Turkish Journal of Agriculture - Food Science and Technology, 13(8): 2201-2212, 2025
DOI: https://doi.org/10.24925/turjaf.v13i8.2201-2212.7838

Turkish Journal of Agriculture - Food Science and Technology

Available online, ISSN: 2148-127X | www.agrifoodscience.com | Turkish Science and Technology Publishing (TURSTEP)

Hot Air Drying of Red Peppers: Enrichment of Drying Characteristics by Different Ethanol Concentrations and Immersion Time and Energy Consumption

Fadime Begüm Tepe[1,a,*], **Tolga Kağan Tepe**[1,b]

[1]Department of Food Technology, Şebinkarahisar Vocational School of Technical Science, Giresun University, Giresun, Türkiye
[*]Corresponding author

ARTICLE INFO

Research Article

Received : 08.05.2025
Accepted : 21.05.2025

Keywords:
Artificial Neural Network
Energy
Ethanol Pretreatment
Red Pepper
Physical Properties

ABSTRACT

The study investigates the effects of ethanol pretreatment on drying characteristics and energy consumption, thin layer and artificial neural network (ANN) modelling, colour and shrinkage properties and principal component analysis (PCA) of red peppers. Ethanol pretreatment had a positive contribution to drying time and rate of red peppers. High concentration and long pretreatment time were found to be highly effective on the increment of drying rate. Thus, drying time was shortened. Additionally, SMER value increased, and SEC value decreased upon the shortening in the drying time. The highest effective pretreatment was revealed as 100% ethanol concentration and 20 min. pretreatment time. On the other hand, Midilli and Kucuk model gave the better results among the thin layer models, while, ANN modelling showed the best prediction performance of the drying of red peppers. Ethanol pretreatments reduced the L^* value in the inner part of red peppers, with the most pronounced decrease observed in samples treated with 50% ethanol for 10 minutes. In the outer part, samples 50ET20 had the highest L^* value, while 100ET20 had the lowest. There was no significant change in the a^* value of the inner part, but the a^* value of the outer part decreased the most in samples 100ET20. The b^* value increased in the inner part with 10-minute treatment in 50% ethanol, while no notable change was in the outer part. All samples showed shrinkage tendance in both width and thickness after drying. The highest shrinkage ratios were obtained from 50ET20 and 100ET20. PCA revealed that fresh samples were positioned significantly farther from the pretreated samples. 50ET20, 100ET20 and C showed a similar arrangement in the same plane. In conclusion, ethanol pretreatment can be considered a highly promising approach. In addition, employing ANN modelling is advisable for enhancing the accuracy of the drying process optimization.

[a] *begumotag@gmail.com* *https://orcid.org/0000-0003-4989-5354* | [b] *tolga.kagan.tepe@gmail.com* *https://orcid.org/0000-0003-0484-7295*

Introduction

Although food preservation, which has been an important requirement since ancient times, has evolved with developing technology, one of the oldest known food preservation methods is drying. The main goal of drying is reducing the water activity, which can cause microbial growth and spoilage (Pandiselvam et al., 2023). Because the free movement of water molecules within foodstuff tissues provides favorable conditions for enzymatic reactions and the growing of undesirable microorganisms, which can change the quality, the shelf life of fresh foods can be extended by reducing water activity. On the other hand, the cost of storage and transportation can be reduced with the decreasing of the volume of dried foods (Xu et al., 2022).

Although, many techniques such as sun drying, hot air, microwave or freeze drying can be used for food drying, hot air drying is the best known and most preferred. Hot air drying has some advantages like basic operation, easy usage and low cost. However, long drying time and low energy efficiency besides loss of nutrients and undesirable color changes (Gu et al., 2022) have been compelled to develop alternatives to improve this method. Some treatments prior to drying such as hot water blanching, ethanol immersion, ultrasound treatment, osmotic dehydration can be considered one of the best options for protection of food quality, saving time and energy consumption. Pretreatments accelerate the drying rate by increasing permeability, provide protection to chemical deterioration by inactivating enzymes and prevent or reduce oxidation oxidation (Bassey et al., 2021). Thus, the application of pretreatment to overcome the disadvantage of hot air drying is quite promising.

Ethanol immersion pretreatment is a promising technique due to its simplicity and low-cost processing. Ethanol pretreatment improves the drying quality by changing cell wall structure, vapor pressure and capillary flow (Santos et al., 2023). The most important mechanism of this pretreatment is Marangoni effect. Marangoni effect can be defined as mass transfer (in drying this mass in drying is water) which occurs because of difference in surface tension between ethanol and water (Albuquerque et al., 2024). In a deep meaning, ethanol and water can form a homogenous mixture in any portion due to ethanol's ability to completely miscible with water when ethanol molecule bond with hydroxyl group of water molecules. Thus ethanol, which has lower surface tension than water can enter the food matrix by mixing water. Water on the surface of food displays from the surface to surrounding ethanol due to differences in osmotic pressure and outer layer of food contains both water and ethanol. During drying, ethanol quickly evaporates and causes a water/ethanol gradient. As a result, water concentration of surface rises and the surface tension increases. Thus, interior water is strongly pulled toward the surface. This transfer continues until reaching the equilibrium in the surface tension. In this way, the more mass (water) transfer, the higher drying rate. The increasing water migration from interior to surface of food at the presence of ethanol is defined as "Marangoni effect" (Albuquerque et al., 2024, Rojas & Augusto, 2018). In addition to these advantages, ethanol is harmless for humans and there is no ethanol residue after drying foods (Feng et al., 2019).

Food drying process is important for not only protection but also chemical and physical properties of foods. During the drying some modifications in food nutrients, color, flavor, texture occur, and these alterations affect the consumers acceptability. Therefore, monitoring the food process plays a crucial role providing high food quality. Mathematical modeling is a key used for optimization of drying process and monitoring the degradation of food components. The correct drying parameters such as drying time and temperature, flow rate and the best drying technique (like hot air, microwave, freeze, vacuum drying etc.) can be chosen with help of mathematical models (Tuly et al., 2023). Various mathematical models can be used for determination of changes in food quality characteristics. Thus, these models lead to a prediction about alteration of quality parameters in the appropriate process conditions. Artificial neural network is also a modelling technique which has attracted a lot of attention recently. An artificial neural network (ANN) consists of a lot of interconnected processing units. Input, hidden and output layers build the three main layers of ANN. The structure of ANN consists of neurons and nodes. ANN establishes a relationship between inputs and outputs of a system with higher learning capability through the simulation of the human nervous system (Dash et al., 2020, Sarkar et al., 2021). Thus, ANN modelling provides the best solution for problems that standard statistical and mathematical approaches fail to solve (Akter et al., 2022). ANN classified as "black box" approaches category due to information, predefined mathematical relationships, assumptions or input-output relations about various phenomenon are not required for the ANN (Aghbashlo et al., 2015).

Fresh fruits and vegetables, which are rich in many bioactive components such as vitamins, minerals, phenolics, are perishable due to their high moisture content (Deng et al., 2019). Therefore, the preservation of fresh fruits and vegetables is important for accessibility for all seasons. Red pepper (*Capsicum annum* L.) that belongs to *Solanacea* family, *Capsicum* species is a valuable plant product due to its antioxidant properties, vitamin, mineral and phenolic content (Guclu et al., 2021). Besides fresh consumption, red peppers are commonly used as a food ingredient for color and flavor alterations (Arimboor et al., 2015). Like many fruits and vegetables, fresh red peppers are perishable and have a very short shelf life after harvest (Yang et al., 2018). Drying is one of the best options for extending the shelf life of red peppers.

