different hazelnut types using 16 RAPD-primer with RAPD-PCR analysis. They distinguished the various types of hazelnuts with agarose gel electrophoresis band pattern. They transferred the band pattern to the bar chart in order to verify the selection of the one hazelnut type and better understand which primer should be used as well. In addition, a cultivated tree was created in order to classify hazelnut species rapidly in case the validation of the hazelnut type fails. Thus, they developed a rapid and low-cost method to validate the accuracy of the hazelnut species [19]. In light of the above findings, many studies were perfomed on the drying processes. However, in terms of drying process of the hazelnuts, it is observed that the overburning and spoiling issues occured due to the high temperature of the inner cabinet and immobile of the hazelnuts. in order to prevent those issues, the products must be moved in constat motion and the temperature should be kept as stabil. Besides, increasing the inner temperature of the cabinet by solar energy is an important and a key point for the drying process in terms of energy conservation. in this sense, this study presents design of a novel drying system for drying process of the hazelnuts and production of designed system. The moisture ratios (MR) and drying ratios (DR) charts were created by calculating weight loss after the 8 hours drying process of the 20kg weight hazelnuts in order to determine proper kinetic drying model at the end of the drying process.

## 2. Material and Method

In this study, a hazelnut drying system supported by solar energy to dry a specific number of nuts was designed. For the drying system, the dimensions of the main body are about 50 cm x 70 cm x 150 cm. Besides, the body structure of the drying chamber was built with steel rectangular shape profiles and all profiles were welded. After the welding process, the body structure was covered with a 1 mm thickness plane sheet. The spiral shaft with 48 mm diameter and 150 cm length was mounted into the drying chamber and the pulley-belt mechanism with an electric motor was used to trigger this spiral shaft. The grid circuit of the city was used for triggering electrical motor with 220V. PVC pipes with 25mm diameter that are generally used for underfloor heating were installed on the lower plate of the drying chamber. Steel grate was placed on the pipes to prevent the contact between nuts and the PVC pipes. Shown in Figure 1, the drying system was placed on the horizon with a 45-degree angle using steel profile legs and the drying system was operationalized by establishing the collector connections.

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**Fig. 1.** View of the drying camber and solar energy production unit

The schematic connection view of the solar drying system is shown in Figure 2. As seen in Figure 2, when the nuts were placed into the product entrance, the drying system was started to operate the drying process. The shaft was triggered with the pulley-belt mechanism and electric motor and the amount of the nuts was carried by rotation of the spiral shaft from the bottom of the drying chamber to the top of it. When the nuts were reached to the top of the system, they dropped down on the steel grate and continued to the movement by means of the gravity to the bottom of the system. Accumulated nuts at the bottom of the system were once again carried by the shaft to the top of the system. So, this circulation movement continues until the nuts were dried. In the meanwhile, the calescent water in collector passed through in PVC pipes to increase the temperature of the drying chamber.

