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Convective Drying of the Zucchini Slices; Impact of Pretreatments on the Drying Characteristics and Color Properties, Evaluation of Artificial Neural Network Modeling and Thin-Layer Modeling

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Abstract

This study focused on the impact of citric acid, hot water blanching, and ultrasound pretreatment on the drying of zucchini slices, color properties, and the comparison of artificial neural network (ANN) and thin-layer modeling. The pretreatments enhanced the drying rate and reduced drying time. Ultrasound pretreatment was observed as the most effective, with a reduction rate of the drying time as 40%. Besides, mass transfer and moisture diffusion phenomena were positively affected by pretreatments, depending on the increment of the drying rate. The highest mass transfer coefficient (h_m), moisture diffusivity (D) by the Dincer and Dost model, and effective moisture diffusivity (D_{eff}) by the Crank equation were obtained with ultrasound pretreatment. On the other hand, Midilli and Kucuk, Parabolic, and Page gave the best predictions among the thin-layer models. However, ANN modeling had a better performance than thin-layer modeling due to a higher determination coefficient (R^2) and lower root mean square error (RMSE) values. Color properties of the zucchini slices were affected by drying processes. In general, the redness and yellowness of the zucchini slices increased; however, lightness did not show statistical significance. Additionally, citric acid pretreatment gave the lowest total color difference (ΔE).

Keywords: Zucchini, Drying, Modeling, Pretreatments, Mass Transfer

Kabak Dilimlerinin Konvektif Kurutulması; Ön İşlemlerin Kurutma Karakteristikleri ve Renk Özellikleri Üzerine Etkisi, Yapay Sinir Ağı Modellemesi ve İnce Tabaka Modellemesinin Değerlendirilmesi

Öz

Bu çalışmada, sitrik asit, sıcak suda haşlama ve ultrason ön işlemlerinin kabak dilimlerinin kurutulması, renk özelliklerine etkisi ile yapay sinir ağı (YSA) ve ince tabaka modellemesinin karşılaştırılması araştırılmıştır. Uygulanan ön işlemler kuruma hızını arttırmış ve kuruma süresini azaltmıştır. Ultrason ön işleminin en etkili ön işlem olduğu görülmüş ve kuruma süresindeki azalma oranı 40% olarak tespit edilmiştir. Ayrıca, kütle transferi ve nem difüzyonu olayları, kurutma hızının artışına bağlı olarak ön işlemlerden olumlu yönde etkilenmiştir. Ultrason ön işlemi ile en yüksek kütle transfer katsayısı (h_m), Dincer ve Dost modeline göre nem difüzyonu (D) ve Crank denklemi ile hesaplanan efektif nem difüzyonu değerlerine (D_{eff}) ulaşılmıştır. Öte yandan, Midilli ve Küçük, Parabolik ve Page ince tabaka modelleri arasında en iyi tahminleri vermiştir. Bununla birlikte, YSA modellemesi, daha yüksek determinasyon katsayısı (R^2) ve daha düşük kök ortalama karesel hata (KOKH) değerleri nedeniyle ince tabaka modellerine kıyasla daha iyi performans göstermiştir. Kabak dilimlerinin renk özellikleri kurutma işlemlerinden etkilenmiştir. Genel olarak, kabak dilimlerinin kırmızılığı ve sarılığı artmış, ancak açıklık değeri istatistiksel olarak anlamlılık göstermemiştir. Ayrıca, sitrik asit ön işlemi en düşük toplam renk farkını (ΔE) vermiştir.

Anahtar Kelimeler: Kabak, Kurutma, Modelleme, Ön işlem, Kütle Transferi

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1. Introduction

Fruits and vegetables play a pivotal role in our daily diet due to their rich nutrient content, which includes vitamins, minerals, antioxidants, and dietary fibers (Hasan et al., 2019). As consumer awareness and the demand for healthy dietary choices grow, there is an increasing preference for low-calorie, nutritionally dense products free from food additives.

Within the vast *Cucurbitaceae* botanical family, consisting of 125 genera and 960 species, several vegetables stand out for their significance (Karaye et al., 2021; Verdejo-Lucas and Talavera, 2019). Notable species like *Cucurbita* maxima, C. moschata, C. pepo, C. ficifolia, and C. argyrosperma are widely cultivated (Decker, 1988; Yoo et al., 2023). Zucchini (*Cucurbita pepo* L.), a tropical vegetable (Carvajal et al., 2011; Santosh and Maitra, 2021) from the Cucurbita pepo L. species (Neves et al., 2019), is cherished for its cucumber-like shape, low calorie content, and high nutritional value (Adnan et al., 2017; Iswaldi et al., 2013; Ratnam et al., 2017).

In Turkey, the most grown *Cucurbitaceae* species include *Citrullus lanatus* Thunb., *Cucumis flexuosus* L., *Cucumis sativus* L., *Cucurbita maxima* Duch., *Cucurbita moschata* Duch., and *Cucurbita pepo* L. (Ermiş and Yanmaz). Notably, summer squash (*Cucurbita pepo* L. cv. Sakız) is harvested at 1/3 of its normal size and enjoyed both cooked and raw (Yildirim et al., 2021). According to the 2022-2023 report of the Turkish Statistical Institute (TUIK); In 2022, the quantity of 'Vegetables cultivated for their fruits' was reported as 25,303,925 by TUIK. this production quantity is composed of 590,362 tons of summer squash (Anonymous, 2023).

The water content in fresh foods directly influences their shelf life and quality. Foods with high water content are prone to rapid spoilage (Huang et al., 2021). Hence, timely harvesting and appropriate processing techniques are essential to extend shelf life and enhance consumer convenience (Sruthi et al., 2021). Water activity is reduced by using the drying technique in foods (Bassey et al., 2021; Brandão et al., 2022; Onwude et al., 2017; Pu and Sun, 2017). This reduction, in turn, prolongs the shelf life of products by inhibiting the activities of microorganisms, enzymes, and fermentation processes (Priecina et al., 2018).

Drying processes play a key role in the food industry, with over 200 drying methods available. These methods must be tailored to specific product characteristics, purposes, and dryer types. However, drying is energy-intensive, accounting for 10-15% of total energy consumption in developed countries (Erbay and Icier, 2010). Hot air convective drying, a widely used method, suffers from drawbacks like quality losses, low energy efficiency, and extended drying times (Priecina et al., 2018; Zang et al., 2023). Innovations in drying techniques, such as microwave drying, aim to address these issues (Huang et al., 2021; Patidar et al., 2021; Zang et al., 2023).

Scientific efforts have focused on improving hot-air drying through pre-treatment applications, mitigating oxidation, inactivating enzymes and enhancing permeability. Traditional pre-treatments like steam blanching and hot water blanching have been complemented by non-thermal techniques like ultrasound, known for its mass transfer capabilities and minimal impact on heat-sensitive nutrients.