Studies regarding the effect of ethanol pretreatment on hot air drying of red peppers are quite limited in literature. In this study, red pepper slices (control group and ethanol pretreated samples) were dried with hot airdrying method at 60°C. It aimed to investigate the drying kinetics and properties of red peppers, analyzing drying behavior and alterations during drying with mathematical and ANN models, reveal energy consumption and determine the color and shrinkage properties of samples. Due to the complex structure of food and variety of quality criteria, choosing the best drying parameter is difficult. Principal component analyze (PCA) is versatile statistical analyses used for the best explaining variants of all variables (Greenacre et al., 2022). Therefore, the results of this study were also examined by PCA.

Material and Methods

Sample Preparation

The red peppers were procured from a local market in Şebinkarahisar, Giresun, Türkiye. Following removing undesired materials on the surface by washing, the red peppers were cut along the length. After removing the seeds and the white parts (placenta), the red pepper slices were prepared in the form of square with (4 x 4 cm ± 0.1 cm) with the average thickness 5.94 ± 0.17 mm. The initial moisture content of the red peppers was calculated as 90.51 ± 0.14% on a wet basis (WB).

Drying Procedure

The hot airdrying process was conducted at a constant temperature of 60°C and 1 m s^{-1} air velocity in a drying oven. 100 g of red pepper sample (untreated or pretreated) was weighed and placed into the drying trays. During the drying process, the weight of samples was measured with a digital scale (precision of 0.01 g) at certain intervals. When the moisture content of samples reached 5% WB, the drying process was finished. Due to ensuring accuracy and reproducibility, all experiments were performed in triplicate.

Ethanol Pretreatment

A suggested method by da Cunha et al. (2020) was used for ethanol immersion pretreatment. 50% and 100% concentrations of ethanol solution were prepared and red pepper samples were immersed in these solutions at a ratio of 1:4 (w:v) for 10 min. Different concentrations and a duration of 10 minutes were chosen to allow the solution to diffuse into the sample so that the ethanol pretreatment could take effect. At the end of the pretreatment process the surface solution was removed helping with filter paper. Unrtreated samples was coded as "C", while samples immersed in 50 and 100% ethanol for 10 min and samples immersed in 50 and 100% ethanol for 20 min were marked as 50ET10, 100ET10, 50ET20 and 100ET20, respectively.

Drying Properties

Moisture Content

During the drying moisture content alterations at intervals were observed and calculated with the Eq. (1) (Demiray et al., 2023);

$$M_t = \frac{m-DM}{DM} \tag{1}$$

M_t: Moisture content of the sample at any given time (g water g^{-1} dry matter (d.m.))

m: the weight (g) of the sample

DM: Dry matter content (g) of the sample

Moisture Ratio

The moisture ratio (MR) of the red peppers was determined via The Eq. (2).

$$\mathrm{MR} = \frac{M_t-M_e}{M_i-M_e} \tag{2}$$

M_e: The equilibrium moisture content

M_t: The moisture content at any time,

M_i: The initial moisture content**.**

The value of M_e can be assumed as 0 for hot air drying due to M_e having too small value when compared to both "M_t" and "M_i (Evin, 2012).

Drying Rate

the Eq. (3) enables to calculate Drying rate (DR) (Demiray et al., 2023).

$$DR = \frac{M_t-M_{t+\Delta t}}{\Delta t} \tag{3}$$

where $M_{t+\Delta t}$ is moisture content at t + Δt (g water g^{-1} d.m.), t is the time (min) and Δt time difference (min).

Effective Moisture Diffusivity

The drying behavior of biological materials during the falling rate phase is typically described by Fick's diffusion equation. The Eq. (4) derived by Crank (1979) from Fick's diffusion equation, is applicable to multiple geometrical configurations, including rectangular, cylindrical, and spherical forms. In this methodology, the tissue sheet is conceptualized as an infinite slab, with the assumption that the ambient temperature remains constant. The diffusion coefficient is treated as uniform, while other diffusion processes and sample shrinkage are neglected. Furthermore, mass transfer is considered to occur exclusively in one dimension, specifically within the confines of the infinite slab.

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

The Eq. (5) was employed to determine the effective moisture diffusivity (*Deff*), where t denotes the drying duration and L signifies half the thickness of the fresh red pepper samples. For extended drying periods, under the assumption that n = 1, The Eq. (4) reduces to The Eq. (5) (Crank 1979).

$$ln(MR) = \ln\left(\frac{8}{\pi^2}\right) - \left(\frac{\pi^2}{4L^2}D_{eff}t\right) \tag{5}$$

A linear relationship exists between drying time and the natural logarithm of moisture ratio (MR), resulting in a straight line. The slope of this line is defined by the Eq. (6) (Crank 1979).

$$\mathrm{Slope} = -\frac{\pi^2}{4L^2}D_{eff} \tag{6}$$

Mathematical Modelling

The thin layer models utilized in the current study are given in Table. To determine the most appropriate model, some statistical such as lower root mean square error (RMSE) and reduced chi-square (χ^2), and higher coefficient of determination (R^2) (Demiray et al., 2017).

MATLAB software (version R2015a, 8.5) was employed, using its nonlinear curve-fitting toolbox, which applies the trust-region algorithm to estimate statistical parameters and perform curve fitting. The selection of the most suitable thin layer model was determined based on the highest R^2 values, along with χ^2 and RMSE criteria (Demiray et al., 2017).

Modeling of Artificial Neural Network

The ANN modeling was conducted by using Neural Net Fitting Toolbox. The algorithm was the Levenberg-Marquardt backpropagation (Omari et al., 2018). Hidden layer transfer function and neuron number were tansig function and six neurons, respectively. Training, validation and testing were arranged as 60, 20 and 20% for ANN modeling, respectively. Training was completed by 1000 epochs, six validation checks, and a gradient limit of 1e-07 (Yıldız et al., 2015).

Energy Consumption

To determine the energy consumption of drying processes was performed by using a power meter (Polaxtor, PLX-15366). Specific moisture evaporation rate (SMER, kg kWh^{-1}) and specific energy consumption (SEC, kWh kg^{-1} water) of drying process was calculated by using the Eq. (7) and the Eq. (8), respectively (Aksüt et al., 2023).

$$SMER = \frac{Moisture\ removing\ during\ drying\ process\ (kg)}{Consumed\ Energy\ by\ the\ Microwave\ Oven\ \ (kWh)} \tag{7}$$

$$SEC = \frac{Total\ consumed\ Energy\ (kWh)}{Total\ removed\ moisture\ \ (kg)} \tag{8}$$

Color Properties

Color attributes of red peppers both inner and outer parts of samples were determined by a color measurement device (3NHNR10QC, China). For this purpose, five different samples were selected, and color attributes were measured. In addition to $L*$, $a*$, $b*$ values, total color differences (ΔE) were also calculated to monitor the alteration in fresh and dried samples. ΔE was calculated by using the Eq. (9) (Horuz et al., 2017).

$$\Delta E = \sqrt{(L_0^* - L^*)^2 + (a_0^* - a^*)^2 + (b_0^* - b^*)^2} \quad (9)$$

Shrinkage Properties

A suggested method by Granella et al. (2022) was used for determining the dimensional changes of dried red peppers. Five different red pepper samples were selected, and width and thickness of samples were measured with a digital caliper. Width shrinkage ratio (WS) and thickness shrinkage ratio (TS) were calculated by the Eq. (10) the Eq. (11).

$$WS = 100 - \left(\frac{W_f}{W_i}100\right) \quad (10)$$

$$TS = 100 - \left(\frac{T_f}{T_i}100\right) \quad (11)$$

Statistical Analysis

Using SPSS software, variance analysis (ANOVA) was conducted to determine the mean differences among the evaluated parameters, with a significance level of p=0.05. The Tukey test was utilized for post-hoc comparisons. Moreover, principal component analysis (PCA) was performed with Minitab® 21.

