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Using Gene Expression Programming (GEP) for Modelling the Drying Characteristics of Onion Slices (Allium Cepa)

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ABSTRACT

In this study, the drying properties of onion slices were experimentally investigated under the different drying temperatures of 45, 50, 55, and 60°C for different thicknesses of 2, 3, 4, and 5mm. The drying characteristics of the onion slices were significantly influenced by drying temperature. Thin slices with higher temperature dried in the shortest time while thick slices with low temperature took longer to dry. In modeling drying curves, the moisture ratio values of the onion slices were compared with five models commonly used in the literature. In addition, Gene Expression Programming (GEP) was used to model the drying characteristics of the onion slices, and mathematical formulas were derived to calculate moisture ratio values. The results indicated that the moisture ratio values predicted by all models agreed with the experimental moisture ratio values for onion slice samples at different temperatures. The scientific findings we obtained here showed that *the two model* provided a better simulation of onion slice drying kinetics than other models in different experimental temperature and thickness ranges. Also, the GEP model was able to usefully determine the moisture ratio of onion slices with appropriate accuracy in a shorter time without the need for complicated formulas.

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Soğan Dilimlerinin Kuruma Özelliklerinin Modellenmesinde Gen İfade Programlamasının (GEP) Kullanımı (Allium Cepa)

ÖZET

Bu çalışmada soğan dilimlerinin kuruma özellikleri 45, 50, 55 ve 60˚C farklı kurutma sıcaklıklarında ve 2, 3, 4 ve 5 mm kalınlıklarında deneysel olarak incelenmiştir. Soğan dilimlerinin kuruma özellikleri kurutma sıcaklığından önemli ölçüde etkilenmiştir. Yüksek sıcaklıktaki ince dilimler daha kısa sürede kururken, düşük sıcaklıktaki kalın dilimlerin kuruması daha uzun sürmüştür. Kurutma eğrilerinin modellenmesi için soğan dilimlerinin nem oranı değerleri, literatürde yaygın olarak kullanılan beş model ile karşılaştırılmıştır. Ayrıca soğan dilimlerinin kurutma özelliklerinin modellenmesi için Gen İfade Programlama (Gene Expression Programming, GEP) kullanılmıştır. Nem oranı değerlerinin hesaplanması için matematiksel formüller çıkarılmıştır. Sonuçların, tüm modeller tarafından tahmin edilen nem oranı değerlerinin, farklı sıcaklıklarda soğan dilimi örnekleri için deneysel nem oranı değerleriyle uyumlu olduğu görülmüştür. Burada elde ettiğimiz bilimsel bulgular, *two-term model*, farklı deneysel sıcaklık ve kalınlık değerleri aralığında soğan dilimlerinin kurutma kinetiğinin diğerlerine göre daha üstün simülasyonunu sağladığını belirlemiştir. Bununla birlikte, GEP modeli, soğan dilimlerinin nem oranı değerlerinin karmaşık formüllere ihtiyaç duymadan daha kısa sürede ve uygun doğrulukla belirlenmesinde kullanışlı olmuştur.

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INTRODUCTION

The onion (*Allium cepa L.*) is originated in Central Asia. It belongs to the *Alliaceae* family and is an important commercial crop. The onion is a vegetable with economic and cultural importance in Turkey, where consumption is very common (Candar, 2013). It is used as a vegetable or flavoring (Muhammad et al., 2017). Onions are planted on over 60000 hectares in Turkey, and 2200000 tons are produced annually (TUIK, 2020). Especially when the demand for dehydrated onions is high, there is a need to develop effective and efficient techniques for drying. .

Due to their relatively high moisture content, spring onions have a short shelf life. Dried onion can be consumed in numerous ways such as directly, in drugs and medical treatments, as a spice, as a food additive, or in instant soups or salad dressings. However, it also needs to be noted that the physicochemical properties of the onion may be altered during the drying process (Talens et al., 2017).The drying process can improve the efficiency of packaging, storing, and transporting the product (Sharma et al., 2005 a). Drying is one of the most frequently used techniques for preservation as it can prevent the growth and reproduction of microorganisms (Wang et al., 2017).

Blanco-Cano et al. (2016) conducted the thermogravimetric analysis of the thin-layer drying kinetics of apples. The experimental drying curves obtained were fitted to the Wang-Singh equation, so that the moisture ratio of apples was predicted. Szadzinska et al. (2017) showed that hybrid drying methods considerably shortened drying time, reduced energy consumption, and positively influenced product quality factors. Rabha et al. (2017) determined the drying characteristics of Ghost Chilli peppers and selected the drying model which best fitted the experimental moisture content data. For their study, the Page and Modified Page models for open sun drying and the Midilli and Kucuk model for the solar dryer drying were found to be suitable. On the other hand, Jafari et al. (2016) used nonlinear regression techniques, fuzzy logic, and artificial neural networks to estimate the dynamic drying behavior of onions.

In this study, a hot air dryer was designed and manufactured for drying onion slices of different thicknesses. Drying experiments were carried out at different thicknesses and temperatures. Drying behaviors were investigated using models commonly used in the literature. In addition, Gene Expression Programming was used to model the drying properties of onion slices. Mathematical formulas were obtained for calculating the moisture ratio values.

MATERIALS and METHODS

Experimental Setup

An experimental hot air dryer was designed and constructed to dry onion slices of different thicknesses at different drying temperatures. Temperature-humidity recording devices were installed in the air inlet and outlet sections of the drying system and also in the sections where the shelves were located. A schematic diagram and photograph of this system are shown in Figure 1. Fresh onions were employed for the tests.

