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Effect of Different Pretreatments on Drying Characteristics and Physicochemical Properties of Apricot (*Prunus armeniaca* L.)

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ABSTRACT

In this study, apricot samples were dried by using different drying methods (tray drying, microwave drying, and freeze drying). Moreover, different pretreatments (infrared, ultrasound, and treatment with dipping green tea extract) were also applied to the samples. The effect of process conditions on physical and chemical quality of dried apricot samples were investigated. It was aimed to come of age of these technologies as an alternative to conventional pretreatments. Among all drying techniques, the shortest processing time was achieved by microwave drying at 270 W. Midilli was found to be the best model that fits the moisture ratio values among 10 thin layer models. Freeze dried samples had the lowest water activity which ranged from 0.2260 to 0.4868 and rehydration capacity of dried samples were found to be between 2.40 and 3.09. Besides, it was found that the total phenolic content of dried apricots varied between 99.24 and 512.60 mg GAE/100 g dry matter. In addition, the maximum antioxidant activity values for microwave drying (270 W) were obtained in the green tea extract pretreated samples and calculated to be 1.85 ± 0.01 mg TE/g dry matter. NMR and SEM analysis were also applied to the samples. To sum up, it can be declared that microwave technology and green tea extract pretreatments were superior and had beneficial impacts on the end product's quality.

1 | Introduction

Apricot (*Prunus armeniaca* L.) is known to be one of the dietary sources with the highest polyphenol content and can also be considered as a natural functional food (Iglesias-Carres et al. 2019). It is cultivated in many countries, especially in Turkey, Italy, and Iran (Li et al. 2022). Turkey is one of the leading producers with 833,998 tons (FAO 2022) of capacity. Apricot fruit cannot be stored fresh for a long time, partly due to its high respiration rate and rapid ripening process (Vega-Gálvez et al. 2019). In addition, the high water content of fresh fruits causes microbial deterioration, biochemical reactions, and enzymatic reactions (Iqbal, Akbar, and Aftab 2019). Therefore, different preservation techniques such as canning, drying, or packaging in controlled atmosphere can be used to increase the shelf life of apricot fruit (Vega-Gálvez et al. 2019). Drying procedure decreases the moisture content which enables the fruit to be stored safely for a longer time. According to the Codex Alimentarius for dried apricots, the moisture content of unsulfured samples which were not treated with sorbic acid should not be higher than 20% (Codex Alimentarius, International Food Standards 1981). Accordingly, in the literature, the moisture content of dried apricots were reported as 23%–25% (Karabulut et al. 2007); 20% (Madrau et al. 2009); 25% (Horuz et al. 2017); 19% (Ozturk and Mutlu Ozturk 2022); and < 15% (Yang et al. 2024).

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Sun drying, which is the most widely used food drying method in the world, is also preferred for apricots in Turkey. However, long hours of drying are not always recommendable, due to economic reasons and the risk of being contaminated (Doymaz 2004; Karabulut et al. 2018). Different drying techniques have been developed to get rid of the negative effects of sun drying method and to produce higher quality products in a shorter time. Some of these methods are hot air drying, microwave drying, and freeze drying. Each method has its own cons and pros. Compared to sun and hot air drying, microwave technology provides dried products with better quality in a shorter period of time. On the other hand, freeze drying is the method which produces the best quality products but it takes much longer time and can be less economic due to investment and operating cost.

Dried apricots are often treated with sulfur dioxide (SO_2) to inhibit enzymatic browning during drying, to provide protection from nonenzymatic browning reactions, and to prevent microbial spoilage during drying and storage (Karabulut et al. 2007; Li et al. 2023). However, it has been reported that inhaling or swallowing sulfur may trigger asthma and allergic reactions in sensitive individuals (Miranda et al. 2009; Kıran et al. 2019). These side effects encouraged researchers to try and come up with new technologies to prevent and at the same time to improve the quality of dried fruits. Infrared (IR) heating, which is the first technology applied to apricots instead of sulfur addition in this study, has lots of advantages over conventional heating under similar conditions, such as shorter and homogeneous heating, reduced quality losses, and significant energy savings. IR integration to other processes such as bleaching, dehydration, thawing, roasting, baking, and cooking generally improves the efficiency of processes. Besides, the use of this method has become more common to control pathogenic or spoilage microorganisms on the surface of fruits and vegetables (Rastogi 2012). Pretreatment with ultrasound is the second technology investigated within the scope of this study. It causes a more porous structure and accelerates the drying process. Generally, when fresh fruit is cut, enzymatic browning starts due to polyphenol oxidase and other oxidative enzymes. The ultrasound process can be applied as a pretreatment to control enzymatic browning and to develop desired color of dried products (De la Fuente-Blanco et al. 2006; Sogi, Siddiq, and Dolan 2015). Treating the apricots with green tea extracts before drying procedure was the last method investigated in this study. Green tea is the unfermented form of tea leaves and is rich in phenolic compounds (Radi et al. 2017; Xu et al. 2018). Green tea is effective on anti-inflammatory, anticarcinogenic, cardiovascular diseases, and also has antioxidant and antimicrobial properties (Reygaert 2014). It has been reported that the addition of green tea extract to the coating material formulation prevents the formation of mold in the products (Sabaghi et al. 2015).