Results and Discussion

Effect of Ethanol Pretreatment on Drying of Red Peppers and Energy Consumption

As illustrated by the drying curve (a) and drying rates (b) given in Figure 1, ethanol pretreatments have been shown to exert a significant influence on the drying time. While drying untreated red peppers took 720 min, the shortest drying time was observed in the samples pretreated 100% ethanol immersion for 20 min. At 50% ethanol concentration drying times of red peppers were calculated to be 600 min and 450 min for 10 min and 20 min pretreated samples, respectively. For samples pretreated with 100% ethanol, drying took 390 and 330 min for 10 min and 20 min immersion time, respectively. Increasing immersion time and ethanol concentration caused a decrement in drying time as shown in Table 1. *Deff* values (shown in Table 1) of the red peppers also proved the effect of immersion time and ethanol concentration on drying rate and time. D*eff* indicates dehydration ability of products for determining optimum drying process. Increasing effective moisture diffusivity is related to reducing drying time and increasing drying rate. Dissolving cell wall components resulting from ethanol pretreatment changes the structure of food and so increases permeability (Llavata et al., 2020). Increment in drying rate can be explained by this phenomenon. Moreover, the Marangoni effect explained in detail in the section of introduction can be caused to reduction in drying time of ethanol pretreated samples by enhancing water transportation. Osmotic dehydration can be also another possible explanation for increasing drying rate with ethanol pretreatment due to ethanol solution acts as a hypertonic medium that cause removing the water from food material (Guedes et al., 2021). As the results indicated by da Cunha et al. (2020) ethanol pretreatment presented lower drying time of melon slices with 56.9% reduction compared to control group at the 100% ethanol solution concentration. Additionally, it was notified that concentration of ethanol solution has a direct effect on the drying rate (da Cunha et al., 2020). Similar findings were reported by de Freitas et al. (2021), Tepe (2024), Santos et al., (2023) in pineapple, potato and papaya, respectively. Increased pretreatment time may have resulted in greater removal of air, further thinning of the cell walls and increased permeability. Furthermore, immersion in the solution at higher ethanol concentration may have increased the ethanol concentration on the surface, resulting in a stronger Marangoni effect. The synergetic effect of longer time and higher concentration contributed to decrement in drying time.

To determine the performance of the dryer during drying, specific moisture extraction rate (SMER), specific energy consumption (SEC) and energy efficiency are important indicators. The energy consumption metrics for hot air drying of untreated and pretreated red peppers were given in Table 2. SMER can be calculated as removal moisture amount (kg) per supplying energy (kilowatt hour) to the dryer (Surendhar et al., 2019). SEC is reciprocal of SMER value and is also defined as the required heat for removing one kg of water from fresh agricultural products (Nwakuba et al., 2016). The higher SMER, the more moisture evaporated from food, and it means that more water is removed with less energy. On the other hand, decrement in SEC value indicates that less energy is consumed for removing 1 kg of moisture (Aksüt et al., 2023). Therefore, higher SMER and lower SEC values should be preferred in terms of energy efficiency. According to Table 1, SMER values increased, and SEC values decreased with the reducing drying time. The highest SMER value was detected in the samples pretreated with 100% ethanol solution for 20 min, while the lowest value was observed in the untreated samples. Similarly, Abbaspour-Gilandeh et al. (2021) noted that SEC values of pretreated terebinth are lower than untreated samples.

Modeling of Drying Curves

Thin layer ANN modeling was used to describe the drying behavior of red peppers. Lower RMSE and χ^2 values alongside higher R^2 values were used to select the model that best describes the drying. The statistical parameters for mathematical and ANN models were given in Table 3. Midilli and Kucuk model well estimated the drying curves of both untreated and pretreated samples. χ^2 and RMSE values of Midilli and Kucuk model were found between 1.57×10^{-5} – 0.000142834 and 0.003467 – 0.01091, respectively. Similarly, Arslan et al. (2020) notified that Midilli and Kucuk model was found to be the best model for describing red peppers. Vega et al. (2007) reported that Page modeling gave the best prediction performance in the hot airdried red bell pepper. In general, drying curves of many fruits and vegetables can be well described by Midilli and Kucuk and Page models.

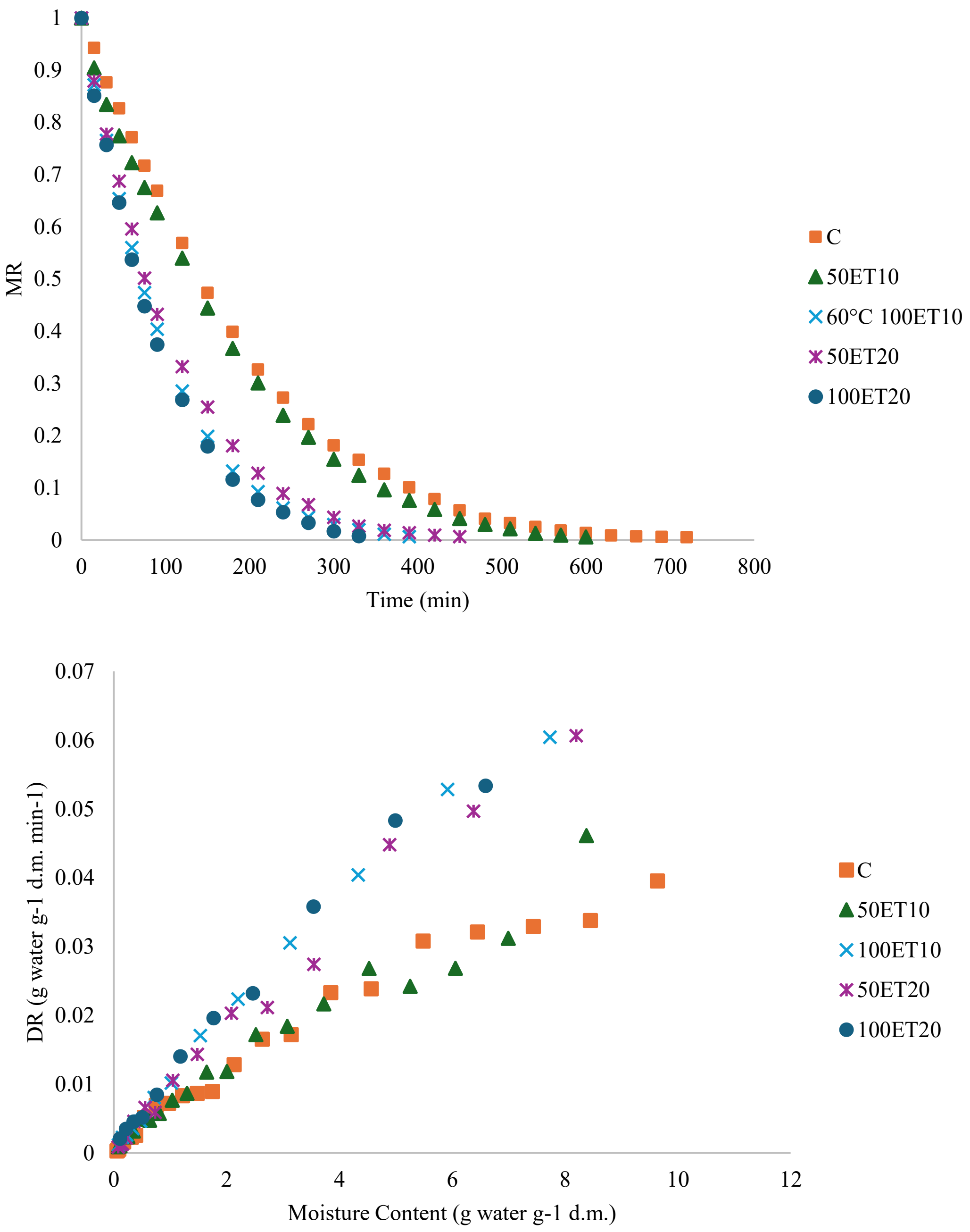

Figure 1. Moisture ratio (a) and drying rate (b) of dried red peppers

Table 1. Thin -layer drying models selected for modeling of drying curves

Model name	Model	References
Lewis	$exp(-kt)$	Lewis (1921)
Henderson and Pabis	$aexp(-kt)$	Henderson and Pabis (1961)
Page	$exp(-kt^n)$	Page (1949)
Parabolic	$a + bt + ct^2$	Doymaz (2010)
Midilli and Kucuk	$aexp(-kt^n) + bt$	Tunckal and Doymaz (2020)