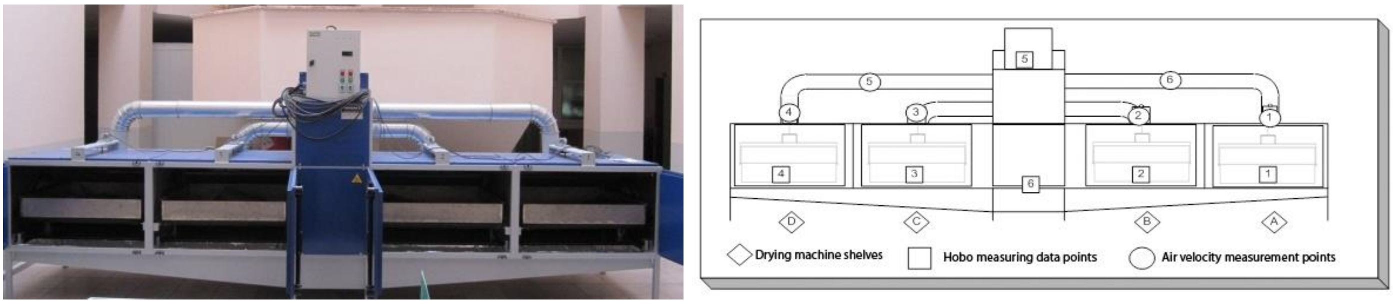

Figure 1. Schematic diagram and photograph of the experimental drying system
Şekil 1. Deneysel kurutma sisteminin şematik diyagramı ve görseli

The mean diameter of the onion rings used in the experiments was 65.55 ± 7.05mm. The skin of the onions was removed, and they were washed and then cut into slices of 2, 3, 4, and 5mm thickness for the tests. The sliced onions were placed on sample trays, each containing a weight of 50g (Figure 2). All products were evenly distributed on the shelves.

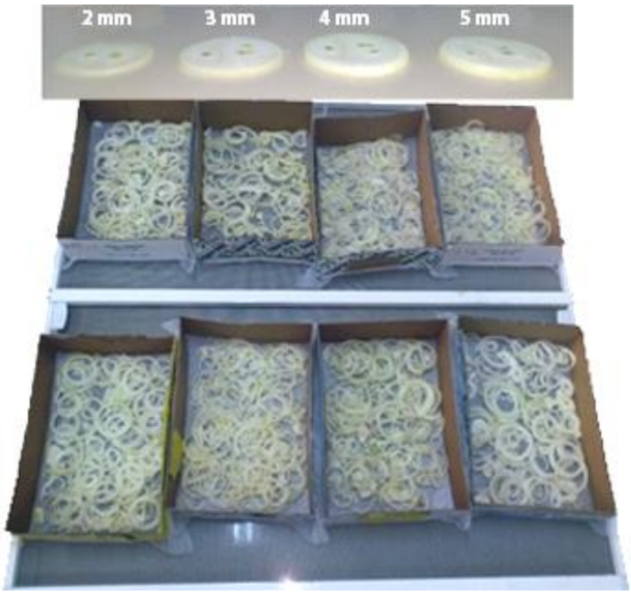

Figure 2. Sliced onions of different thicknesses and the location of samples on trays
Şekil 2. Farklı kalınlıklarda dilimlenmiş soğanlar ve tepsi içerisindeki numune yerleri

The drying experiments were performed at temperatures of 45, 50, 55, and 60°C. After specific trying, the sample trays were set to dry in a controlled manner for periods of 30, 60, 120, 240, and 360 minutes. After drying, the colors of the samples were measured in three reps with the Minolta CR-400 color measuring device. In addition, the color and odor of the samples were sensorially controlled before and after drying.

Thin Layer Drying Equations

Drying is a complex process associated with the coupled mechanisms of heat and mass transfer. Therefore, it is beneficial to use mathematical equations for the drying characteristics of products. Loss of nutritional value of the dried products must be kept to a minimum. Therefore, modeling is a necessity (Saavedra et al., 2017).

The drying process is described by the moisture ratio (MR), which quantifies the reduction of the moisture content of the product with time. There are many mathematical expressions in the literature to predict the moisture ratio (Saavedra et al., 2017). The MR is defined as:

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

where M, M_0, and M_e are the instantaneous moisture content, initial moisture content, and equilibrium moisture content respectively.

It is important to model drying behavior, that is, to investigate the drying characteristics of onions. To determine the best drying model, the experimental moisture content data were compared with the outputs of five thin layer drying models in the literature. The five commonly used thin layer model equations in the literature are given in Table 1 (Dhanushkodi et al., 2017).