There are various studies in literature which reports drying of apricots by using different technologies such as hot air, microwave, IR, radiofrequency, and freeze drying (Toğrul and Pehlivan 2003; Karataş and Kamışlı 2007; Fratianni et al. 2013; Özbek et al. 2022; Aydın 2022). Besides, the effect of ultrasound pretreatment on drying conditions was also studied and reported in literature (Yıldız et al. 2021).

In this study, it was focused to investigate the possibility of usage of new techniques as a pretreatment to eliminate the side effects of SO_2 and sun drying methods. For this purpose, apricots, which were pretreated with IR, ultrasound, and green tea extract, were dried by tray drier, microwave drier, and freeze drier and their effects on physical and chemical quality was investigated. Besides, both the pretreatment and drying conditions were also optimized.

2 | Materials and Methods

2.1 | Materials

The apricots used in this study were obtained from a producer in Malatya. Hacıhaliloğlu variety was chosen and stored at +4°C before drying process. They were divided into two pieces and the kernels were removed before experiments. Folin–Ciocalteau's phenol reagent, sodium carbonate ($NaCO_3$), 1,1-diphenyl-2-picrylhydrazyl, methanol, ethanol, trolox, and gallic acid were purchased from Sigma-Aldrich (USA) with high purity. Green tea (Çaykur, Organic Zümrüt Green Tea) was obtained from local markets.

2.2 | Methods

2.2.1 | Pretreatment Methods

Three different pretreatment types were applied in the study:

1. Infrared pretreatment was applied using an IR system (UHF Brand, INF-9-5050 Model) till the moisture content of samples decreased to 55%. As a result of the preliminary experiments, it was decided to apply 200°C by using eight IR lamps. In each drying process, an average of 600 g fresh sample was placed to the IR dryer.
2. The ultrasound pretreatment application was carried out at 35 kHz for 20 min in an ultrasonic bath (Balerina, Berlin, Germany) at 25°C. The duration of the treatment was decided according to the preliminary experiments: ultrasound application longer than 20 min caused a deterioration of fruit integrity. The solid to liquid ratio was adjusted as 1:1 (w/v) for treatment. After the process, the samples were filtered with the help of a strainer for 5 min and the samples were wiped by using a tissue paper to get rid of the water on the surface.
3. For pretreatment with dipping green tea extract, the ground green tea leaves were mixed with water at a solid to solvent ratio of 1:9 (w/v) for 15 min in a water bath which was set at 80°C. For dipping process, apricots were dipped in extract solution, the solid to solvent ratio of the system was adjusted to 1:1 (green tea extract:apricot (w/v)) ratio, and continued for 1 h. After filtering with the help of a strainer for 5 min and wiping by using a tissue paper to get rid of the water on the surface, the drying process was started (Igual et al. 2012; Sabaghi et al. 2015).

2.3 | Drying Process

Tray drying was performed in a tray drier (TK-LAB, Eksis Industrial Drying Systems, Turkey). Drying temperature and hot air velocity were set as 70°C and 1.5 m/s, respectively.

According to Turkish standard (TS 485 2019), the drying process was continued till the final moisture content reached to 20%. The apricots were dropped across the trays' surface. Tray dried samples were used as a control group.