Table 2. Energy consumption data, efficiency, D*eff* and drying times of red peppers

Experiment	SMER (kg kWh^{-1})	SEC (kWh kg^{-1} water)	Efficiency (%)	Deff (m^2 s^{-1})	Drying Time (min)
C	0.03686	27.13	0	3.39×10^{-10}	720
50ET10	0.04742	21.09	22.25	3.60×10^{-10}	600
100ET10	0.05771	17.33	36.18	6.42×10^{-10}	390
50ET20	0.05457	18.33	32.44	5.73×10^{-10}	450
100ET20	0.06271	15.95	41.21	6.77×10^{-10}	330

Table 3. Model parameters and statistical data of experimental models

Model	Experiment	Model Constants				χ^2	RMSE	R^2
Page	C	k= 0.001993	n= 1.184			4.85164E-05	0.006712	0.9996
	50ET10	k= 0.003223	n= 1.113			0.000289133	0.01628	0.9977
	100ET10	k= 0.006041	n= 1.116			1.55237E-05	0.003701	0.9999
	50ET20	k= 0.006183	n= 1.086			5.11342E-05	0.006764	0.9996
	100ET20	k= 0.006426	n= 1.117			8.54576E-05	0.008606	0.9994
Henderson and Pabis	C	k= 0.005628	a= 1.050			0.000592708	0.02346	0.9954
	50ET10	k= 0.005978	a= 1.020			0.000625748	0.02395	0.995
	100ET10	k= 0.01066	a= 1.029			0.00028436	0.01584	0.9979
	50ET20	k= 0.009516	a= 1.023			0.000201381	0.01333	0.9985
	100ET20	k= 0.01124	a= 1.025			0.000406948	0.01878	0.997
Parabolic	C	a= 0.9608	b= -0.003442		c= 0.000003049	0.00101743	0.03014	0.9927
	50ET10	a= 0.9457	b= -0.003762		c= 0.000003773	0.000567822	0.02229	0.9959
	100ET10	a= 0.9335	b= -0.006317		c= 0.00001052	0.002120634	0.04179	0.9863
	50ET20	a= 0.9211	b= -0.005444		c= 0.000007901	0.002336986	0.04387	0.9843
	100ET20	a= 0.9474	b= -0.007114		c= 0.00001339	0.001487813	0.0345	0.9908
Lewis	C	k= 0.005334				0.000876364	0.02907	0.9926
	50ET10	k= 0.005849				0.000626859	0.02451	0.9945
	100ET10	k= 0.01032				0.000361678	0.01845	0.9969
	50ET20	k= 0.009272				0.000243868	0.01515	0.9979
	100ET20	k= 0.01092				0.000447198	0.02043	0.9962
Midilli and Kucuk	C	k= 0.001954	a= 0.9913	n=1.183	b=-0.00001347	2.71607E-05	0.004825	0.9998
	50ET10	k= 0.003052	a= 0.9759	n=1.110	b=-0.00004649	0.000142834	0.01091	0.9991
	100ET10	k= 0.005946	a= 0.9958	n=1.118	b=-0.000007324	1.57186E-05	0.003467	0.9999
	50ET20	k= 0.006408	a= 0.9976	n=1.075	b=-0.00001728	5.30954E-05	0.006372	0.9997
	100ET20	k= 0.006516	a= 0.9935	n=1.109	b=-0.00003001	8.95566E-05	0.008104	0.9995
ANN	C						0.0025443	0.9999
	50ET10						0.0014488	0.9999
	100ET10						0.0012989	0.9999
	50ET20						0.0007307	0.9999
	100ET20						0.0007831	0.9999

Table 4. Color values of inner part of red peppers

Experiment	$L*$	SD (±)	$a*$	SD (±)	$b*$	SD (±)	ΔE	SD (±)
Fresh	47.23^{a}	2.18	26.99^{a}	2.20	25.91^{b}	3.2298	0^{c}	0
C	51.22^{a}	2.36	27.69^{a}	0.43	35.10^{a}	3.22	10.53^{b}	4.20
50ET10	29.19^{d}	0.15	27.34^{a}	9.07	19.58^{b}	1.91	19.90^{a}	2.80
100ET10	34.26^{c}	0.55	30.66^{a}	5.13	24.93^{b}	3.77	14.25^{ab}	3.04
50ET20	40.46^{b}	2.58	29.36^{a}	3.16	27.22^{ab}	3.54	8.94^{b}	1.15
100ET20	40.32^{b}	1.49	32.00^{a}	3.96	28.05^{ab}	3.91	10.45^{b}	2.89

*Different letters in the same column indicate significant differences with confidence of 95%.

Drying curves of ANN modeling, best validation performance and regressions are shown in Figure 2, 3 and 4, respectively. Compared to all thin layer models, R^2 values of the ANN modeling for all samples were observed the highest. Additionally, RMSE values of ANN modeling were found lower than Midilli and Kucuk model. In the current study, ANN modeling described the drying curves of the samples better than the thin layer models. According to this result, ANN may be selected as an alternative prediction approach to the thin layer modeling. Similarly, Sasikumar et al. (2023) stated the better prediction performance of ANN modeling of dried red pepper cubes than thin layer models. Sousa et al. (2025) also reported an effective description of drying curves of pimenta-de-cheiro pepper by ANN modeling.

Color Properties of Fresh and Dried Red Peppers

Color is one of the most important quality criteria that affects consumer preference (Deng et al., 2018). Color is the most striking feature that makes red pepper attractive, and carotenoids are responsible for its red color (Deng et al., 2022). In this study color properties of outer and inner surface are evaluated separately. Color values of fresh and dried red peppers are given in Table 4 and Table 5 for inner and outer parts of samples, respectively. The highest $L*$ value (51.22) of the inner part was observed in untreated (control) samples. While ethanol pretreatment caused reducing the $L*$ value for all concentration and treatment time, The 20-minute pretreatment period caused the least reduction for both ethanol concentrations ($p>0.05$). 10 min immersion in 50% ethanol solution was the most negatively effective pretreatment with the lowest $L*$ value (29.19). For the outer parts of the red peppers, the highest L^* value was observed in the samples 20 min pretreated with 50% ethanol solution, while the lowest value was in the samples 20 min pretreated with 100% ethanol solution. The reduction in L^* values can be linked with brown pigment formation originating from Maillard reaction during drying (El-Hamzy & Ashour, 2016). It has been observed that L^* value of the outer parts is less affected than the inner parts. The color of red peppers pulp is directly related to the presence of carotenoids. It is possible to associate more reduction in L^* value in pretreated samples with the carotenoids dissolving in ethanol solution (da Cunha et al., 2020).

Table 5. Color values of outer part of red peppers

Experiment	L^*	SD (±)	a^*	SD (±)	b^*	SD (±)	ΔE	SD (±)
Fresh	30.54^{a}	0.81	23.24^{a}	2.11	10.11^{b}	0.98	0^{b}	0
C	26.63^{cd}	0.23	17.59^{bc}	0.73	16.22^{b}	0.86	9.38^{a}	0.64
50ET10	27.95^{bc}	0.60	19.96^{ab}	2.61	10.05^{b}	2.56	4.89^{ab}	1.85
100ET10	26.60^{d}	0.32	17.32^{bc}	0.65	13.49^{b}	4.36	8.11^{ab}	3.88
50ET20	28.68^{b}	0.34	23.18^{a}	1.18	15.42^{b}	5.23	6.72^{ab}	5.41
100ET20	25.24^{e}	0.40	13.55^{c}	0.80	15.06^{b}	5.31	13.08^{a}	2.99

*Different letters in the same column indicate significant differences with confidence of 95%.