Table 1. Equations of thin layer models
Çizelge 1. İnce tabaka model denklemleri

Model no *Model no*	Name *İsim*	Equation *Denklem*
1	Newton	$MR = exp(-kt)$
2	Page	$MR = exp(-kt^n)$
3	Henderson and Pabis	$MR = a*exp(-kt)$
4	Logarithmic	$MR = a*exp(-kt) + c$
5	Two-term model	$MR = a*exp(-k_0t) + b*exp(-k_1t)$

The appropriate models are qualified by root mean square error (RMSE), coefficient of determination (R^2), and reduced chi-square. These parameters can be calculated as follows (Mitra et al., 2011; Avhad and Marchetti, 2016; Jiang et al., 2017):

$$R^2 = \frac{SSTotal - SSError}{SSTotal} \quad (2)$$

Where

$$SSTotal = \sum_{i=1}^{n}(MR_{exp,i} - MR_{avg})^2 \quad (3)$$

$$SSError = \sum_{i=1}^{n}(MR_{exp,i} - MR_{pred,i})^2 \quad (4)$$

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n}(MR_{exp,i} - MR_{pred,i})^2}{N}} \quad (5)$$

$$chi - square = \frac{\sum_{i=1}^{n}(MR_{exp,i} - MR_{pred,i})^2}{N - z} \quad (6)$$

and MR_{exp} is the experimental moisture ratio, MR_{pred} is the predicted moisture ratio, MR_{avg} is the average value of moisture ratio, N is the number of observations and z is the number of constants in the model.

GEP Model Application

Gene Expression Programming (GEP) is an evolutionary algorithm (EA). It can emulate biological evolution based on computer programming. GEP belongs to the wider class of genetic algorithms. The important difference between GEP and other EAs is the form of the solution provided. GEP has the ability to provide a reasonably succinct solution to a given situation. GEP, a computer software program, is encoded by one or more genes. GEP uses characteristic linear chromosomes. The chromosomes consist of a random combination of terminals and functions (Ferreira, 2001; Ferreira, 2006). Figure 3 shows a brief flowchart of GEP.

In this study, the GEP algorithm was used to estimate the moisture ratio of onion slices of different thicknesses. Moisture ratio values depending on drying air temperature (T), drying time (t) and the thickness of the onion slices (s) were estimated. The optimal GEP parameters for estimating the moisture ratio of the onion slices are shown in Table 2.

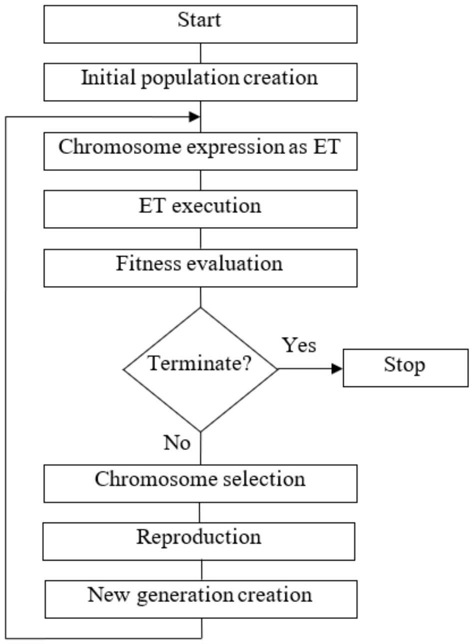

Figure 3. Flowchart of GEP algorithm (Das et al., 2019)

Şekil 3. GEP algoritmasının akış şeması (Das et al., 2019)

RESULTS and DISCUSSION

The model which best describes the drying curve of a thin layer of onion slices was evaluated by comparing the predicted MR with the experimentally observed MR in the hot air dryer.

Table 2. Parameters used in the GEP model

Çizelge 2. GEP modelinde kullanılan parametreler

Parameters of the GEP model *GEP modeli parametreleri*	**Moisture Ratio (MR)** *Nem Oranı*
Number of generations	396364
Number of chromosomes	30
Number of genes	3
Head size	7
Linking function	Addition
Mutation rate	0.0020
Inversion rate	0.005
One-point combination rate	0.005
Two-point combination rate	0.005
Gene combination rate	0.002
Gene transposition rate	0.002
Function set	+, –, *, /, power, √, ln, log, sin, cos, tan, sinh, cosh, tanh, 10^x, e^x, 1/x, (1-x)
R^2	0.9905

Experimental Approach – Drying Characteristics

In the experimental part of the study, the onions were dried in a drier with a shelf-type system. To minimize the loss of the aroma, taste, and odor of the onions, it was decided to keep the drying parameters at low temperatures. After the drying process, an average of 12-15% dry matter was obtained from the onion. Experimental results showed that the dried onions had a good color and odor.

The variation of the moisture ratio of the onion slices with time for the different thicknesses and drying temperatures are plotted in Figures 4-7. The general result showed that the moisture ratio decreased as the drying time increased.

The drying temperature has a considerable impact on the drying properties of the onion slices. The results showed that the moisture content decreased by 90% in a drying time in the range of 240-360 min, after which the drying rate slowed down. Similar behaviors also have been observed in many foodstuffs such as Shiitake mushrooms and Jinda chilis (Artnaseaw et al., 2010), apples (Aktaş et al., 2009), and onion slices (Sarsavadia et al., 1999; Praveen Kumar et al., 2005; Sharma et al., 2005 a).

The thinner slice samples dried faster than the others, because of faster transfer from the surface. Similar results were reported for banana slices by Samadi et al. (2014).

Power Consumption

The variation in the total electricity consumption in the drying process according to the drying temperature is shown in Figure 8. As the drying temperature decreases, the drying time increases and the heat loss in the dryer increases. Accordingly, the energy consumption of the fan and heaters also increases. It was found that the greatest power consumption occurred with a temperature of 45°C. It was determined that to make it more profitable in terms of cost, the system should be set to a drying temperature of 60°C, as long as this was appropriate for the ambient conditions and the machine.