The fact that the hot-air drying method is the most used method by the industry has caused scientific studies to focus on the improvement of this method. As it is known, the protective layer that covers the outer shell of fruits and vegetables prevents moisture from escaping during the drying process, causing prolongation of the process and quality losses in the product. As a result of the scientific studies conducted, quality improvements are made in the final product with pre-treatment applications prior to drying. Prior to the drying process, pre-treatments serve to expedite the procedure by augmenting permeability, deactivating enzymes, and mitigating oxidation (Bassey et al., 2021). Among the traditional pre-treatment techniques, hot water blanching, steam blanching, alkaline solutions, sulphate, and acid liquor has been extensively explored (Chhe et al., 2018; Erol et al., 2023; Ren et al., 2018; Priecina et al., 2018; Wang et al., 2021; Bassey et al., 2021). These approaches serve to shorten drying time and enhance product quality. However, this method also causes problems such as insufficient rehydration, structural collapse, nutrient losses, and high energy consumption. Non-thermal and thermal pre-treatments have been developed to maintain and improve the quality of the product (Bassey et al., 2021; Deng et al., 2019). According to the results of many scientific studies, it has been determined that non-thermal processing techniques have a positive effect on food quality which has also caught the attention of the industry. One of the major techniques used is ultrasound. Ultrasound, as a form of mechanical wave, exhibits a frequency range between 20 kHz and 1 MHz, necessitating the presence of an elastic medium for its propagation (Paniwnyk, 2016). One notable phenomenon associated with ultrasound is cavitation, an interaction of sound waves with a liquid medium leads to the formation, expansion, and subsequent collapse of bubbles (Bermúdez-Aguirre and Barbosa-Cánovas, 2016). It enables mass transfer with direct and indirect effects caused by mechanical fluctuation and ultrasound cavitation effect of ultrasound which is one of the pre-treatments applied to foods. On the other hand, the ultrasound application has low heating effect and thus, causing lower degradation in heat-sensitive compounds (Beck et al., 2014; Chemat and Khan, 2011; Gamboa-Santos et al., 2014; Miano et al., 2016; Tao and Sun, 2015).

Drying is a highly intricate process involving simultaneous heat, mass, and momentum transfers, as well as complex physical and chemical transformations in food materials. Despite extensive research, a theoretical model integrating practical operations with calculations is still lacking. Achieving precise control in drying, given its multitude of influencing factors, remains a challenge, underscoring the need for intelligent real-time control systems and improved endpoint accuracy (Erbay and Icier, 2010; Sun et al., 2019). To accurately predict and model the mass transfer that occurs during drying, it is essential to have a thorough understanding of how moisture moves within the material. In the case of drying food materials, the main factor that governs the movement of moisture is internal diffusion. The concept of moisture diffusion is often explained using a one-dimensional diffusion equation introduced by Crank (1975) based on Fick's second law. This analytical solution allows us to understand the behavior of the moisture diffusivity equations under certain assumptions, such as isothermal drying, minimal shrinkage, negligible external resistance, uniform diffusivity, and uniform initial moisture content (Chen and Putranto, 2013; Rajoriya et al., 2019). However, it is important to note that using the Crank equation without verifying these underlying assumptions can lead to inaccuracies when estimating effective diffusivity values (Agrawal and Methekar, 2017). For high precision in data acquisition, the Dincer and Dost model, which takes into account both external and internal diffusion mechanisms, presents a more comprehensive approach (Dincer and Dost 1996; Dincer and Dost 1995; Rajoriya et al, 2019; Dincer and Hussain 2002).

Drying process modeling is an important consideration (Naderinezhad et al., 2016). In order to estimate the drying kinetics of food materials, semi-theoretical and empirical modeling studies are commonly performed by researchers. More accurate predictions of nonlinear interactions can be achieved by using an artificial neural network (ANN) (Sarkar et al., 2021). ANN is a model based on the biological neural system, which receives inputs from other neurons or external stimuli. ANNs offers a new approach for nonlinear computational modeling in food material analysis and provides advantages in solving engineering problems. This model has the potential to effectively model complex nonlinear processes in food engineering and successfully reflects the biological characteristics of food. Additionally, ANN stands out with its high performance, predictive capability, and robustness, learning from experimental data. Therefore, ANN plays a significant role in the field of food processing research (Bhagya Raj and Dash, 2022) The use of Artificial Neural Networks (ANN) in drying processes offers effective modeling, optimization, prediction, diagnosis, monitoring and control capabilities, especially for complex and large data sets. Although ANN can be successful in a variety of drying applications, they are not a one-size-fits-all solution and should be viewed as a complement to existing techniques rather than a complete replacement. ANN, unlike traditional statistical and physics-based models, do not require prior knowledge or assumptions. While there have been limited attempts to apply ANN-based controllers in industrial drying, further research is needed to explore their potential in real-time monitoring and control (Aghbashlo et al., 2015).

Drying processes are significant in engineering due to their status as one of the oldest, most widely used, diverse, and energy-intensive unit operations. However, the potential of ANNs in real-time monitoring and control of industrial drying systems has yet to be fully explored. Research in this area can harness the advantages of ANN technology to address challenges and enhance the efficiency of drying processes. This study proposes the utilization of available techniques and resources to produce alternative, highly nutritious products. In the pursuit of sustainable nutrition and food resource preservation, minimizing losses and improving nutritional value through available techniques and resources are paramount. The exploration of innovative technologies like ANNs, in addition to traditional methods, plays a key role in achieving these objectives.

2. Materials and Methods

2.1. Sample preparation

Zucchini samples (*Cucurbita pepo* L. cv. Sakız) provided from a local market. Following the washing process, the zucchini samples underwent slicing with a thickness of 5 ± 0.1 mm. The zucchini samples were placed in a drying oven set at 105 °C until changes in weight were observed in order to determine the initial moisture content. The initial moisture of the samples was found to be 95.35±0.24%.

2.2. Pretreatments processes

Ultrasound, hot water blanching and dipping in citric acid solution pre- treatments were applied to the zucchini samples. Ultrasound treatment was carried out in an ultrasonic bath (Intersonik Min4, Turkey) at frequency of 25kHz, for 30 min and at 200 W power. The ratio of samples to water was 1:4. After removing the ultrasonic bath, the samples were dried on a filter paper and these samples were coded as US. Other group of samples was citric acid solution immersed samples which were coded as CA. For this pre-treatment, samples were immersed into the 1% citric acid solution at the room temperature for 2 min, then dried on a filter paper. The blanching pre-treatment was conducted in a water bath (Nüve OT 40L, Turkey) at 70°C for 2 min. Following blanching, the samples were dried on a filter paper and coded as B.

2.3. Drying procedure

The drying experiments were performed in a drying oven (Nüve NS130, Turkey). 50 g zucchini slices were weighed on a drying tray and placed in the oven at 60°C. Periodic weight measurements were recorded using a digital balance with an accuracy of 0.01 g. Drying process was completed when the desired moisture content was achieved to approximately 10% wet basis (w.b.) or in the range of

0.09-0.1 g water g^{-1} d.m.. The final moisture content between 0.09-0.1 g water g^{-1} d.m. is accepted safe level for storage (Chayjan et al., 2017; Kumar et al., 2014). All drying experiments were performed in duplicate.