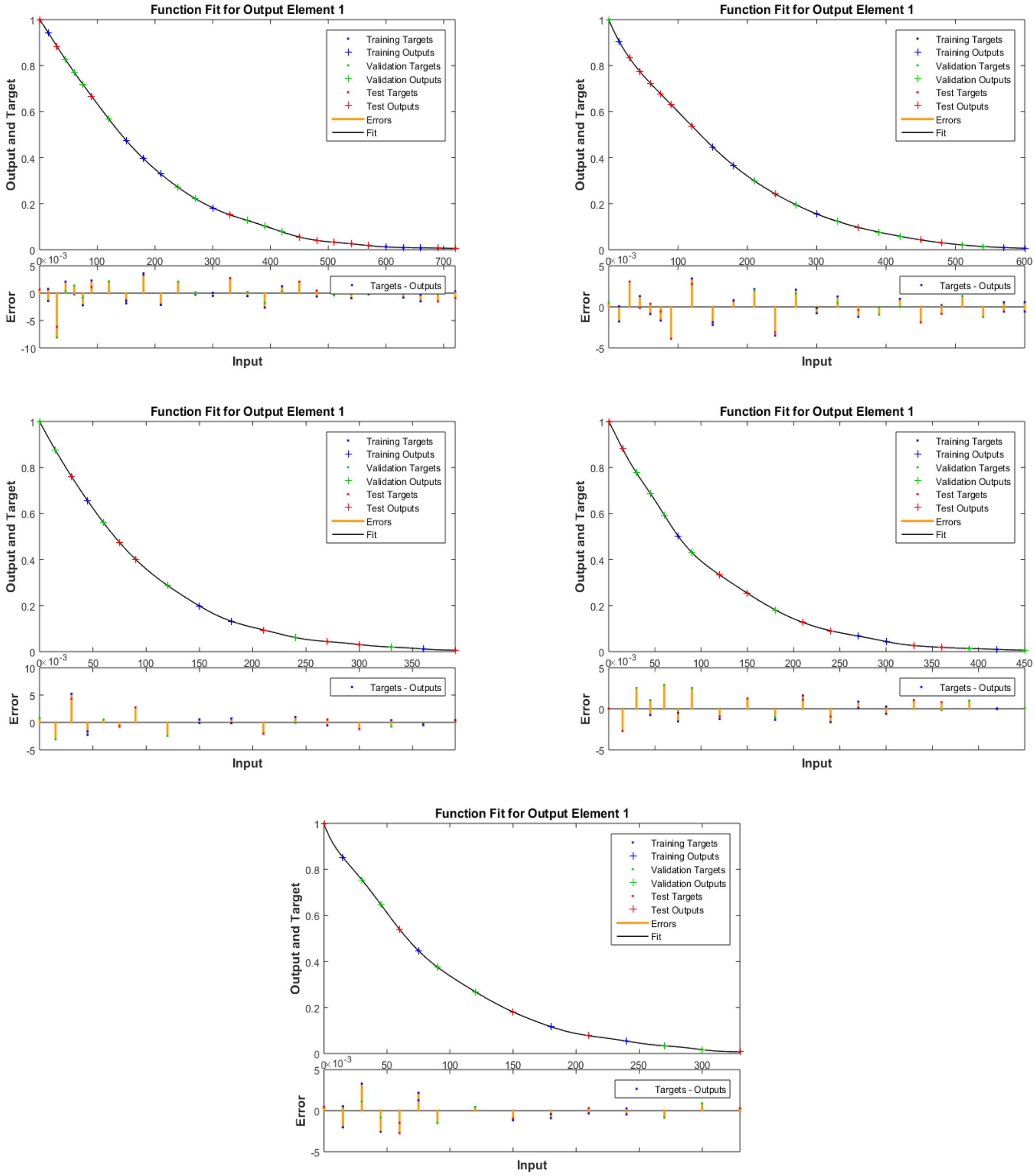

Figure. 2. Drying curves of the ANN modeling of dried red peppers (a: C, b: 50ET10, c: 100ET10, d: 50ET20, e: 100ET20)

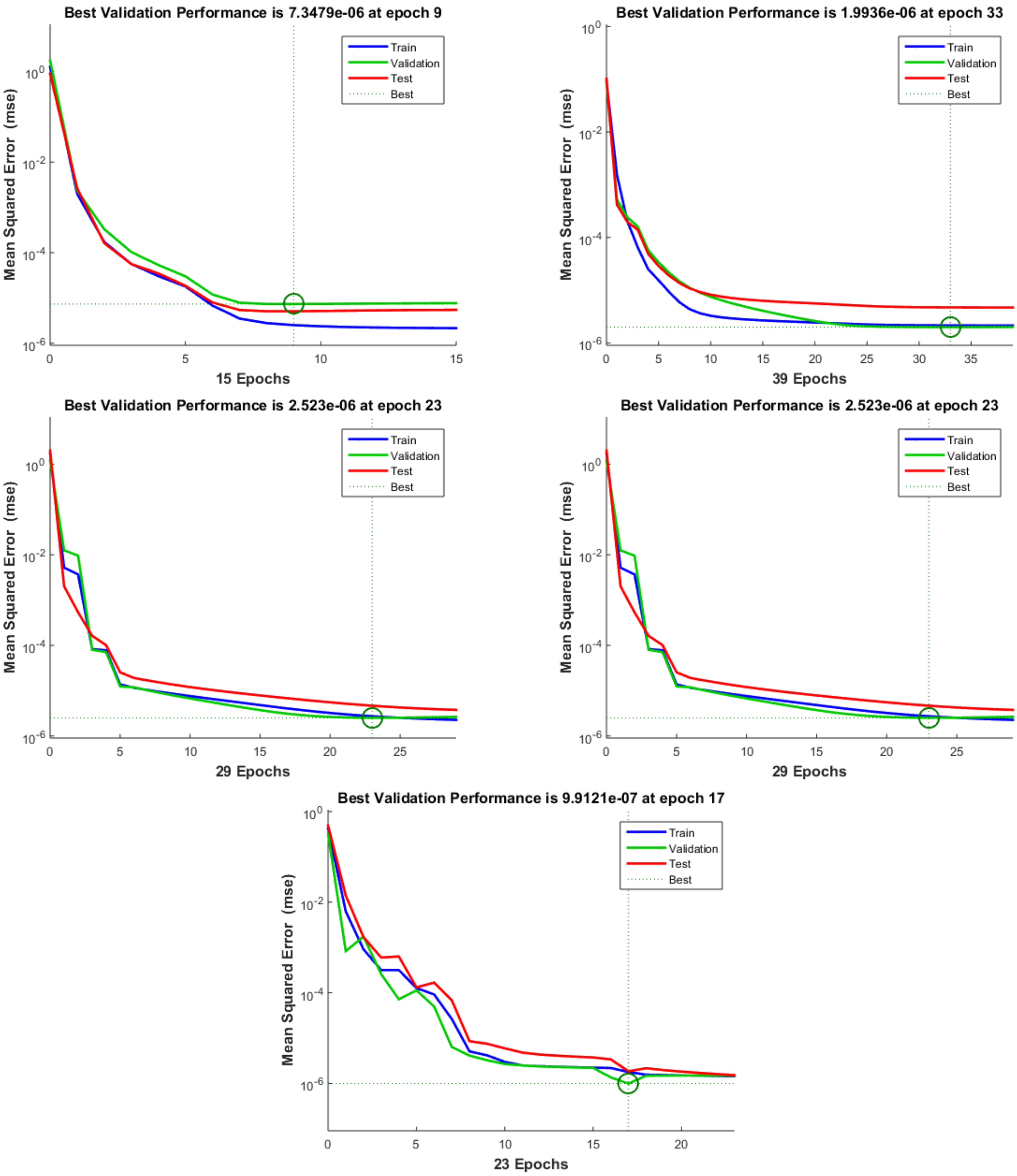

Figure 3. Best validation performance of the ANN modeling of dried red peppers (a: C, b: 50ET10, c: 100ET10, d: 50ET20, e: 100ET20)