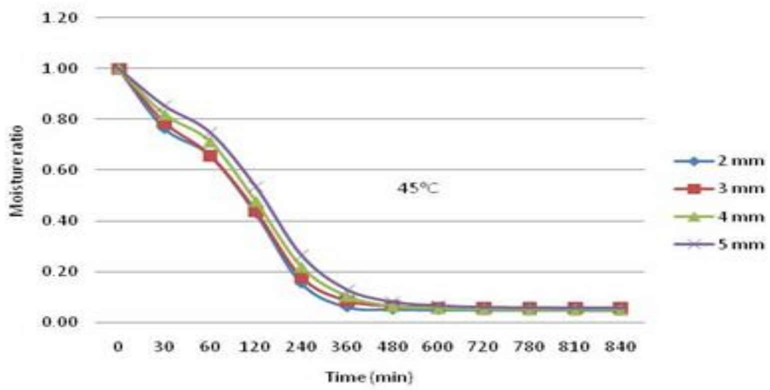

Figure 4. Effect of thickness on drying time for onion slices at 45°C drying temperature
Şekil 4. Soğan diliminin 45°C kuruma sıcaklığında kuruma süresine kalınlığının etkisi

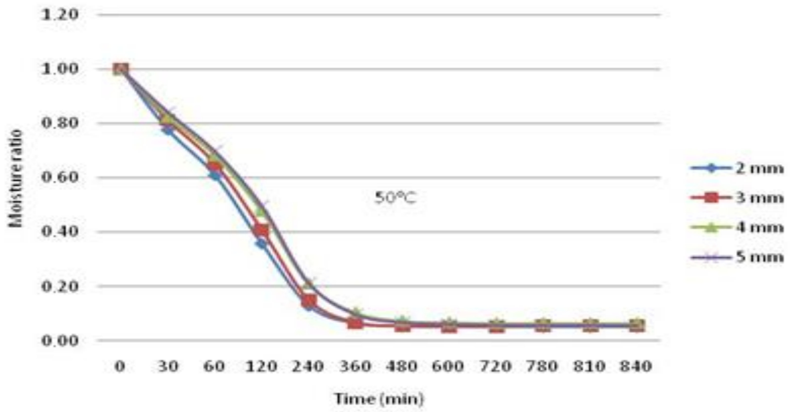

Figure 5. Effect of thickness on drying time for onion slices at 50°C drying temperature
Şekil 5. Soğan diliminin 50°C kuruma sıcaklığında kuruma süresine kalınlığının etkisi

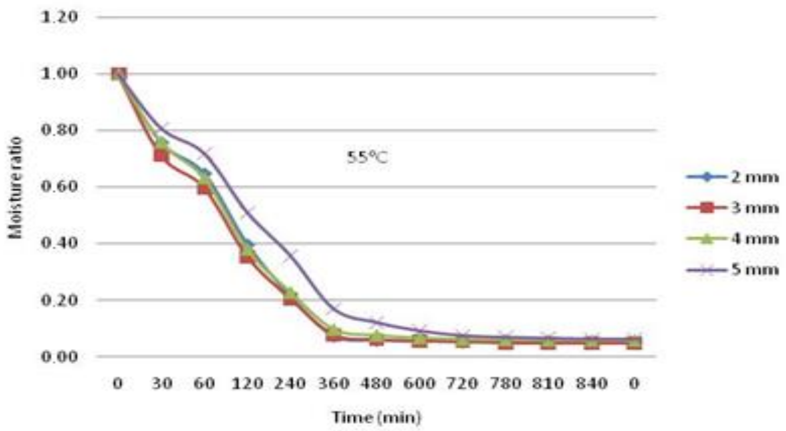

Figure 6. Effect of thickness on drying time for onion slices at 55°C drying temperature
Şekil 6. Soğan diliminin 55°C kuruma sıcaklığında kuruma süresine kalınlığının etkisi

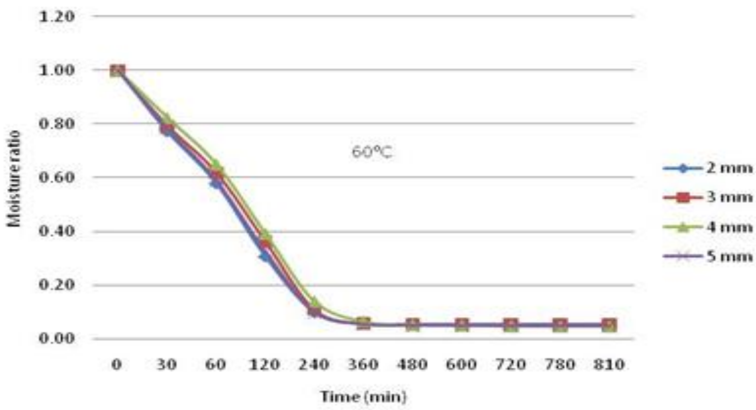

Figure 7. Effect of thickness on drying time for onion slices at 60°C drying temperature
Şekil 7. Soğan diliminin 60°C kuruma sıcaklığında kuruma süresine kalınlığının etkisi