2.4. Drying characteristics of zucchini slices

Moisture ratio (MR) of the zucchini slices was calculated with Eq. (1):

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

The initial moisture content (M_i), moisture content at any given time (M_t), and equilibrium moisture content (M_e) of the samples were considered in the analysis. According to previous research reports by Zarein et al., (2015) and Bi et al., (2015), M_e was found to be negligible and equal to zero when compared to M_t and M_0. It is important to note that all moisture content values were expressed on a dry matter basis (d.m.) (g water g^{-1} d.m.).

Eq. (2) was used for the calculation of the drying rate (DR) of the samples.

$$DR = \frac{M_t - M_{t+\Delta t}}{\Delta t} \tag{2}$$

The moisture content at a time difference, represented as $M_{t+\Delta t}$, was considered in the analysis. The time difference, denoted as Δ_t, refers to the interval between two measuring points.

Fick's second law was utilized to determine the effective moisture diffusivity (D_{eff}). Crank (1975) proposed the law shown in Eq. (3).

$$MR = \frac{8}{\pi^2} \sum_{n=1}^{\infty} \frac{1}{(2n-1)^2} \exp\left(-(2n-1)\pi^2 \frac{D_{eff} t}{4L^2}\right) \tag{3}$$

The D_{eff} was calculated using Eq. (3), where L is half of the initial thickness of the sample (in meters) prior to drying, and D_{eff} is expressed in units of $m^2\ s^{-1}$. Eq. (4) is a logarithmic form that results from consideration of only the first term in the series, which simplifies the equation (Demiray et al., 2017).

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

According to Demiray et al., (2017) and Bi et al., (2015), when plotting the natural logarithm of MR against drying time using Eq. (4), a linear relationship is observed. This relationship can be described by Eq. (5), which provides the slope of the straight line.

$$\mathrm{Slope} = -\ \frac{\pi^2}{4L^2}\ D_{eff} \tag{5}$$

Dincer and Dost (1995) and Dincer and Dost (1996) suggested a solution (Eq. 6) of Fick’s second law for slab geometry.

$$\text{MR} = \sum_{n=1}^{\infty} A_n B_n \quad \text{for } 0.1 \leq \text{Bi} \leq 100 \text{ and Bi} \geq 100 \tag{6}$$

A simplified version (Eq. 7) of the Eq. (6) was recommended by Bezerra et al., (2015) as the Fourier number (F_0) is negligible due to too small value.

$$\text{MR} \cong A_1 B_1 \tag{7}$$

Where A1 and B1 are the slab geometry dimensions as shown below.

$$A_1 = \text{G} \tag{8}$$

$$B_1 = \exp(-\mu_1^2 F_0) \tag{9}$$

A plotting (Eq. 10) of MR vs drying time was employed for the calculation of moisture diffusivity coefficient and coefficient of mass transfer (Rajoriya et al., 2019).

$$\text{MR} = G \exp(-St) \tag{10}$$

G: The lag factor

S: The drying coefficient (s^{-1}) measures the rate of drying per unit time for a product and determines its drying capacity (Rajoriya et al., 2019).

Eq. (11) was used for the calculation of the Biot number (Rajoriya et al., 2019).

$$G = exp\left[\frac{0.2533Bi}{1.3 + Bi}\right] \tag{11}$$

Eq. (12) was utilized to calculate the moisture diffusivity (*D*, m^2 s^{-1}) (Rajoriya et al., 2019).

$$D = \left[\frac{SL^2}{\mu_1^2}\right] \tag{12}$$

μ_1 represents a characteristic root that is influenced by the geometry (Rajoriya et al., 2019).

If the Bi is between 0.1 and 100, $\mu_1 = \tan^{-1}(0.640443\text{Bi} + 0.380397)$.

If the Bi ≥ 100, $\mu_1 = \pi/2$.

The coefficient of mass transfer (h_m, m s^{-1}) was calculated by Eq. (13) (Rajoriya et al., 2019).

$$h_m = \left[\frac{DBi}{L}\right] \tag{13}$$

2.5. Mathematical Modeling of Drying Curves

The listed thin layer mathematical models in Table 1 were utilized to identify the most appropriate model. The relationship between predicted and experimental data for zucchini slices, subjected to various pre-treatments, was assessed using statistical parameters such as the determination coefficient (R^2), root mean square error (RMSE), and reduced chi-square (χ^2). The RMSE and χ^2 values were derived using Eq. (14) and Eq. (15), respectively. The model that demonstrated the highest R^2 value, along with the lowest RMSE and χ^2 values, was determined to be the optimal model for predicting the experimental data.

Table 1. Mathematical models employed in the current study.

Model name	Model	References
Lewis	$exp(-kt)$	Lewis (1921)
Henderson and Pabis	$aexp(-kt)$	Henderson (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)

$$\text{RMSE} = \left[\frac{1}{N}\sum_{i=0}^{N}(MR_{pre,i} - MR_{exp,i})^2\right]^{\frac{1}{2}} \quad (14)$$

$$\chi 2 = \frac{\sum_{i=0}^{N}(MR_{pre,i} - MR_{exp,i})^2}{N - n} \quad (15)$$

The predicted moisture ratio ($MR_{pre,i}$) and experimental moisture ratio ($MR_{exp,i}$) were used in the calculation of statistical parameters. N represents the number of observation data and n denotes the constants of the thin-layer drying models (Demiray, 2019). Statistical analysis was performed using SPSS (ver. 22), while the drying process modeling of zucchini slices was conducted using Curve Fitting Toolbox by the MATLAB software (R2015a, version 8.5).

2.6. Modeling of Artificial Neural Network

The study employed the Neural Net Fitting Toolbox by using MATLAB software (R2015a, ver. 8.5) alongside the algorithm of Levenberg-Marquardt back-propagation, following the recommendation by Omari et al., (2018). The configuration of ANN model consists of drying time as input and moisture ratio as output, with the tansig function selected for the hidden layer, according to Omari et al., (2018). Mathematical definition of the tansig function was given in Eq. (16). According to mean square error (MSE) and R^2, optimal neuron number of configuration was 3 neurons in the hidden layer. Three subsets, 60% for training, 20% for validation, and 20% for testing, of the data collected from the drying experiments were used. Sample numbers for training, validation and testing were given in Table 2. The performance of the ANN model was evaluated by calculating RMSE and R^2 values, which were used to compare with experimental data to verify the model-predicted data. On the other hand, training was completed when termination conditions formed, to prevent over-fitting. Termination conditions were maximum 1000 epoch, 6 validation checks and 10^{-7} performance gradient (Yıldız et al. 2015). Besides, learning rate and momentum coefficient were 0.01 and 0.9, respectively. Arı and Berberler (2017) reported that learning rate between 0.01 and 0.09 shows great results. In addition, momentum coefficient is recommended in the range of 0 and 1. In the current study, the important markers for reproducibility of the ANN model were in the range of recommended values.