The redness of samples is related to hire *a** value. There is no statistically important change in *a** value for inner parts. Whereas *a** values for outer parts of red peppers decreased during drying. The highest reduction was observed in the samples treated with 100% ethanol solution for 20 min (13.55) ($p<0.05$). This dramatically decrement can be explained with higher ethanol concentration and higher treatment duration may cause more loss of carotenoids before drying. The *b** value of the inner parts statistically increased with 10 min ethanol pretreatment compared to control group, but same in fresh samples. However, there is no significant difference in *b** values from the outer parts. The total color difference (ΔE), which implies the magnitude of the color difference between fresh and dried material and greater than 2 means that the color difference is noticeable to the naked eye (Rybak et al., 2021). ΔE values ranged from 8.94-19.91 and 4.89-13.08 for inner and outer parts, respectively.

Among the inner part, the sample treated with 50% ethanol for 10 min have the highest ΔE value ($p<0.05$). On the other hand, pretreatments have no significant effect on ΔE for the outer part.

Shrinkage of Dried Red Peppers

Table 6 shows the width and thickness shrinkage ratio of hot airdried red pepper samples. The width of samples decreased compared to fresh samples. The lowest width shrinkage was observed in 50% ethanol immersed samples for 10 min ($p<0.05$), while there was no significant difference between control and 20 min treated samples ($p>0.05$).

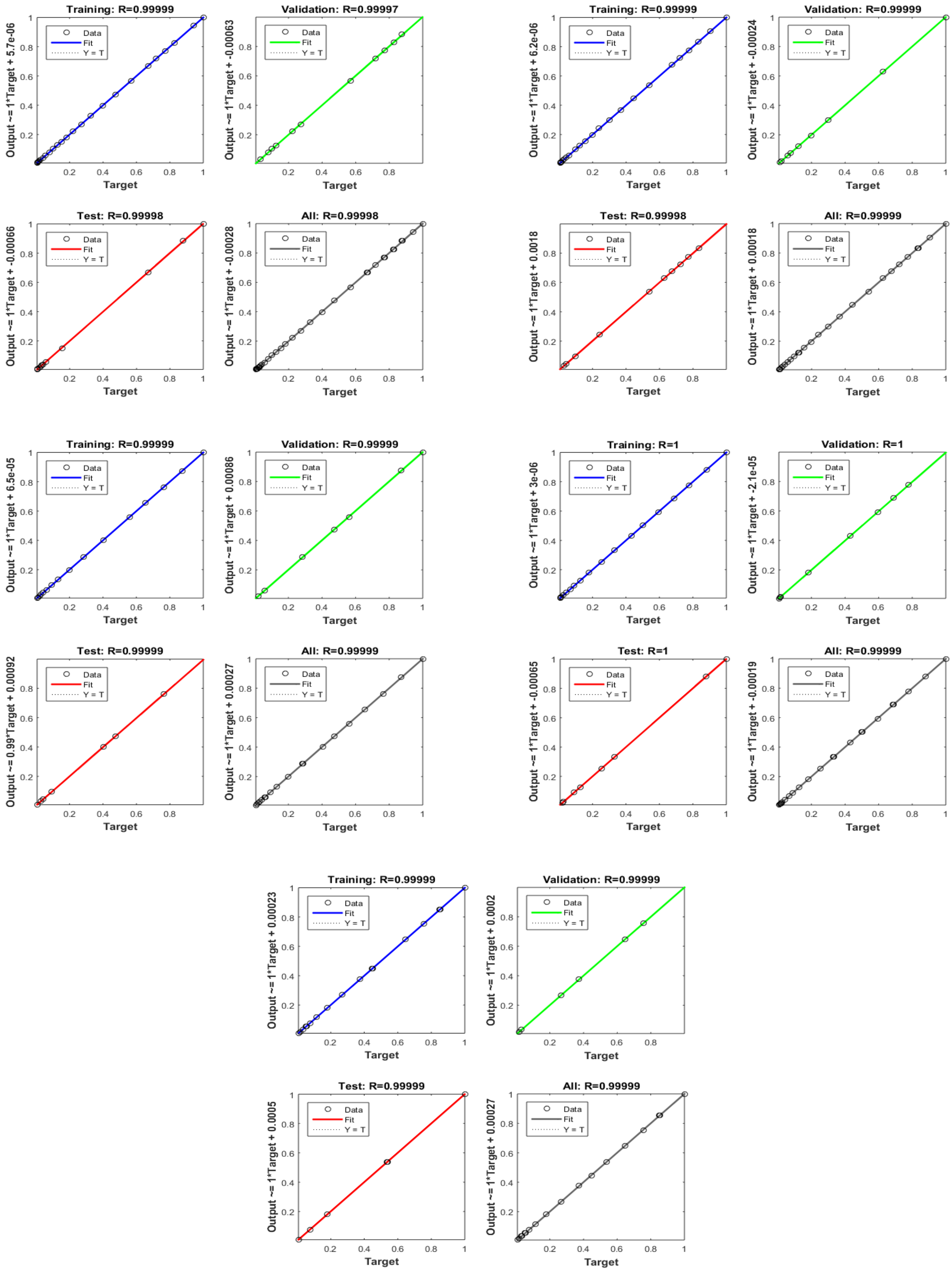

Figure 4. Regressions of the ANN modeling of dried red peppers (a: C, b: 50ET10, c: 100ET10, d: 50ET20, e: 100ET20)

Table 6. Shrinkage ratios of red peppers

Experiment	Width Shrinkage (%)	SD (±)	Thickness Shrinkage (%)	SD (±)
Fresh	0^{d}	0	0^{c}	0
C	18.29^{ab}	1.63	71.45^{b}	2.62
50ET10	11.69^{c}	2.43	69.85^{b}	0.73
100ET10	13.66^{bc}	1.92	69.28^{b}	1.45
50ET20	18.10^{ab}	2.79	77.62^{a}	1.61
100ET20	20.27^{a}	1.26	80.97^{a}	1.51

*Different letters in the same column indicate significant differences with confidence of 95%.

On the other hand, the thickness of samples remarkably decreased by drying. The highest thickness shrinkage occurred in ethanol treated (both two concentrations) during 20 min samples. Heating causes cellular collapse due to cell wall and membrane damage. Therefore, shrinkage naturally occurs during hot air drying. higher shrinkage deformation observes at the initial stage of drying due to mass transfer is higher (Buvaneswaran et al., 2022).

PCA Analysis of Fresh and Dried Red Peppers

Figure 5 presents the PCA of fresh and dried red peppers (L^* (Outside), a^* (Outside), b^* (Outside), ΔE (Outside), L^* (Inside), a^* (Inside), b^* (Inside), ΔE (Inside), Width Shrinkage (%), Thickness Shrinkage (%), SMER and SEC, Efficiency). Fresh samples are positioned in a different plane. It clearly reveals that properties of fresh samples showed differences from the dried samples. However, the samples coded 50ET20, 100ET20 and C are in the same plane. This same arrangement states that these samples are in similarity. Besides, samples called 50ET10 and 100ET10 are in different planes from both each other and the other samples. It can be concluded that the samples exhibiting a similar configuration within the same plane are closely related concerning the specified parameters.