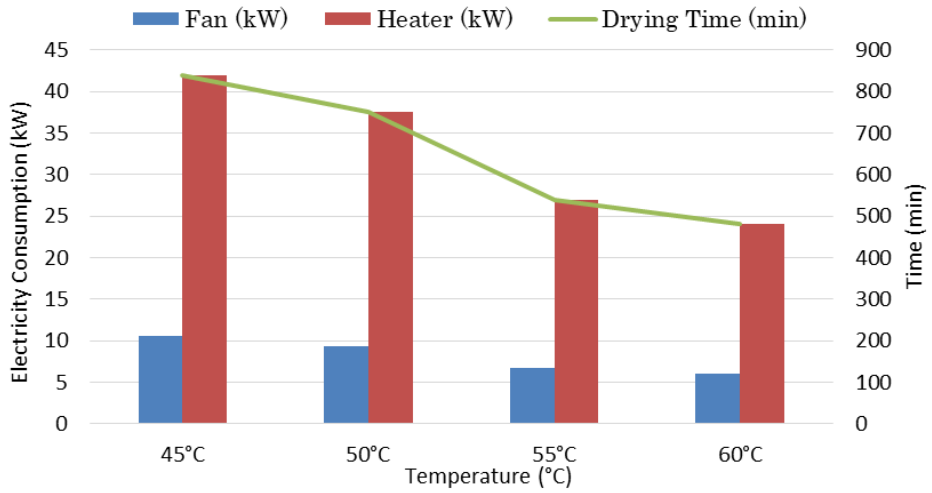

Figure 8. Total electricity consumption (kW)
Şekil 8. Toplam elektrik tüketimi (kW)

Theoretical Approach – Modeling of Drying Curves

More accurate modeling of the drying conduct of onion slices is essential for the study of drying kinetics. Thin-layer drying models such as the Newton, Page, Henderson and Pabis, Logarithmic, and Two-term models are commonly used to describe the drying characteristics of foodstuff. Five different equations were used to simulate the curve fitting of the experimental data. The statistical results of the models tested are given in Tables 3-6.

In order to accurately define the drying treatment of onion slices, five mathematical models were compared according to their R^2, RMSE and chi-square deviations. The resulting mathematical model provided values of R^2 varying from 0.97249 to 0.99685 for onion slice samples, and the RMSE values of onion slices ranged from 0.00810 to 0.00238 at different temperatures. chi-square values were found to vary from 0.00010 to 0.00001 for onion slice samples at different temperatures. The constants and coefficients of the two-term drying model with the highest R^2 and lowest RMSE gave better fits than the others (R^2=0.99685, RMSE=0.00238, chi-square=0.00001).

The predicted moisture ratio values were compared with the two-term version and the experimental moisture ratio values of onion slices at different drying temperatures. As seen in Figures 9, it was found that the predictions made by the two-term model were in good agreement with the experimental data. The points are located on a 45-degree slope line and deserve a very high correlation rate ($R^2 > 0.99$). Therefore, it can be concluded that the two-term model are suitable for predicting the moisture ratio of onions. Similar results were reported by Sharma et al. (2005 b).

GEP Model Approach

Thin layer drying models, the Newton, Page, Henderson and Pabis, Logarithmic, and Two-term models, were used to determine the drying behavior of onion slices. In addition, the GEP model was used. The mathematical formulations obtained from the GEP model for the moisture ratio values of onion slices were presented as follows:

$$\mathrm{MR} = \left(0.8869^{0.5758\,t} + (2.7861 - s)\right)^{0.25} + \tanh\left(\frac{1}{s}\left(\frac{-10.7767}{t} - (s + 5.7877)\right)\right) + \tanh(2.2443\,t) + \frac{10.4754}{T} + 0.1830 \quad (7)$$

The regression curve of the moisture ratio of onion slices for the test data set is shown in Figure 10. As seen in Fig. 10, the correlation coefficient obtained for the moisture ratio value of onion slices is 0.9905. The obtained results show that the GEP model exhibits a successful performance for predicting the moisture ratio values of onion slices.

The statistical results of the GEP model compared with thin layer drying models are given in Tables 3-6. GEP model can be an appropriate approach for predicting of the moisture ratio values of onion slices according to given results in Table 3-6. The formulas obtained from the GEP model are relatively short and simple. Also, no software is required for these formulas.

In recent years, evolutionary algorithms have received a great deal of attention for its wide applications. In particular, the gene expression programming (GEP) is acknowledged as a powerful and problem-independent algorithm for multivariate optimization. GEP outperform considerably existing adaptive algorithms. Therefore, GEP offers new possibilities for solving more complex technological and scientific problems.

However, GEP has also been shown to have certain disadvantages, such as slow convergence and low solution accuracy, particularly for problems with a high-dimensional and large space (Ferreira, 2001; Yang and Ma, 2016).

Table 3. Constants and performance evaluation obtained from drying models for different thicknesses of onion slices (for the drying temperature T=45°C)

Çizelge 3. Farklı soğan dilimleri kalınlıkları için kurutma modellerinden elde edilen sabitler ve performans değerlendirmesi (kurutma sıcaklığı T=45°C için)