Due to the high moisture content of apricot, microwave drying process could not be applied directly. For this reason, samples were pre-dried in a tray dryer at 70°C to a intermediate moisture content of 55% (the value was decided according to preliminary experiments) and it took 232 min as average. Then microwave drying was carried out in a household microwave oven (General Electric, GMOM 25 model). The apricots were placed at the center of the microwave. Apricots were dried with 90, 180, and 270 W microwave power with the average weight of the sample processed at each batch was approximately 50 g and the final moisture content of the dried sample was 20%.

Pretreated apricots were stored at −18°C before freeze drying. Freeze drying was carried out for 48 h in a lyophilizer (TOPT-100 Model Pilot Type).

2.4 | Investigation of Drying Curve, Effective Moisture Diffusivity (D_{eff}), and Activation Energy (E_A)

The moisture variation data obtained from different drying procedures were modeled by using 10 thin layer models (Table 1). The moisture ratio was expressed as $(M-M_e)/(M_0-M_e)$ in these models, where M is the moisture content at time t, M_0 is the initial moisture content, and M_e is the equilibrium moisture content. The ratio was simplified to M/M_0, since M_e value was too small compared to M and M_0. SigmaPlot 12.0 (Systat Inc., USA) was used to calculate model parameters. The best model was chosen according to higher R^2 and Adj-R^2 and lower RMSE values (Doymaz 2012).

The effective diffusion coefficient during drying was calculated using a mathematically simplified version of Fick's second equation for diffusion. Equation (1) provides an analytical solution to Fick's second law, taking into account a uniform initial moisture distribution, infinite slab geometry, and constant moisture diffusivity.

$$\mathrm{MR}=\frac{8}{\pi^2}\sum_{n=0}^{\infty}\frac{1}{(2n+1)^2}\exp\left(-\frac{[2n+1]^2\pi^2 D_{\mathrm{eff}}t}{4L^2}\right) \tag{1}$$

In this equation, MR, t, D_{eff}, and L refer to moisture ratio (M_t/M_0), time (s), effective diffusion coefficient (m^2/s), and slice thickness (m), respectively. For long drying times, the first terms of the formula series are simplified to obtain the following Equation (2) (Dehghannya et al. 2019).

$$\ln\mathrm{MR}=\ln\frac{8}{\pi^2}-\frac{\pi^2 D_{\mathrm{eff}}t}{4L^2} \tag{2}$$

In the study, the natural logarithmic transformations of the MR values were plotted against time, and the D_{eff} values were calculated from the slope of the line obtained from equation below. Half thickness was used for tray drying process since the heat transfer was symmetrical due to perforated trays. The slope was calculated by using the equation below and it was abbreviated as K (Equation 3).

$$K=\frac{\pi^2 D_{\mathrm{eff}}}{4L^2} \tag{3}$$

The variation of the diffusion coefficient can be explained by exponential function of Arrhenius. The activation energy for tray drying were calculated using equation below. In order to calculate activation energy for control group, samples were also dried at 60°C and 80°C and moisture content values were recorded.

$$D_{\mathrm{eff}}=D_0\exp\left(-\frac{E_A}{RT}\right) \tag{4}$$

where D_{eff} is effective diffusion coefficient (m^2/s), D_0 is pre-exponential factor (m^2/s), E_A is activation energy (kJ/mol), R is universal gas constant (kJ/mol K) and T is drying air temperature (K).

TABLE 1 | Thin layer drying models.

Model equation	Model name	Reference
$\mathrm{MR}=\exp(-kt)$	Newton	Lewis (1921)
$\mathrm{MR}=\exp(-kt^n)$	Page	Page (1949)
$\mathrm{MR}=\exp[(-kt)^n]$	Modified page I	Lahsasni et al. (2004)
$\mathrm{MR}=a\exp(-kt)$	Henderson and Pabis	Henderson and Pabis (1961)
$\mathrm{MR}=a\exp(-kt)+c$	Logarithmic	Yaldiz, Ertekin, and Uzun (2001)
$\mathrm{MR}=a\exp(-k_0t)+b\exp(-k_1t)$	Two term	Zielinska and Markowski (2010)
$\mathrm{MR}=1+at+bt^2$	Wang and Sing	Wang and Sing (1978)
$\mathrm{MR}=a\exp(-kt)+(1-a)\exp(-gt)$	Verma	Verma et al. (1985)
$\mathrm{MR}=a\exp(-kt)+b\exp(-gt)+c\exp(-ht)$	Modified Henderson and Pabis	Karathanos (1999)
$\mathrm{MR}=a\exp(-kt^n)+bt$	Midilli	Midilli, Kucuk, and Yapar (2002)

For microwave drying, the activation energy was calculated by using the equation below which is a function of microwave power (Equation 5) (Özbek and Dadali 2007).

$$D_{\text{eff}} = D_0 \exp\left(-\frac{E_A m}{P}\right) \quad (5)$$

where m is weight of wet product (g), P is microwave power (W), D_0 is pre-exponential factor (m^2/s), and E_A is also activation energy (W/g).