Table 2. Sample numbers of ANN modeling

Experiment	Training	Validation	Test
C	28	10	10
CA	20	7	7
B	24	8	8
US	20	6	6

$$y = \frac{2}{[1 + \exp\,(-2x)]} - 1 \tag{16}$$

2.7. Measurement of Color Properties

The color attributes of the zucchini samples were determined by utilizing a color meter (PCE-CSM 1, England). To enhance precision, measurements were conducted at ten different points on the surface of each sample. Differences in color values between the fresh and dried products were evaluated by means of the total color differences (ΔE) calculation (Eq. 17). According to Tepe (2022), the ΔE value provides a quantified measure of color change magnitude. High values indicate significant color changes in the product.

$$\Delta E = \sqrt{(L_0^* - L^*)^2 + (a_0^* - a^*)^2 + (b_0^* - b^*)^2} \tag{17}$$

2.8. Statistics

Statistical evaluation was conducted by using SPSS package program with the ver. 22. One-way analysis of variance (ANOVA) was performed, followed by the Duncan post-hoc test, to compare means at a significance level of $p<0.05$. The standard deviation (SD) values were also reported.

3. Results and Discussions

3.1. Influence of Pretreatments on Drying of the Zucchini Slices

Figure 1 shows the moisture ratio (A) and drying rate (B) of the untreated and pretreated zucchini slices. In addition, Figure 2 illustrates the drying time of the samples. As seen from Figure 1, pretreatments enhanced the drying rate and thus, drying time decreased. The shortest drying time was observed at the samples pretreated with US, whereas the longest was obtained from the untreated samples. Besides, a falling rate period was determined in all samples according to Figure 1 (b). Pretreatments shortened the falling rate period. Thus, the drying rate increased, and the drying time decreased. Tepe and Kadakal (2022) noted that long falling rate period is a part of the reasons causing long drying time. The findings of the study aligned well with the results stated by Tepe and Kadakal (2022). Pretreatments have a mechanism that enables easier water evaporation and a faster drying rate. In the current study, the effect of US pretreatment can be related to the sponge effect by rapid compression and expansion which creates a microchannel and removes dissolved oxygen in the tissue of the food. As a result, mass transfer from the inner of food to the outer is facilitated (Bozkır and Ergün, 2020; Wang et al., 2019). The mechanism of HWB can be explained by the relation of tissue and increment in cell membrane permeability (Wang et al., 2018; Hiranvarachat et al., 2011; Doymaz 2017). The increment of drying rate of the samples pretreated with CA can be associated with inactivating degradative enzymes, texture modification, and loosening pectin (Hiranvarachat et al., 2011; Deng et al., 2019). In the literature, there are limited studies on the effect of pretreatments on zucchini slices. Bagheri and Dinani (2019) noted that US pretreatment had a positive contribution to the drying rate of zucchini slices. Similar results have been documented in other fruits and vegetables such as potato slices (Jarahizahed and Dinani, 2019), pineapple slices (Rani and Tripathi, 2019), kiwifruits (Wang et al., 2019), and garlic slices (Bozkır et al., 2019). Additionally, similar reports were noted by Doymaz et al., (2015) in quince slices for HWB, Soydan and Doymaz (2021) in apple slices for HWB, Hiranvarachat et al., (2011) in carrot slices for HWB, Doymaz (2020) in kiwifruits for CA, Doymaz and Bilici (2014) in peach slices fo CA and Doymaz and Sahin (2016) in broccoli slices for CA.