Model *Model*	**Thickness (mm)** *Kalınlık (mm)*	**Constant** *Sabit*	R^2	**RMSE**	**Chi-square**
Newton	2	k=0.00725	0.97848	0.00886	0.000105
	3	k=0.00681	0.97425	0.00881	0.000124
	4	k=0.00595	0.98289	0.00737	7.77E-05
	5	k=0.00515	0.97377	0.00695	7.57E-05
Page	2	k=0.010992, n=0.913243	0.97521	0.008620	0.000103
	3	k=0.012859, n=0.868986	0.97070	0.008055	9.63E-05
	4	k=0.008315, n=0.933585	0.97888	0.006901	6.95E-05
	5	k=0.006395, n=0.958419	0.98804	0.007101	7.19E-05
Henderson and Pabis	2	k=0.007079, a=0.984538	0.97808	0.008757	0.000110
	3	k=0.006617, a=0.982114	0.97385	0.008548	0.000130
	4	k=0.005890, a=0.992823	0.98213	0.007323	8.42E-05
	5	k=0.005143, a=0.999507	0.98731	0.006928	8.56E-05
Logarithmic	2	a=0.958955, k=0.008018 c=0.039294	0.99094	0.004683	0.000036
	3	a=0.951537, k=0.007833 c=0.050083	0.99512	0.003082	0.000015
	4	a=0.968114, k=0.006765 c=0.040892	0.99645	0.003052	0.000016
	5	a=0.974155, k=0.005946 c=0.042336	0.99428	0.003476	0.000021
Two-term model	2	a=0.005247, k_0=-0.002763 b=0.987925, k_1= 0.007469	0.99430	0.003796	0.000025
	3	a=0.013547, k_0=-0.001784 b=0.983204, k_1= 0.007297	0.99737	0.002300	0.000009
	4	a=0.999274, k_0= 0.006290 b=0.004665, k_1=-0.002867	0.99810	0.002102	0.000009
	5	a=1.009025, k_0= 0.005481 b=0.002044, k_1=-0.003910	0.99615	0.002467	0.000011
GEP model	2		0.9956	0.017578	0.00038
	3		0.9963	0.015769	0.00030
	4		0.9935	0.021605	0.00056
	5		0.9860	0.330880	0.00130

Table 4. Constants and performance evaluation obtained from drying models for different thicknesses of onion slices (for the drying temperature T=50°C)
Çizelge 4. Farklı soğan dilimleri kalınlıkları için kurutma modellerinden elde edilen sabitler ve performans değerlendirmesi (kurutma sıcaklığı T=50°C için)

Model *Model*	**Thickness (mm)** *Kalınlık (mm)*	**Constant** *Sabit*	R^2	**RMSE**	**Chi-square**
Newton	2	k=0.008176	0.974755	0.00796	9.56E-05
	3	k=0.007174	0.976623	0.00791	9.51E-05
	4	k=0.006005	0.984741	0.00755	8.26E-05
	5	k=0.005902	0.982375	0.00602	5.51E-05
Page	2	k=0.013682, n=0.889044	0.984070	0.007779	7.50E-05
	3	k=0.009888, n=0.933129	0.983190	0.007870	8.03E-05
	4	k=0.009966, n=0.900884	0.990920	0.005659	4.80E-05
	5	k=0.007389, n=0.956211	0.991870	0.005500	4.43E-05
Henderson and Pabis	2	k=0.008071, a=0.991641	0.974283	0.007807	0.000103
	3	k=0.007159, a=0.998637	0.976552	0.007942	0.000104
	4	k=0.005872, a=0.984890	0.978333	0.007100	8.35E-05
	5	k=0.005880, a=0.997349	0.990629	0.005736	5.70E-05
Logarithmic	2	a=0.965689, k=0.009336 c=0.043305	0.997867	0.001941	0.000008
	3	a=0.974102, k=0.008311 c=0.042865	0.994613	0.003299	0.000019
	4	a=0.960567, k=0.007040 c=0.047217	0.995786	0.002460	0.000011
	5	a=0.977893, k=0.006703 c=0.035726	0.993131	0.003165	0.000018
Two-term model	2	a=0.994563, k_0= 0.008784 b=0.010529, k_1=-0.002348	0.999100	0.001292	0.000003
	3	a=1.008742, k_0= 0.007674 b=0.002900, k_1=-0.004380	0.997850	0.002008	0.000007
	4	a=0.998737, k_0= 0.006472 b=0.003716, k_1=-0.003969	0.998140	0.001385	0.000004
	5	a=0.000935, k_0=-0.005713 b=1.008215, k_1= 0.006252	0.998250	0.001892	0.000009
GEP model	2		0.9983	0.011005	0.00015
	3		0.9988	0.009962	0.00012
	4		0.9980	0.012880	0.00020
	5		0.9974	0.016340	0.00033

CONCLUSION

The results showed that the drying characteristics of the onion slices were significantly influenced by drying temperature. As the drying time increased, the moisture ratio decreased. The thinner slice samples dried faster than the others, because of faster transfer from the surface. It was found that the greatest power consumption occurred at a temperature of 45°C. For the models of drying curves, the moisture ratio values of the onion slices at the different drying temperatures were compared with five commonly used models. The results indicated that the predicted moisture ratio values in all models were in accord with the experimental moisture ratio values. In addition, the GEP model for predicting the moisture ratio values of onion slices was used. Mathematical formulas were derived for the calculation of moisture ratio values. It was proved that both traditional methods and GEP modeling methods could predict the drying characteristics of onion slices. Generally, the scientific findings obtained here showed that the two-term model provided a simulation which was slightly superior to the other models for determining the drying characteristics of onion slices. However, the GEP model helped to determine the moisture ratio of the onion slices with acceptable accuracy in a shorter time, without the need for complicated formulas.

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Researchers' Contribution Rate Statement Summary

The authors declare that they have contributed equally to the article.