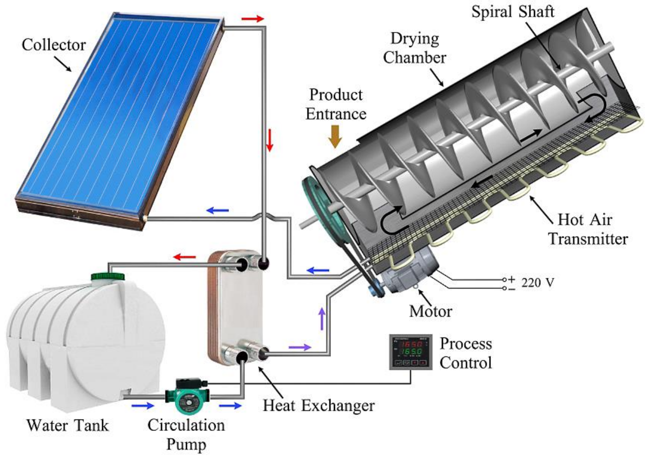


**Fig. 2.** The schematic connection view of the solar drying system

The inner temperature of the drying chamber can increase up to 70°C at hours with intense sun rays. Since this situation damages the product, the inner temperature must be kept at 40°C. Therefore, the temperature was kept constant by directing the hot water coming from the collector to the heat exchanger. An external water tank was mounted to the other outlet of the heat exchanger and the water circulation was achieved with a circulation pump. The connected process control device was used to keep the temperature of the drying chamber as constant. The temperature of the hot water coming from the collector decreased by means of activation of the process control device and circulation pump. In the experiments, 20kg weight hazelnut husk was used, and those hazelnuts were dried for 8 hours. The experiments were started at 09:00 on 22.10.2019 and ended at 17:00. The inner temperature, outer temperature, and radiation intensity were measured at every hour. Elimko-6000 temperature measurement instrument with 12 measurement channels was used to determine inner and outer temperatures of the drying system. The working temperature range of the instrument is between 0-50°C. Haenni solar meter was used for measuring the intensity of the radiation.

The moisture ratio (MR) that is a non-dimensional term and shows the changes of the hazelnut as a function of time can be calculated by equation (1). The drying rate (DR) can be calculated using equation (2) as well [20].

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

$$DR = \frac{M_{t+dt} - M_t}{dt} \quad (2)$$

In equation (1), ($M_0$), ($M_t$), and ($M_d$) define the initial moisture, moisture at a time t, and final equilibrium moisture contents respectively. MR indicates the moisture ratio (MR) at different t moments of the drying process [20]. In equation (2), DR and $M_t$ define the drying rate and moisture at t moment respectively. $M_{t+dt}$ indicates the moisture at t+dt as well [21].

## 3. Results and Discussion

The measured inner temperature values are shown in Figure 3.

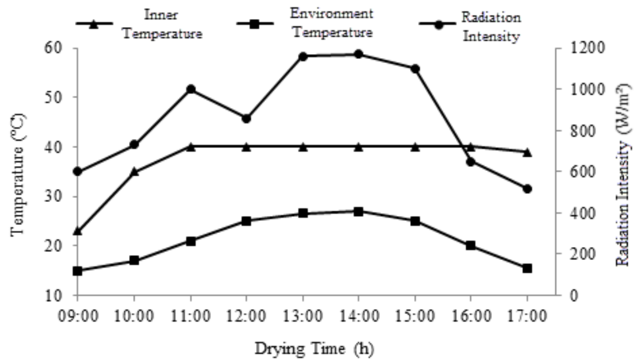


**Fig. 3.** Temperature and radiation intensity as a function of the drying time

As shown in Figure 3, the outer temperature was about 15°C at the beginning of the experiments. It is seen that the temperature increased in the following hours and it decreased after 14:00. Mean temperature was low because the experiments were performed at the end of October. Besides, the clouds effected the intensity of radiation directly. The decreasing of the intensity of radiation at 12:00 shows the high cloud salinity concentration in meanwhile. However, after 12:00, the intensity of radiation increased due to the scattering of clouds. The inner temperature of the chamber was kept about 40°C as constant although the decreasing of the intensity of radition at 12:00.

In the study, the weight loss was measured by scaling hazelnut in each hour. The weight loss curve of the hazelnuts measured each hour is given in Figure 4. As shown in Figure 4, the weight loss was increased rapidly in the first hours of the drying experiments. However, after 14:00, it exhibited slowing behavior. Herein, the release of moisture was rapidly at the beginning of the drying process due to the fact that hazelnuts were constantly in motion by means of the rotation movement of the spiral shaft and the inner temperature was about 40°C as constant.

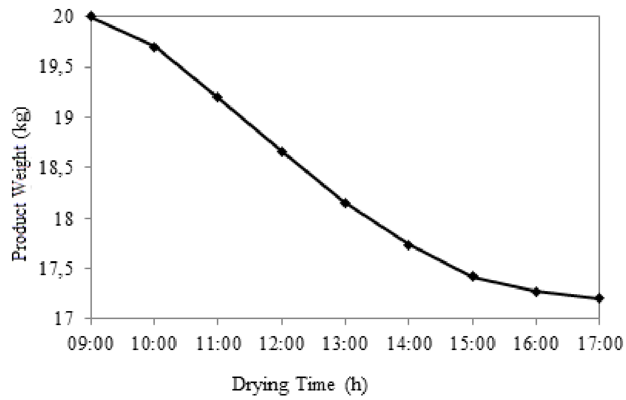

**Fig. 4.** The weight loss of the hazelnut as a function of the drying time

The experimental moisture ratio curve as a result of 8 hours drying process is shown in Figure 5.