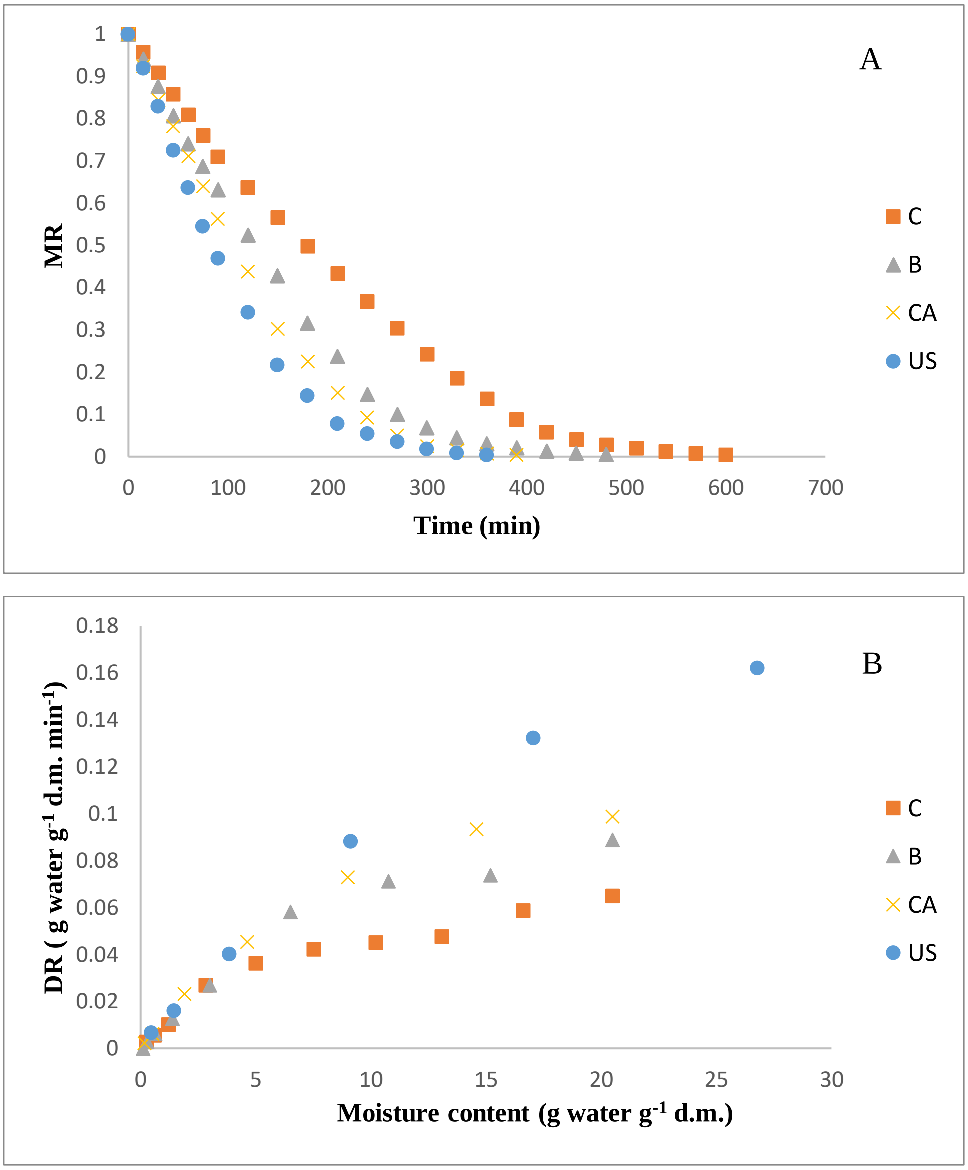

Figure 1. Changes of the MR (A) and DR (B) of the zucchini slices

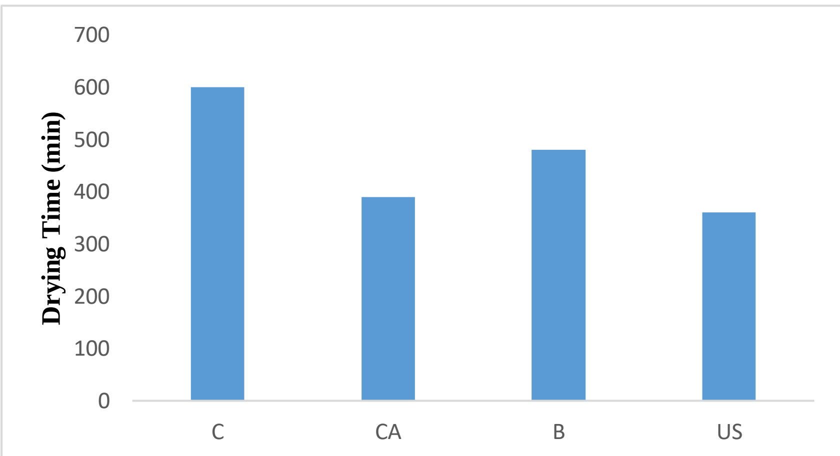

Figure 2. Drying time of the untreated and pretreated zucchini slices.

3.2. Drying Characteristics of the Zucchini Slices

Table 3 showcases the drying characteristics of zucchini slices throughout the drying process. The determination of the drying characteristics serves to offer valuable insights into the drying properties of the zucchini slices during the drying process.

The pretreated zucchini slices exhibited higher S values compared to the untreated samples. The S value, representing the rate at which a solid object undergoes drying per unit of time, plays a crucial role in influencing the drying process of agricultural products. This parameter is influenced by factors such as moisture content at initial and final stage of the drying, drying type, and prevailing conditions (Beigi 2017). According to Beigi (2017) and Beigi (2016), the S value increased with the drying rate for celeriac and apple slices, respectively. Moreover, Liu et al., (2013) noted a greater S value for blanched eggplants compared to their unblanched counterparts, attributable to the higher drying rate. Rojariya et al., (2019) noted a higher S value for refractance window dried apple slice than hot air dried apple slices due to a higher drying rate at refractance window drying. The findings of this study align with these previous reports, as all pretreatments led to an increased drying rate for the zucchini slices.

The lag factor, representing solid material resistance to heat and mass transfer during drying, is determined by the Biot number. Three components constitute The Biot number. A Biot number below 0.1 signifies that moisture transfer and gradients within the food are minimal, indicating a minor internal resistance but substantial external resistance. When the Biot number falls within the range of 0.1 to 100, both internal and external resistance factors are at play, which is commonly observed in material drying processes. However, if the Biot number surpasses 100, it indicates a significantly higher internal resistance compared to external resistance (Dincer 1998; Beigi 2016; Oladejo et al., 2021). In this study, Biot numbers were computed to range from 0.49 to 0.58, while the G values fell between 1.072 and 1.081. These results indicate the coexistence of both internal and external resistance factors during the drying process. This finding aligns with similar observations performed by Oladejo et al., (2023) in roselle, Oladejo et al., (2020) in yellow casava, Torki-Harchegani et al., (2015) in whole lemon slices, Beigi (2016) in apple slices, Liu et al., (2013) in eggplant slices, and Beigi (2017) in celeriac slices.

Table 3. Drying characteristics of the untreated and pretreated zucchini slices.

Experiment	G	Bi	u_1	S	D	D_{eff}	h_m
C	1.072	0.49182	0.6076	8.35 x 10^{-5}	1.41 x 10^{-9}	2.12 x 10^{-10}	2.78 x 10^{-7}
CA	1.079	0.55761	0.6355	13.89 x 10^{-5}	2.15 x 10^{-9}	3.52 x 10^{-10}	4.79 x 10^{-7}
B	1.081	0.57722	0.6435	11.81 x 10^{-5}	1.78 x 10^{-9}	2.99 x 10^{-10}	4.11 x 10^{-7}
US	1.074	0.51018	0.6155	16.58 x 10^{-5}	2.73 x 10^{-9}	4.20 x 10^{-10}	5.58 x 10^{-7}

The application of pretreatments resulted in significant increases in moisture diffusivity (D), effective moisture diffusivity (D_{eff}), and mass transfer coefficient (hm) for the zucchini slices, as presented in Table 3. These values displayed an upward trend as the drying time decreased, indicating the crucial role of moisture diffusion and mass transfer in the drying behavior of materials. Among the pretreated samples, those subjected to ultrasound (US) treatment exhibited the highest recorded values for D, D_{eff}, and hm, measuring at 2.73 x 10^{-9} m^2 s^{-1}, 4.20 x 10^{-10} m^2 s^{-1}, and 5.58 x 10^{-7} m s^{-1}, respectively. It is noteworthy that D values consistently exceeded D_{eff} values, which can be attributed to the different calculation approaches employed by the Crank equation and the Dincer and Dost model. The Crank equation, derived from Fick's second law, employs a super-diffusion model to calculate D_{eff}, while the Dincer and Dost model considers resistance of internal or external to mass transfer during drying (Rajoriya et al., 2019). The significant enhancements in mass transfer and moisture diffusion observed in the pretreated zucchini slices in comparison to untreated samples can be based on the improved moisture diffusion capability, increased evaporation rate, and drying rate facilitated by the pretreatment processes. This trend aligns with findings from previous studies on yellow cassava slices treated with ultrasound (Oladejo et al., 2021), guava slices treated with ultrasound (Santos et al., 2020), and carrot slices treated with hot water blanching (Doymaz, 2017).