Conclusion

Drying times and effective moisture diffusivities (D*eff*) of samples were calculated as 720, 600, 450, 390, 330 min and 3.39×10^{-10}, 3.60×10^{-10}, 5.73×10^{-10}, 6.42×10^{-10} and 6.77×10^{-10} $m^2 s^{-1}$ for C, 50ET10, 50ET20, 100ET10 and 100ET20, respectively. D*eff* indicates dehydration ability of products for determining optimum drying process. Increasing effective moisture diffusivity is related to reducing drying time and increasing drying rate. Moreover, the highest D*eff* was obtained from the samples 100ET20. Additionally, ethanol concentration and immersion time had positive contribution to drying rates. Although drying curves of samples were well described by Midilli and Kucuk model, ANN showed a better modeling performance with the highest R^2 and the lowest RMSE (0.000730741- 0.00254425) values. Inner and outer color values of fresh red peppers were 47.23, 26.99, 25.91 and 30.54, 23.24, 10.11 L^*, a^* and b^*, respectively. If the total color difference (ΔE) values of samples were higher than 2, meaning that non-trained observer can detect color change in the products. For the inner part of red peppers, 50ET20 caused the lowest value (8.94) in terms of ΔE, whereas 50ET10 gave the lowest change in total color with the 4.89 value.

Shrinkage serves as a critical quality indicator for plant products characterized by elevated water content, as the drying process can significantly affect their morphology, density, and porosity. Consequently, the assessment of shrinkage is an essential procedure. All samples showed shrinkage tendance in both width and thickness after drying. The highest shrinkage ratios were obtained from 50ET20 and 100ET20. On the other hand, the assessment of the SMER and SEC for the samples was conducted. With a decrease in drying time, the samples demonstrated an increase in SMER values, whereas SEC values showed a general decline.

The highest SMER and lowest SEC were observed at 100ET20 with 41.21% efficiency. PCA revealed that fresh samples were positioned significantly farther from the pretreated samples. The configurations of 50ET20, 100ET20, and C were observed to align within the same plane, while 50ET10 and 100ET10 were positioned in distinct planes. In conclusion, the use of ethanol immersion can be considered a highly promising approach. In addition, employing ANN modeling is advisable for enhancing the accuracy of the drying process optimization.

Author Contributions

The authors equally contributed to the work.

References

Abbaspour-Gilandeh, Y., Kaveh, M., Fatemi, H., Khalife, E., Witrowa-Rajchert, D., & Nowacka, M. (2021). Effect of pretreatments on convective and infrared drying kinetics, energy consumption and quality of terebinth. *Applied Sciences*, *11*(16), 7672.

Aghbashlo, M., Hosseinpour, S., & Mujumdar, A. S. (2015). Application of artificial neural networks (ANNs) in drying technology: a comprehensive review. *Drying technology*, *33*(12), 1397-1462.

Aksüt, B., Polatcı, H., & Taşova, M. (2023). The effect of pre-treatment and drying temperatures on energy consumption and quality characteristics in drying of lemon (Citrus limon L.) slices. Journal of Thermal Analysis and Calorimetry, 148(19), 10415-10427.

Akter, F., Muhury, R., Sultana, A., & Deb, U. K. (2022). A comprehensive review of mathematical modeling for drying processes of fruits and vegetables. *International Journal of Food Science*, *2022*(1), 6195257.

Albuquerque, C. F., Ribeiro, T. C., de Castro Melo, E., & de Ávila, M. B. R. (2024). Literature review: use of ultrasound and ethanol as pre-treatment in the drying of vegetable products with bioactive compounds. *Caderno Pedagógico*, *21*(3), e3023-e3023.

Arimboor, R., Natarajan, R. B., Menon, K. R., Chandrasekhar, L. P., & Moorkoth, V. (2015). Red pepper (Capsicum annuum) carotenoids as a source of natural food colors: analysis and stability—a review. *Journal of food science and technology*, *52*(3), 1258-1271.

Arslan, A., Soysal, Y., & Keskin, M. (2020). Comparing hot air-drying kinetics and color quality of organic and conventional sweet red peppers. *Mustafa Kemal Üniversitesi Tarım Bilimleri Dergisi*, *25*(2), 271-283.

Bassey, E. J., Cheng, J. H., & Sun, D. W. (2021). Novel nonthermal and thermal pretreatments for enhancing drying performance and improving quality of fruits and vegetables. *Trends in Food Science & Technology*, *112*, 137-148.

Buvaneswaran, M., Natarajan, V., Sunil, C. K., & Rawson, A. (2022). Effect of pretreatments and drying on shrinkage and rehydration kinetics of ginger (Zingiber officinale). *Journal of Food Process Engineering*, *45*(3), e13972.

Crank, J. 1979. The mathematics of diffusion. Glasgow Cape: Oxford University Press, Ely House, London W.I.

da Cunha, R. M. C., Brandão, S. C. R., de Medeiros, R. A. B., da Silva Júnior, E. V., da Silva, J. H. F., & Azoubel, P. M. (2020). Effect of ethanol pretreatment on melon convective drying. *Food Chemistry*, *333*, 127502.

Dash, K. K., Chakraborty, S., & Singh, Y. R. (2020). Modeling of microwave vacuum drying kinetics of Bael (Aegle marmelos L.) pulp by using artificial neural network. *Journal of the Institution of Engineers (India): Series A*, *101*, 343-351.

de Freitas, L. D. C., Brandão, S. C. R., Fernandes da Silva, J. H., Sá da Rocha, O. R., & Azoubel, P. M. (2021). Effect of ethanol and ultrasound pretreatments on pineapple convective drying. *Food Technology and Biotechnology*, *59*(2), 209-215.

de Sousa, M. M., Guirlanda, C. P., Cordeiro, A. C. C., Marques, H. M., Leite, N. R. P., & Neto, J. C. B. (2025). Artificial Neural Networks Applied to Drying Curves of Capsicum Chinense. *Revista de Gestão Social e Ambiental*, *19*(3), 1-15.

Demiray, E., Seker, A., & Tulek, Y. (2017). Drying kinetics of onion (Allium cepa L.) slices with convective and microwave drying. *Heat and Mass Transfer*, *53*(5), 1817-1827.

Demiray, E., Yazar, J. G., Aktok, Ö., Çulluk, B., Çalışkan Koç, G., & Pandiselvam, R. (2023). The effect of drying temperature and thickness on the drying kinetic, antioxidant activity, phenolic compounds, and color values of apple slices. Journal of Food Quality, 2023(1), 7426793

Deng, L. Z., Mujumdar, A. S., Zhang, Q., Yang, X. H., Wang, J., Zheng, Z. A., ... & Xiao, H. W. (2019). Chemical and physical pretreatments of fruits and vegetables: Effects on drying characteristics and quality attributes–a comprehensive review. *Critical reviews in food science and nutrition*, *59*(9), 1408-1432.

Deng, L. Z., Xiong, C. H., Sutar, P. P., Mujumdar, A. S., Pei, Y. P., Yang, X. H., ... & Xiao, H. W. (2022). An emerging pretreatment technology for reducing postharvest loss of vegetables-a case study of red pepper (Capsicum annuum L.) drying. *Drying Technology*, *40*(8), 1620-1628.

Deng, L. Z., Yang, X. H., Mujumdar, A. S., Zhao, J. H., Wang, D., Zhang, Q., ... & Xiao, H. W. (2018). Red pepper (Capsicum annuum L.) drying: Effects of different drying methods on drying kinetics, physicochemical properties, antioxidant capacity, and microstructure. *Drying Technology*, *36*(8), 893-907.

Doymaz, İ. (2010). Effect of citric acid and blanching pre-treatments on drying and rehydration of Amasya red apples. Food and bioproducts processing, 88(2-3), 124-132.

El-Hamzy, E. M., & Ashour, M. M. (2016). Effect of different drying methods and storage on physico-chemical properties, capsaicinoid content, rehydration ability, color parameters and bioactive compounds of dried red jalapeno pepper (Capsicum annuum) slices. *Middle East Journal of Applied Sciences*, *6*(4), 1012-1037.