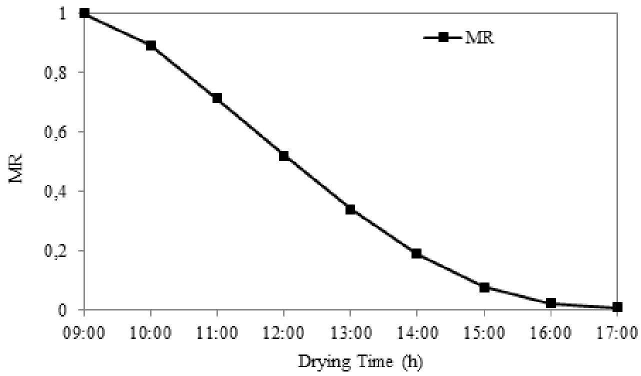


**Fig. 5.** The moisture ratio curve as a function of the drying time

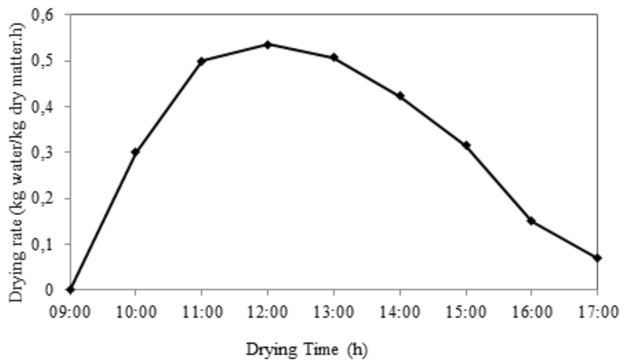


**Fig. 6.** Drying rate of the hazelnuts as a function of time

As shown in Figure 6, the drying rate showed incremental behavior throughout the first two hours of the drying process. It was seen that the drying rate decreased rapidly after 12:00. This is because the moisture on the outer perimeter of the hazelnut evaporated rapidly by reason of rising of the temperature. However, the moisture in the product could not evaporate as fast as the moisture on the outer perimeter because the inner moisture does not contact with the hot air directly. Therefore, more time is needed to remove the inner moisture from the product. As shown in Figure 5, the decline of the drying rate after 12:00 occurred because the moisture in the product showed slowing evaporation behavior during the drying process. After 16:00, the drying rate showed decreasing behavior and become a minimum value.

After the determination of the moisture ratios and measurements of the time-dependent weight losses, 8 different drying kinetic models were performed on the experimental results. MATLAB software was used for kinetic models. In Table 1, the estimated moisture ratio (MR) values for 8 different drying kinetic models used in MATLAB are given [22].

**Table 1.** Drying kinetic models

| Model No | Model Name | Model |
|---|---|---|
| 1 | Newton | $MR = \exp(-kt)$ |
| 2 | Page | $MR = \exp(-kt^n)$ |
| 3 | Modified Page I | $MR = \exp[-(kt)^n]$ |
| 4 | Henderson and Pabis | $MR = a.\exp(-kt)$ |
| 5 | Logarithmic | $MR = a.\exp(-kt) + c$ |
| 6 | Two-term exponential | $MR$ = aexp(-kt)+(1-a)exp(-kat) |
| 7 | Wang and Singh | $MR = 1 + at + bt^2$ |
| 8 | Diffusion Approach | $MR$ = aexp(-kt)+(1-a)exp(-kbt) |

Equation (3), equation (4), and equation (5) are used to calculate root mean square errors (RMSE) and reduced chi-square ($\chi^2$) of estimated values, and coefficient of determination ($R^2$) of kinetic models respectively in order to reveal the agreement between moisture ratios obtained by experiments (exp) and estimated (est) by kinetic models as statistical approach [23, 24].

$$RMSE = \left[\frac{1}{N}\sum_{i=1}^{n}\left(MR_{est} - MR_{exp}\right)^2\right]^{1/2} \quad (3)$$

$$X^2 = \frac{\sum_{i=1}^{n}\left(MR_{exp} - MR_{est}\right)^2}{N-z} \quad (4)$$

$$R^2 = 1 - \left[\frac{\Sigma\left(MR_{exp} - MR_{est}\right)^2}{\Sigma(MR_{est})^2}\right] \quad (5)$$

The Root Mean Square Error (RMSE) in equation (3) shows the deviation between the experimental value and estimated kinetic model value. Besides, it is seen that the decreasing of reduced chi-square (χ2) in equation (4) indicates the increment of the good agreement between experimental and kinetic model values. In addition, the usability of the kinetic model is stated when the coefficient of determination ($R^2$) in equation (5) closes to (1). According to the results of the statistical approach, the coefficients of the proper kinetic model is determined by multiple regression analysis.