Table 5. Constants and performance evaluation obtained from drying models for different thicknesses of onion slices (for the drying temperature T=55°C)
Çizelge 5. Farklı soğan dilimleri kalınlıkları için kurutma modellerinden elde edilen sabitler ve performans değerlendirmesi (kurutma sıcaklığı T=55°C için)

Model *Model*	**Thickness (mm)** *Kalınlık (mm)*	**Constant** *Sabit*	R^2	**RMSE**	**Chi-square**
Newton	2	k=0.007074	0.972680	0.009130	0.000107
	3	k=0.007976	0.958219	0.011460	0.000158
	4	k=0.006973	0.943355	0.012030	0.000166
	5	k=0.004789	0.985840	0.007580	0.000080
Page	2	k=0.015701, n=0.837859	0.987220	0.005464	4.47E-05
	3	k=0.025714, n=0.755256	0.993190	0.003859	2.23E-05
	4	k=0.020517, n=0.781481	0.991110	0.004810	3.39E-05
	5	k=0.010371, n=0.860207	0.996000	0.002651	1.23E-05
Henderson and Pabis	2	k=0.006692, a=0.965346	0.975704	0.007953	8.88E-05
	3	k=0.007242, a=0.945176	0.958034	0.009887	0.000128
	4	k=0.006416, a=0.951722	0.972546	0.009081	0.000116
	5	k=0.004513, a=0.955225	0.99061	0.005079	4.02E-05
Logarithmic	2	a=0.943625, k=0.007933 c=0.043310	0.997134	0.002749	0.000017
	3	a=0.921668, k=0.008969 c=0.051337	0.997608	0.002402	0.000019
	4	a=0.926298, k=0.008247 c=0.058586	0.995637	0.001986	0.000010
	5	a=0.934279, k=0.005177 c=0.036525	0.996887	0.002345	0.000016
Two-term model	2	a=0.021898, k_0=-0.001079 b=0.962831, k_1=0.007651	0.99758	0.002237	0.000021
	3	a=0.322836, k_0=0.003146 b=0.665809, k_1=0.012985	0.99450	0.003858	0.000030
	4	a=0.795203, k_0=0.009916 b=0.198116, k_1=0.001975	0.99534	0.002810	0.000020
	5	a=0.864451, k_0=0.004087 b=0.133904, k_1=0.030248	0.99424	0.003082	0.000025
GEP model	2		0.9975	0.021340	0.00059
	3		0.9971	0.015550	0.00031
	4		0.9962	0.020270	0.00053
	5		0.9916	0.037920	0.00185

Conflict of Interest

The authors declare that they have no conflicts of interest.

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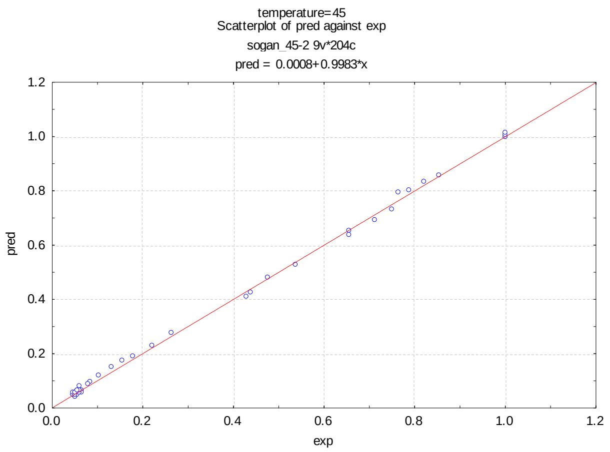
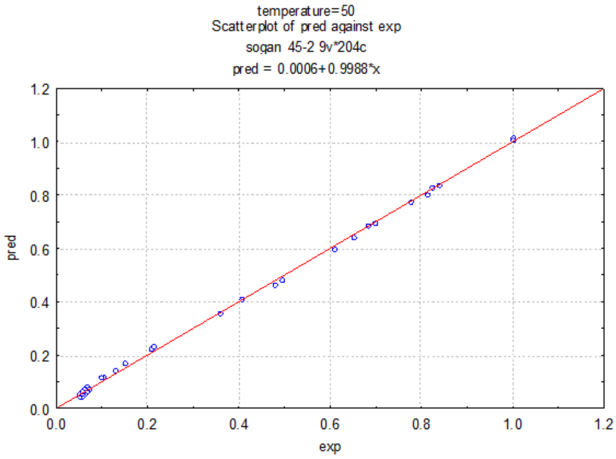
Table 6. Constants and performance evaluation obtained from drying models for different thicknesses of onion slices (for the drying temperature T=60°C)
Çizelge 6. Farklı soğan dilimleri kalınlıkları için kurutma modellerinden elde edilen sabitler ve performans değerlendirmesi (kurutma sıcaklığı T=60°C için)