2.5 | Determination of Moisture Content

The moisture contents of the samples were determined with an IR moisture analyzer (MA-150, Sartorius, Germany).

2.6 | Determination of Water Activity

Water activity values of samples were determined using a water activity measuring device (Aqua Lab, 4TE, USA). Dried apricots in homogeneous pieces were placed in plastic containers and measurements were made at 25°C (Cichowska and Kowalska 2018).

2.7 | Determination of pH Value and Titratable Acidity

The pH value was determined with a pH-meter (AD8000, Adwa, Hungary). For this purpose, approximately 10 g of homogeneous dried apricot samples were weighed and rehydrated in 90 mL distilled water at +4°C for 24 h and the mixture was then mixed with a homogenizer (MICCRA D-9, Germany) for 2 min. The sample was homogenized and filtered through a filter paper. pH measurement and titration acidity analysis were performed with the filtrate (Cemeroğlu 2010).

2.8 | Determination of Color Values

L^* (lightness–darkness), a^* (redness–greenness), b^* (yellowness–blueness) color values of fresh and dried samples were determined by a color reader (Minolta Chroma Meter CR-400, Minolta Co. Ltd., Osaka, Japan) (Akbulut and Çoklar 2008). The data are the average of five replicates from the surface of the samples.

2.9 | Determination of Rehydration Capacity

One gram of dried sample was added to 30 mL of distilled water (24°C ± 2°C) and kept at room temperature for 24 h, then filtered through a 300 μm sieve for 3 min and weighed. The rehydration capacity was calculated by using Equation (6) below (Quintero-Ramos, Bourne, and Anzaldua-Morales 1992).

$$\text{Rehydration capacity} = W_r / W_d \quad (6)$$

where W_r is the weight of rehydrated product weight (g) and W_d is weight of dried product (g).

2.10 | Determination of Total Phenolic Content

Apricots were extracted by using the method declared by Leccese, Bartolini, and Viti (2007) with small modifications. Three grams of sample was homogenized with 15 mL of ethanol–water mixture (80%) and shaked (N-BIOTEK, NB-101MT) at 200 rpm at room conditions for 1 h. Then it was centrifuged at 4°C at 4600 rpm for 10 min (SIGMA, 3-18K, Germany). Total phenolic content analysis was applied to the supernatant by making minor changes in the Folin–Ciocalteu method used by Karav and Ekşi (2012). Sample of 50 μL was mixed with 450 μL of distilled water and 2.5 mL of 0.2 N Folin solution and left for 4 min, then 2 mL of saturated $NaCO_3$ (75 g/L) solution was added and kept in the dark for 2 h, then it was measured in a spectrophotometer (Lambda35, Perkin Elmer, USA) at 760 nm wavelength. Gallic acid was used as the standard and results were given as mg gallic acid equivalent (GAE)/100 g dry matter.

2.11 | Determination of Antioxidant Activity With DPPH Method

DPPH (1,1-diphenyl-2-picrylhydrazyl) method was used to determine the antioxidant activity of the samples. The method which was used by İzli (2016) was modified slightly. According to the method, 0.1 mL of apricot extracts, prepared for total phenolic content analysis, were mixed with 3.9 mL of DPPH solution (6×10^{-5} M) and left in a dark room for 2 h. The absorbances of the extracts were measured at a wavelength of 515 nm in a spectrophotometer (Lambda35, Perkin Elmer, USA). As a control, 0.1 mL methanol and 3.9 mL DPPH (6×10^{-5} M) solution were prepared and the absorbance value was read at the same wavelength. Trolox was used as the standard. Results were given as mg Trolox equivalent (TE)/g dry matter.