3.3 Thin-Layer and ANN Modeling of Drying Curve of the Zucchini Slices

In this study, two distinct methodologies were employed to predict the moisture ratio of the zucchini samples during convective drying: the traditional thin-layer approach and the novel black box approach using Artificial Neural Networks (ANN). The statistical parameters for each modeling type can be found in Table 4. Based on these parameters, Midilli and Kucuk, Parabolic and Page models generally demonstrated excellent performance in characterizing the drying process of the zucchini samples due to high R^2 values and low chi-square and RMSE values compared to the other models across all drying experiments. Kutlu and İsci (2017) reported that Midilli and Wang and Sing models gave the prediction performance to estimate the moisture ratio of convective dried zucchini slices. Fahimi et al., (2014) noted that the moisture ratio of the convective dried zucchini was described by Hii, Law and Cloke model. The variation in model performance can be related to some factors such as the specific fruit variety, variations in drying conditions, equipment specifications, initial moisture content, and the structure of the food matrix. In contrast, the ANN modeling approach outperformed the thin-layer modeling. As indicated in Table 4, the ANN modeling had lower RMSE values and higher R^2 values, indicating its superior predictive accuracy in comparison to thin-layer models. Likewise, Tavakolipour et al., (2014) noted the ANN modeling gave the best performance for the prediction of MR of zucchini slices. Additionally, Şahin and Öztürk (2018), Murthy and Manohar (2014), Rasooli Sharabiani et al., (2021), and Chokphoemphun et al., (2023) reported similar findings prediction of moisture ratio of dried fig, mango ginger, apple, and potato, respectively. Best validation performance, regressions, and plots of the ANN modeling were illustrated in Figure 3, Figure 4, and Figure 5, respectively. Moreover, it is crucial to monitor for over-fitting when training an ANN model. Over-fitting is undesirable and occurs when the validation and test error curves exhibit opposite trends during the training iterations. This indicates that the desired level of success in training the artificial neural network has not been achieved (Kurtulmuş et al., 2020). Kurtulmuş et al., (2020) also emphasized that a similar trajectory of validation and test error vectors indicates the absence of over-fitting during ANN training. In the light of these information, the similar trajectory of validation and test vectors were seen in Figure 3. It means that no over-fitting was observed in the current study. In conclusion, ANN modeling showed greater results than thin-layer modeling for generalization of drying process. Onwude et al. (2016) noted that ANN modeling can describe the drying process in a wide range in comparison to thin-layer modeling. In addition, ANN gives perfect outcomes in the case of adding new experimental conditions and data set. Moreover, effectively employing ANN enables the real-time supervision and regulation of industrial drying processes and operations (Onwude et al. 2016).

Table 4. Model's statistical parameters of the drying of the zucchini slices.

Model	Temperature	Model Constants				χ^2	RMSE	R^2
Lewis	C	*k= 0.004647*				*0.003523588*	*0.058110*	*0.9729*
	CA	*k= 0.007665*				*0.003668534*	*0.058760*	*0.9734*
	B	*k= 0.006511*				*0.003569193*	*0.058230*	*0.9739*
	US	*k= 0.009193*				*0.002556887*	*0.048960*	*0.9811*
Page	C	*k= 0.0007307*	*n= 1.337*			*0.000831011*	*0.027600*	*0.9942*
	CA	*k= 0.001223*	*n= 1.374*			*0.000299271*	*0.016250*	*0.9981*
	B	*k= 0.0009972*	*n= 1.367*			*0.000432087*	*0.019720*	*0.9972*
	US	*k= 0.002023*	*n= 1.321*			*7.76726E-05*	*0.008244*	*0.9995*
Henderson and Pabis	C	*k= 0.005009*	*a= 1.072*			*0.00289786*	*0.05154*	*0.9796*
	CA	*k= 0.008333*	*a= 1.079*			*0.002967485*	*0.05117*	*0.9811*
	B	*k= 0.007083*	*a= 1.081*			*0.002806742*	*0.05026*	*0.9816*
	US	*k= 0.009944*	*a= 1.074*			*0.001939931*	*0.04120*	*0.9875*
Midilli and Kucuk	C	*k= 0.000887*	*a= 0.9796*	*n=1.277*	*b=-0.000108*	*0.0004332*	*0.01900*	*0.9975*
	CA	*k= 0.001102*	*a= 0.9794*	*n=1.382*	*b=-0.00005757*	*0.000192093*	*0.01212*	*0.9991*
	B	*k= 0.0008048*	*a= 0.9754*	*n=1.397*	*b=-0.00003707*	*0.000362101*	*0.01702*	*0.9981*
	US	*k= 0.002001*	*a= 0.9931*	*n=1.319*	*b=-0.00002466*	*7.492E-05*	*0.00749*	*0.9996*
Parabolic	C	*a= 1.009*	*b= -0.003443*	*c= 0.000002932*		*0.000153253*	*0.01158*	*0.9990*
	CA	*a= 1.016*	*b= -0.005857*	*c= 0.000008439*		*0.000187915*	*0.01244*	*0.9990*
	B	*a= 1.015*	*b= -0.004919*	*c= 0.000005948*		*0.000260138*	*0.01487*	*0.9985*
	US	*a= 1.003*	*b= -0.006787*	*c= 0.000001141*		*0.000501209*	*0.02018*	*0.9972*
ANN	C						***0.002042***	***0.9999***
	CA						***0.005755***	***0.9999***
	B						***0.003504***	***0.9999***
	US						***0.004512***	***0.9999***