Evin, D. (2012). Thin layer drying kinetics of Gundelia tournefortii L. *Food and bioproducts processing*, *90*(2), 323-332.

Feng, Y., Zhou, C., Yagoub, A. E. A., Sun, Y., Owusu-Ansah, P., Yu, X., ... & Ren, Z. (2019). Improvement of the catalytic infrared drying process and quality characteristics of the dried garlic slices by ultrasound-assisted alcohol pretreatment. *Lwt*, *116*, 108577.

Granella, S. J., Bechlin, T. R., & Christ, D. (2022). Moisture diffusion by the fractional-time model in convective drying with ultrasound-ethanol pretreatment of banana slices. Innovative Food Science & Emerging Technologies, 76, 102933.

Greenacre, M., Groenen, P. J., Hastie, T., d'Enza, A. I., Markos, A., & Tuzhilina, E. (2022). Principal component analysis. *Nature Reviews Methods Primers*, *2*(1), 100.

Gu, C., Ma, H., Tuly, J. A., Guo, L., Zhang, X., Liu, D., ... & Shan, Y. (2022). Effects of catalytic infrared drying in combination with hot air drying and freeze drying on the drying characteristics and product quality of chives. *Lwt*, *161*, 113363.

Guclu, G., Keser, D., Kelebek, H., Keskin, M., Sekerli, Y. E., Soysal, Y., & Selli, S. (2021). Impact of production and drying methods on the volatile and phenolic characteristics of fresh and powdered sweet red peppers. *Food Chemistry*, *338*, 128129.

Guedes, J. S., Santos, K. C., Castanha, N., Rojas, M. L., Junior, M. D. M., Lima, D. C., & Augusto, P. E. (2021). Structural modification on potato tissue and starch using ethanol pre-treatment and drying process. *Food Structure*, *29*, 100202.

Henderson, S. M., Pabis, S. (1961). Grain drying theory, I. Temperature effect on drying coefficient. J. Agr. Eng. Res., 6(3), 169-173.

Horuz, E., Bozkurt, H., Karataş, H., & Maskan, M. (2017). Effects of hybrid (microwave-convectional) and convectional drying on drying kinetics, total phenolics, antioxidant capacity, vitamin C, color and rehydration capacity of sour cherries. Food chemistry, 230, 295-305.

Lewis, W. K. (1921). The rate of drying of solid materials. Industrial & Engineering Chemistry, 13(5), 427-432.

Llavata, B., García-Pérez, J. V., Simal, S., & Cárcel, J. A. (2020). Innovative pre-treatments to enhance food drying: A current review. *Current opinion in food science*, *35*, 20-26.

Nwakuba, N. R., Asoegwu, S. N., & Nwaigwe, K. N. (2016). Energy consumption requirements of agricultural dryers: An overview. *Agricultural Engineering International: CIGR Journal*, *18*(4), 119-132.

Omari, A., Behroozi-Khazaei, N., & Sharifian, F. (2018). Drying kinetic and artificial neural network modeling of mushroom drying process in microwave-hot air dryer. Journal of Food Process Engineering, 41(7), e12849.

Page, G. E. (1949). Factors Influencing the Maximum Rates of Air-Drying Shelled Corn in Thin layers. Purdue University.

Pandiselvam, R., Aydar, A. Y., Kutlu, N., Aslam, R., Sahni, P., Mitharwal, S., ... & Kothakota, A. (2023). Individual and interactive effect of ultrasound pre-treatment on drying kinetics and biochemical qualities of food: A critical review. *Ultrasonics sonochemistry*, *92*, 106261.

Rojas, M. L., & Augusto, P. E. (2018). Microstructure elements affect the mass transfer in foods: The case of convective drying and rehydration of pumpkin. *Lwt*, *93*, 102-108.

Rybak, K., Wiktor, A., Witrowa-Rajchert, D., Parniakov, O., & Nowacka, M. (2021). The quality of red bell pepper subjected to freeze-drying preceded by traditional and novel pretreatment. *Foods*, *10*(2), 226.

Santos, N. C., Almeida, R. L. J., da Silva, G. M., de Alcântara Silva, V. M., de Alcântara Ribeiro, V. H., de Oliveira Brito, A. C., ... & Saraiva, M. M. T. (2023). Impact of pretreatments with ethanol and freezing on drying slice papaya: Drying performance and kinetic of ultrasound-assisted extraction of phenolics compounds. *Journal of the Science of Food and Agriculture*, *103*(1), 125-134.

Santos, N. C., Almeida, R. L. J., da Silva, G. M., de Alcântara Silva, V. M., de Alcântara Ribeiro, V. H., de Oliveira Brito, A. C., ... & Saraiva, M. M. T. (2023). Impact of pretreatments with ethanol and freezing on drying slice papaya: Drying performance and kinetic of ultrasound-assisted extraction of phenolics compounds. *Journal of the Science of Food and Agriculture*, *103*(1), 125-134.

Sarkar, T., Salauddin, M., Hazra, S. K., Choudhury, T., & Chakraborty, R. (2021). Comparative Approach of Artificial Neural Network and Thin Layer Modelling for Drying Kinetics and Optimization of Rehydration Ratio for Bael (Aegle marmelos (L) correa) Powder Production. *Economic Computation & Economic Cybernetics Studies & Research*, *55*(1).

Sasikumar, R., Mangang, I. B., Vivek, K., & Jaiswal, A. K. (2023). Effect of ultrasound-assisted thin bed drying for retaining the quality of red bell pepper and compare the predictive ability of the mathematical model with artificial neural network. *Journal of Food Process Engineering*, *46*(12), e14468.

Surendhar, A., Sivasubramanian, V., Vidhyeswari, D., & Deepanraj, B. (2019). Energy and exergy analysis, drying kinetics, modeling and quality parameters of microwave-dried turmeric slices. *Journal of Thermal Analysis and Calorimetry*, *136*, 185-197.

Tepe, T. K. (2024). Convective drying of potato slices: impact of ethanol pretreatment and time on drying behavior, comparison of thin-layer and artificial neural network modeling, color properties, shrinkage ratio, and chemical and ATR-FTIR analysis of quality parameters. *Potato Research*, *67*(3), 759-783.

Tuly, S. S., Mahiuddin, M., & Karim, A. (2023). Mathematical modeling of nutritional, color, texture, and microbial activity changes in fruit and vegetables during drying: A critical review. *Critical Reviews in Food Science and Nutrition*, *63*(13), 1877-1900.

Tunckal, C., & Doymaz, İ. (2020). Performance analysis and mathematical modelling of banana slices in a heat pump drying system. Renewable Energy, 150, 918-923.

Vega, A., Fito, P., Andrés, A., & Lemus, R. (2007). Mathematical modeling of hot-air drying kinetics of red bell pepper (var. Lamuyo). *Journal of food Engineering*, *79*(4), 1460-1466.

Xu, B., Tiliwa, E. S., Yan, W., Azam, S. R., Wei, B., Zhou, C., ... & Bhandari, B. (2022). Recent development in high quality drying of fruits and vegetables assisted by ultrasound: A review. *Food Research International*, *152*, 110744.

Yang, X. H., Deng, L. Z., Mujumdar, A. S., Xiao, H. W., Zhang, Q., & Kan, Z. (2018). Evolution and modeling of colour changes of red pepper (Capsicum annuum L.) during hot air drying. *Journal of Food Engineering*, *231*, 101-108.

Yıldız, A. K., Polatcı, H., & Uçun, H. (2015). Farklı Kurutma Şartlarında Muz (Musa cavendishii) Meyvesinin Kurutulması ve Kurutma Kinetiğinin Yapay Sinir Ağları ile Modellenmesi. Tarım Makinaları Bilimi Dergisi, 11(2), 173-178.