**Table 2.** Calculated results using models for drying kinetic

| Model name | Model parameters | $R^2$ | $\chi^2$ | RMSE |
|---|---|---|---|---|
| Newton | k: 0.279 | 0.9251 | 0.0109008 | 0.10440 |
| **Page** | **k: 0.0903**<br>**n: 1.821** | **0.9983** | **0.0002876** | **0.01696** |
| Modified Page I | k: 0.2632<br>n: 1.837 | 0.9980 | 0.0003375 | 0.01834 |
| Henderson and Papis | a: 1.109<br>k: 0.3067 | 0.9404 | 0.0099102 | 0.09955 |
| Logarithmic | a: 1.737<br>c: -0.6836<br>k: 0.127 | 0.9862 | 0.0026688 | 0.05166 |
| Two-term exponential | a: 2.167<br>k: 0.4692 | 0.9886 | 0.0018860 | 0.04346 |
| Wang and Sing | a: -0.1888<br>b: 0.007241 | 0.9851 | 0.0024865 | 0.04986 |
| Diffusion Approach | a: 16.75<br>b: 0.8675<br>k: 0.06289 | 0.9831 | 0.0032834 | 0.05730 |

In Table 2, the $R^2$, $\chi^2$, and RMSE values of the 8 kinetic drying models are given. From Table 2, it is seen that the proper kinetic drying model is the Page model because the $R^2$ value is about 0.9983 which is the closest value to 1 and $\chi^2$ value is about 0.0002876 which is the closest value to 0. Another parameter that supports the usability of the Page model is that the RMSE value is close to 0 as 0.01696.

## 4. Conclusion

This study presents the design of a drying system in order to apply a rapid and efficient drying process for grown hazelnuts in the Black Sea region of Turkey. The low-cost and innovative approach is obtained by means of a designed system supported by solar energy. Decreasing the 20 kg hazelnut to 17.201kg in 8 hours, removing %14 moisture content from products, and having the desired moisture content indicate the operation of the drying system efficiently. It is shown that the spiral shaft which is placed in the system and provides continuous movement for the hazelnut by rotation movement during the drying process has been found to play an important role in the rapid removal of the moisture content in the product. A high-quality drying process is achieved with the help of keeping the inner temperature as the desired level by a process control device and preventing the hazelnuts from roasting at an excessive temperature. In the experiments, the weight losses were measured in every hour by scaling the hazelnuts. In light of experimental results, $MR_d$ and DR values were calculated. After this, calculated $MR_d$ values were inputted to the MATLAB software and 8 kinetic drying models were performed and the proper drying model was determined. $R^2$, $X^2$, and RMSE values considered for determination of the proper kinetic drying models. The main factors for the determination of the proper kinetic drying model are that $R^2$ value is close to 1, $X^2$ and RMSE values are close to 0. As a conclusion, the proper kinetic drying model is determined as Page model for the drying process of 20 kg weight hazelnuts during 8 hours drying time in designed drying system according to the experimental results and calculation in MATLAB software.

### Nomenclature

| | |
|---|---|
| *a, b, c, n* | The constants of the models |
| *z* | Number of parameters in model |
| $k, k_0, k_1$ | Drying rate constants ($min^{-1}$) |
| *t* | Time (min) |
| $M_0$ | The initial moisture content (g water/g dry matter) |
| $M_t$ | The moisture content at a time t (g water/g dry matter) |
| $M_d$ | The final equilibrium moisture content (g water/g dry matter) |
| *MR* | The moisture ratio (dimensionless) |

| | |
|---|---|
| *N* | Number of observations |
| *DR* | Drying rate (g water/g dry matter) |
| $R^2$ | Coefficient of determination |
| $\chi^2$ | Reduced chi-square |
| *RMSE* | Root mean square error |

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