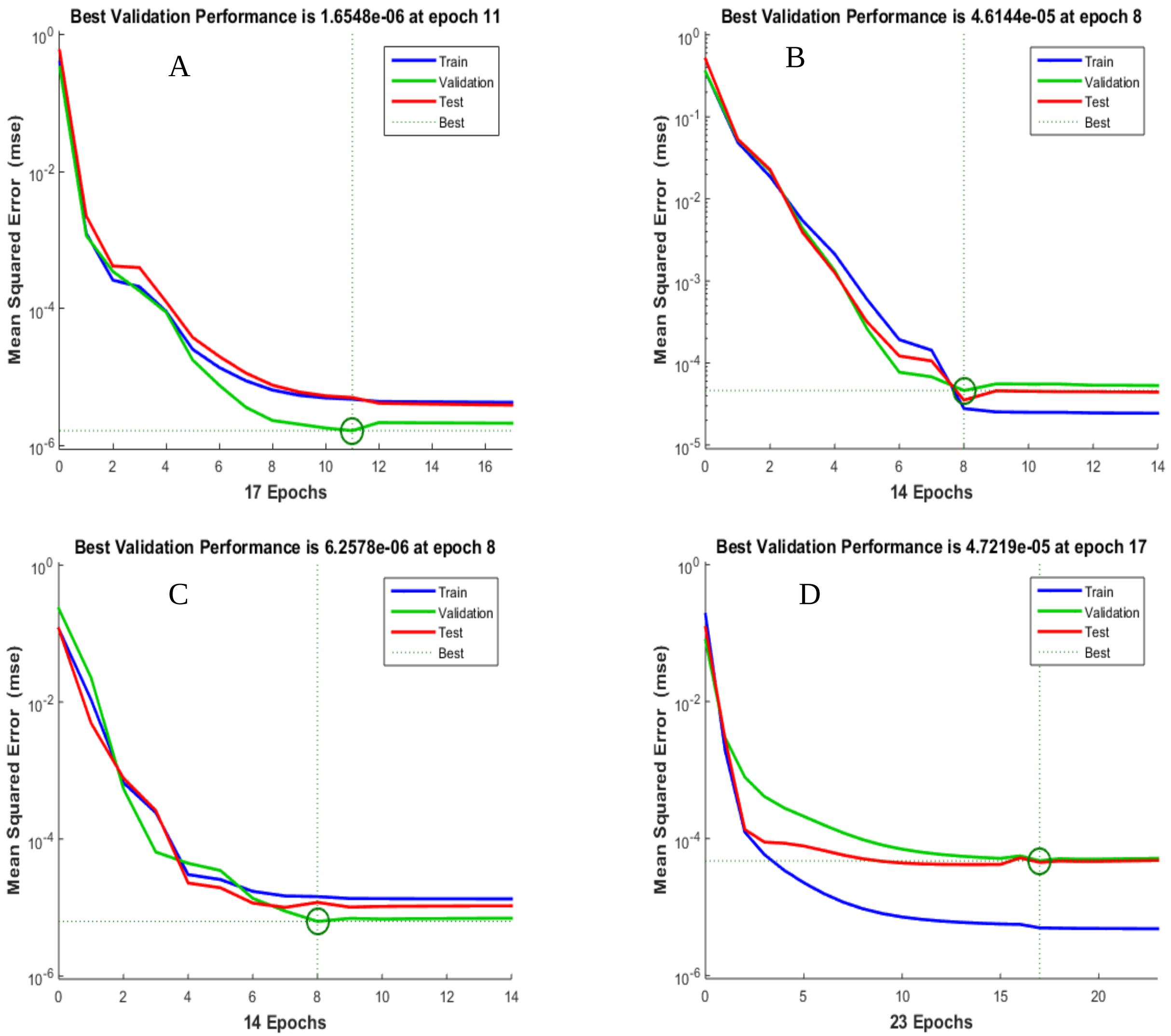

Figure 3. Best validation performance of ANN modeling of the zucchini slices (A: C; B: CA; C: B; D: US).

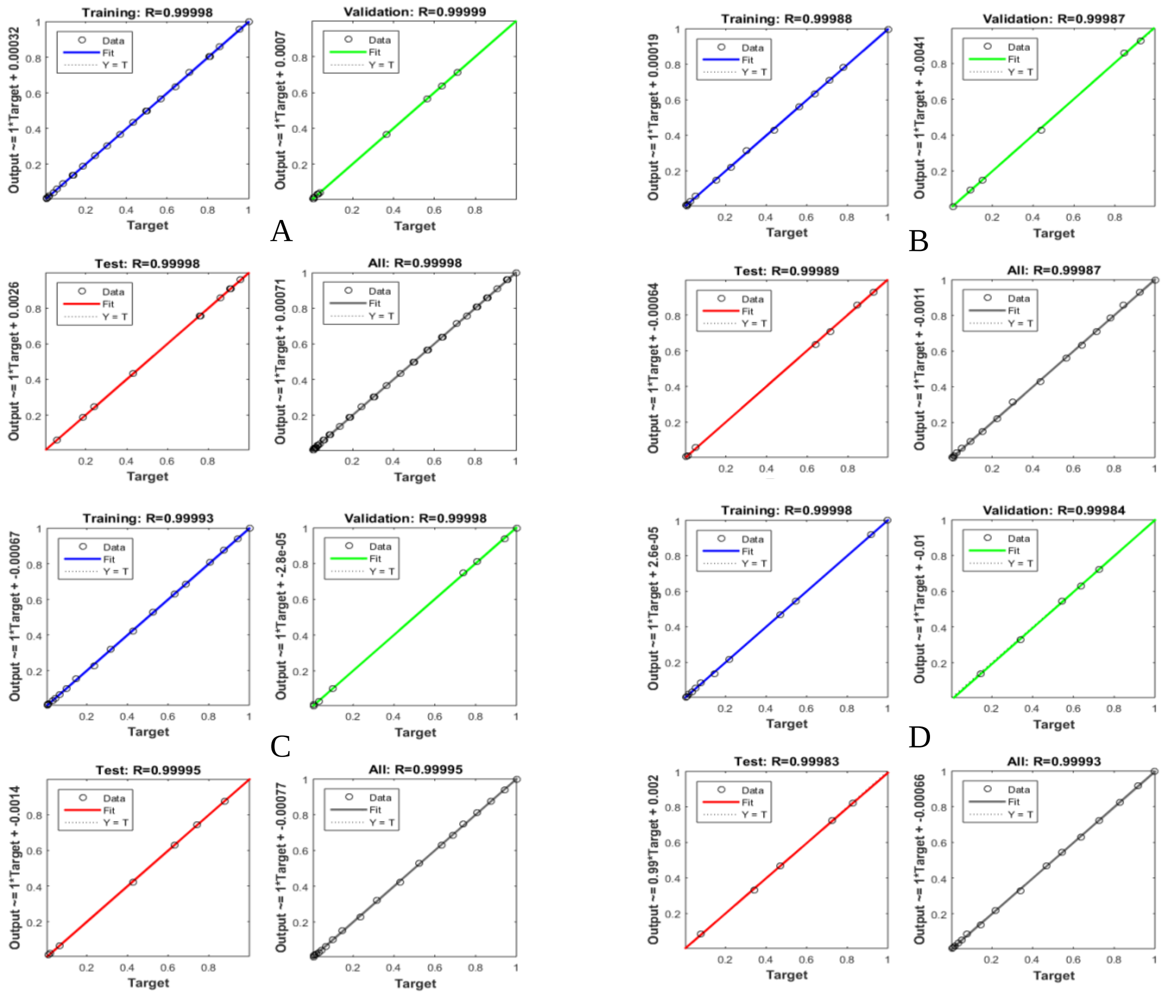

Figure 4. Regressions of ANN modeling of the zucchini slices (A: C; B: CA; C: B; D: US)