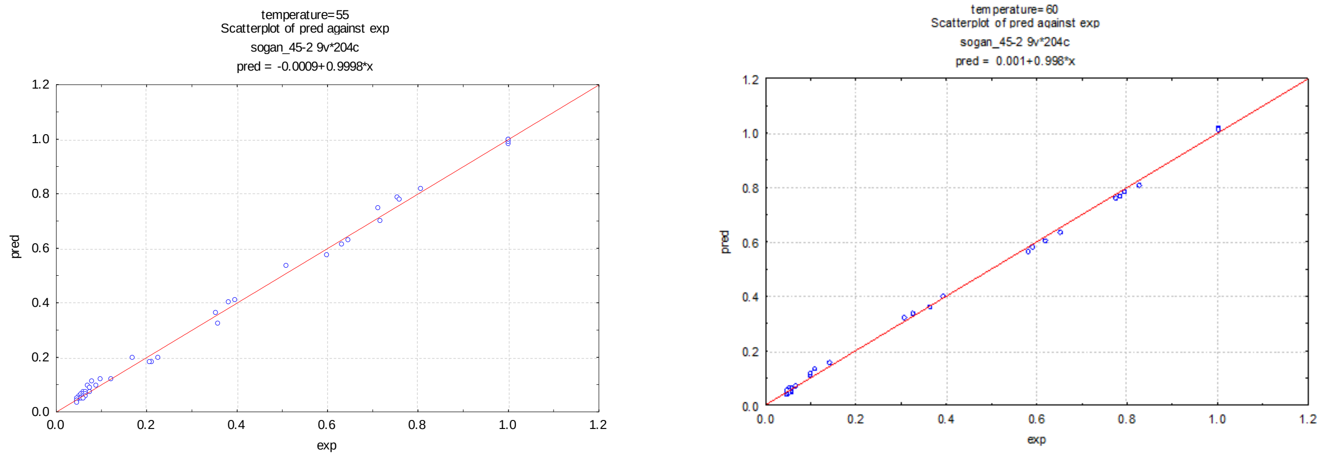
Model *Model*	Thickness (mm) *Kalınlık (mm)*	Constant *Sabit*	R^2	RMSE	Chi-square
Newton	2	k=0.009001	0.980040	0.008390	0.000100
	3	k=0.008064	0.981980	0.006760	0.000070
	4	k=0.007390	0.988580	0.005560	0.000040
	5	k=0.008766	0.986550	0.007220	0.000070
Page	2	k=0.013210, n=0.916019	0.984180	0.007860	8.23E-05
	3	k=0.009646, n=0.962240	0.981890	0.006859	6.49E-05
	4	k=0.007241, n=1.004152	0.995110	0.005128	3.64E-05
	5	k=0.010793, n=0.954911	0.987680	0.006974	6.57E-05
Henderson and Pabis	2	k=0.008974, a=0.998032	0.980134	0.008397	0.000112
	3	k=0.008077, a=1.001179	0.985761	0.006953	8.06E-05
	4	k=0.007484, a=1.009489	0.989239	0.005336	4.29E-05
	5	k=0.008795, a=1.002264	0.986519	0.007213	7.94E-05
Logarithmic	2	a=0.973737, k=0.010403 c=0.042509	0.997196	0.003092	0.000017
	3	a=0.982438, k=0.009118 c=0.033940	0.995270	0.003394	0.000024
	4	a=0.996008, k=0.008167 c=0.024475	0.996482	0.003202	0.000018
	5	a=0.982554, k=0.009904 c=0.034372	0.993543	0.003055	0.000017
Two-term model	2	a=1.007543, k_0=0.009720 b=0.004920, k_1=-0.004491	0.99894	0.002105	0.000009
	3	a=0.000982, k_0=-0.007267 b=1.011726, k_1=0.008561	0.99762	0.002277	0.000012
	4	a=1.017487, k_0=0.007799 b=0.000309, k_1=-0.008854	0.99771	0.002298	0.000011
	5	a=0.002310, k_0=-0.005595 b=1.011160, k_1=0.009331	0.99437	0.002220	0.000009
GEP model	2		0.9853	0.034380	0.00158
	3		0.9855	0.035180	0.00165
	4		0.9846	0.039840	0.00212
	5		0.9845	0.054980	0.00403



45°C drying temperature
45°C kurutma sıcaklığı



50°C drying temperature
50°C kurutma sıcaklığı



55°C drying temperature | 60°C drying temperature

55°C kurutma sıcaklığı | *60°C kurutma sıcaklığı*

Figure 9. Comparison of experimental and predicted MR values of onion slices of different thicknesses for the two-term model
Şekil 9. Two-term model için farklı kalınlıktaki soğan dilimlerinin deneysel ve tahmini MR değerlerinin karşılaştırılması

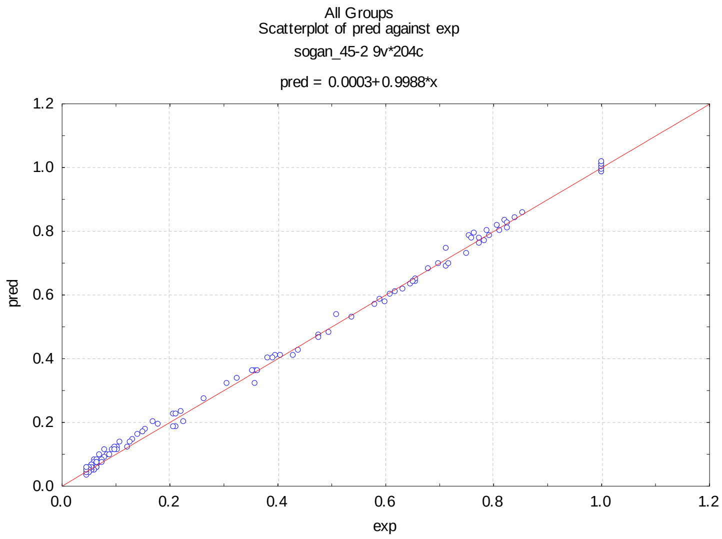


Figure 10. The regression curve of the moisture ratio of onion slices
Şekil 10. Soğan dilimlerinin nem oranının regresyon eğrisi

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