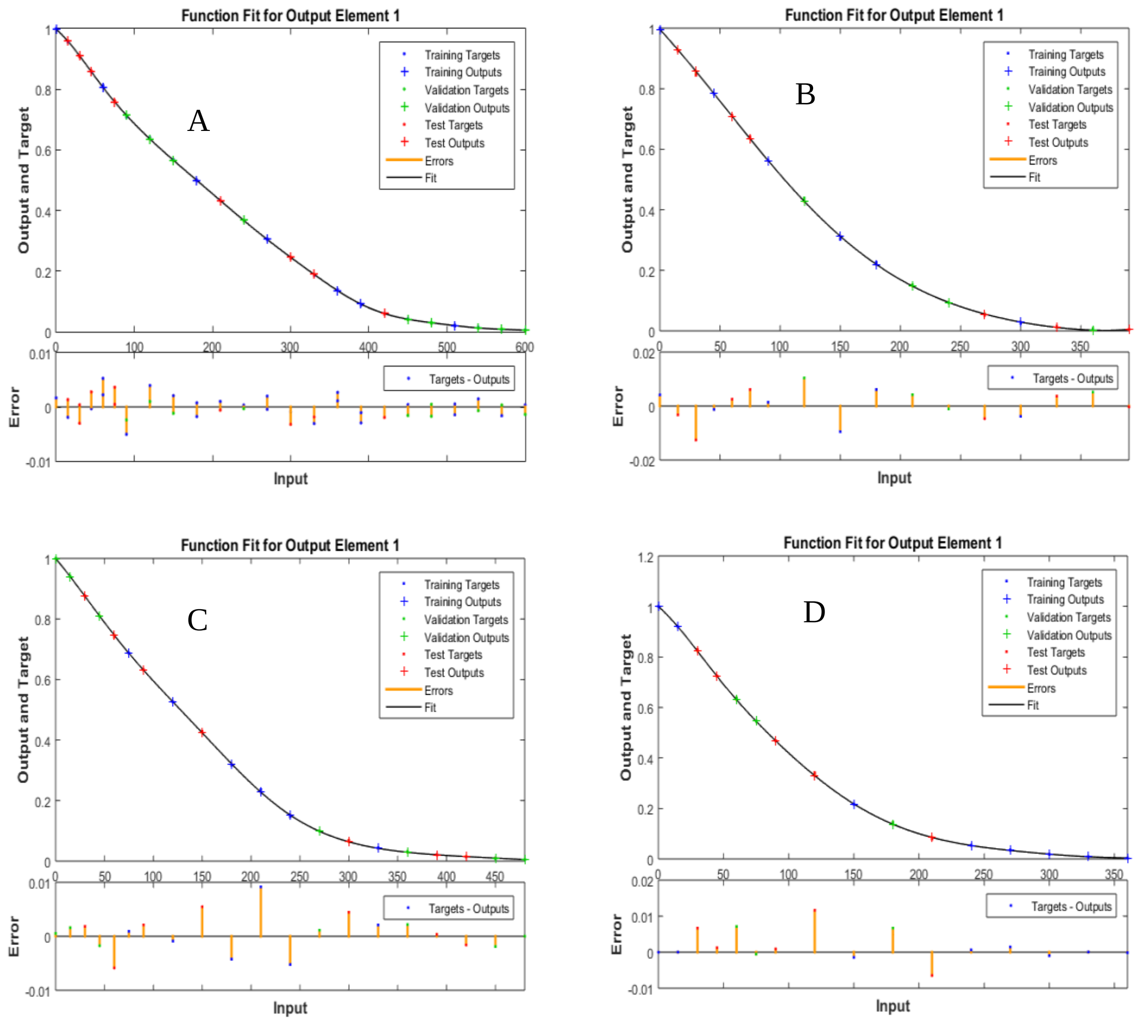

Figure 5. Drying curves of the zucchini slices by ANN (A: C; B: CA; C: B; D: US) (Input: Drying Time (min), Output: Estimated MR (dimensionless) and Target: Experimental MR (dimensionless)).

3.4 Color Properties of the Zucchini Slices

Color properties of the zucchini slices are given in Table 5. L*, a*, and b* values of the dried zucchini slices generally showed differences in comparison to fresh samples ($p<0.05$). The color characteristics of the final dried product are commonly influenced by enzymatic browning attributed to elevated levels of polyphenols, polyphenol oxidase, and peroxidase. Additionally, non-enzymatic browning processes such as the Maillard reaction, caramelization, and the chemical oxidation of polyphenols, as well as maderisation, contribute to the observed effects (Deng et al., 2019). Moreover, the formation of pheophytin and pheophorbide from chlorophylls may play a role in darkening (Tepe et al. 2022). Darker color and appearance are related to loss in L* value of the dried product (Seerangurayar et al., 2019). As seen from Table 5, differences in L* value generally were found to be between fresh and pretreated samples ($p<0.05$). This means that the drying process had remarkable effect on the darkness or lightness of the zucchini slices due to probable minimal enzymatic or non-enzymatic browning. The colors exhibited by fruits and vegetables are attributed to the presence of chlorophylls, carotenoids, and anthocyanins (Cömert et al., 2020). The a* value represents the redness of the product (Seerangurayar et al., 2019). Increasing the a* value indicates that redness of the product increases. Akar and Barutçu Mazı (2019) noted that higher retention chlorophyll causes lower a value, meaning more green color. Besides, Fijalkowska et al. (2016) observed a correlation between the a* value, representing red coloration, and enzymatic browning, providing an explanation for the possible increase in the a* value because of enzymatic browning. In the current study, the a* value of the pretreated zucchini slices showed a statistically increasing in comparison to the fresh samples ($p<0.05$). Decrement in L* values of the pretreated samples support this argument. In addition, the degradation of chlorophylls during drying and air removal from the cells which provides an intense color appearance may contribute to increment of a* value. McGhie and Ainge (2002) and Nowacka et al. (2021) notified that chlorophylls possess the capacity to mask the color expression of carotenoids, which are the main contributors to the yellow color observed in various food products. Zhu et al. (2010) observed a direct relationship between the heightened yellowness of dehydrated products and the elevated concentration of yellowish phytochemicals following the removal of water. An increment in the b* value of the plant-based product may be related these approaches. In this study, the b* value of the dried zucchini slices was found to be higher than fresh zucchini slices. This may be explained by the statement addressed before. On the other hand, Abbaspour-Gilandeh et al., (2021) a ΔE value exceeding 5 signifies a significant difference for untrained observers in color assessment. Consequently, lower ΔE values are indicative of superior color characteristics. ΔE values of All dried samples exceeded 5, and the lowest value was observed in samples treated with citric acid.

Table 5. Color properties of the zucchini samples

Experiment	L*	SD (±)	a*	SD (±)	b*	SD (±)	ΔE
Fresh	84.07^{a}	0.80	-2.44^{b}	0.43	18.68^{c}	1.84	0
C	77.96^{b}	2.11	1.46^{a}	2.14	34.43^{a}	2.52	14.36
CA	77.43^{b}	1.41	2.16^{a}	1.61	33.59^{a}	3.45	13.00
B	75.13^{b}	1.45	0.42^{a}	2.71	26.81^{b}	3.59	15.81
US	76.99^{b}	2.55	1.44^{a}	1.64	32.25^{a}	4.11	20.33

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

4. Conclusion

The current study investigated the effect of hot water blanching, dipping citric acid solution, and ultrasound pretreatment on the drying rate, and drying characteristics of the zucchini slices. Additionally, modeling of thin-layer and ANN of the moisture ratio of zucchini slices were studied. It was clear that the applied pretreatments had a positive contribution to the drying rate of zucchini slices. The lowest drying time and the highest drying rate were obtained from the US pretreated zucchini slices. On the other hand, the drying of zucchini slices was affected by internal and external resistance according to the Biot numbers. Moreover, the pretreatments had a positive impact on moisture diffusivity and mass transfer rate, ultimately leading to an enhanced drying rate for the zucchini slices. ANN modeling was found as the most suitable modeling approach in comparison to thin-layer modeling. Additionally, the redness and yellowness of the dried zucchini slices increased, whereas lightness of the dried zucchini slices generally showed no statistical difference in comparison to fresh samples. Besides, the lowest ΔE value was obtained from the citric acid pretreated zucchini slices.

In the literature, there are limited studies on the drying of zucchini slices after pretreatments. In this context, the study will provide contributions. Additionally, zucchini is widely consumed plant product and has a potential alternative snack food like chips by drying. This study will provide significant contributions to the evaluation of zucchini as an alternative snack food. On the other hand, it is suggested that the effect of convective drying and pretreatments on other quality parameters such as the nutritional composition and sensory properties could be investigated.

Author Contributions

T.K.T; Conceptualization, Methodology, Investigation, Data Curation, Writing Original Draft, Review and Editing, Formal Analysis.

N.A.; Methodology, Investigation; Data Curation, Writing Original Draft, Review and Editing.

F.B.T.; Conceptualization, Methodology, Investigation, Data Curation, Writing Original Draft, Review and Editing.

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