2.12 | Scanning Electron Microscopy (SEM) Analysis

The microstructure of dried samples was investigated by using SEM (Hitachi SU1510, Tokyo, Japan). The samples were cut into slices and covered with a very thin layer of gold. The gold-coated samples were placed in the SEM device and scanned by electron beams, the image was transferred to the monitor and the analyzes were made on the monitor. SEM observations were made using an acceleration voltage of 5 kV. 400× and 600× magnifications were used for apricot samples (Akar and Barutçu Mazı 2019).

2.13 | Nuclear Magnetic Resonance (NMR) Relaxometry Analysis

NMR relaxometry analysis was performed using a 0.5T system operating at 20.34 MHz (Spin Track, Resonance Systems GmbH, Kirchheim/Teck, Germany). T_2 values of the apricot samples placed in the tubes were obtained. Data were acquired using a CPMG (Carr–Purcell–Meiboom–Gill) sequence with an echo time of 1000 ms, a repeat time of 2000 ms, one scan, and

the number of echoes ranging from 300 to 500 ms. In order to calculate the relaxation time, mono exponential analysis was performed using MATLAB (2019b, The MathWorks Inc., USA) (Ertuğrul 2020). The analysis could not be performed for freeze dried samples due to lack of detectable amount of free water molecules in the structure.

2.14 | Statistical Analysis

Statistical analysis was performed using a statistical software program MINITAB 17.1.1.0 (Minitab, State Collage, PA, ABD). The comparisons were made by a Tukey test with which a confidence interval of 95% was used.

3 | Results and Discussion

3.1 | Drying Time

The drying times of different processes were given in Table 2. The drying was continued till moisture content of the samples decreased to 20% for each process. Table 2 shows that the longest drying time was experienced in the freeze drying process. However, since moisture content variation could not be analyzed, mathematical modeling could not be done for freeze dried samples. Compared to other processes, it was observed that the shortest time was reached with ultrasound pretreatment and drying using 270 W microwave power. That is why, the ultrasound pretreatment was chosen to be the most effective method to shorten the drying time. Additionally, microwave drying provides higher rate and shorter process time, thanks to water molecules which absorb energy quickly and consequently, evaporate rapidly (Kipcak and İsmail 2018). In literature, there are various studies which supports this finding (Taiwo et al. 2003; Rodrigues and Fernandes 2007; Fernandes, Linhares Jr, and Rodrigues 2008).

3.2 | Drying Curve, Effective Moisture Diffusivity (D_{eff}), and Activation Energy (EA)

The RMSE, R^2, and, Adj-R^2 values of drying processes for different conditions were given in Table S1 and model coefficients were given in Table S2. It can be seen from Table S1 that RMSE, R^2, and Adj-R^2 values vary between 0.00109 and 0.07960, 0.9131 and 1.0000, and 0.8938 and 1.0000, respectively. When the parameters of all equations were compared, it was found that the most appropriate equations for IR pretreatment–tray drying combination were Newton's and Midilli equations. Moreover, Midilli was chosen as the best fitting equation for all other procedures. Similar to our results, Midilli model is the most commonly used models to explain drying kinetics in literature. Midilli is the best model for pomegranate peels (Mphahlele, Pathare, and Opara 2019), black mulberry drying (Kipcak and Doymaz 2020), fenugreek leaves (Bishnoi et al. 2020), apple drying (Rasooli Sharabiani et al. 2021), and saffron petal (Sharifian et al. 2023).

The effective diffusivities valid for different drying methods were also given in Table 2. It can be seen that D_{eff} values varied between 5.45×10^{-10} and 6.54×10^{-8} m^2/s. It was observed that the effective diffusion coefficients of microwave dried samples were up to 120 times higher than the samples dried with tray dryer. In addition, an increase in D_{eff} values was detected depending on an increase in microwave power. This positive relation can be explained by faster movement of water molecules

TABLE 2 | Effect of different pretreatments and drying methods on drying times and D_{eff} (m^2/s).

Pretreatment	Drying method	Drying time (min)	D_{eff} (m^2/s)
Control	Tray drying	410	6.13×10^{-10}
Infrared pretreatment	Tray drying	525	6.13×10^{-10}
	Microwave drying (90 W)	345	5.45×10^{-9}
	Microwave drying (180 W)	247	3.27×10^{-8}
	Microwave drying (270 W)	237	6.00×10^{-8}
	Freeze drying	3105	—
Ultrasound pretreatment	Tray drying	390	6.81×10^{-10}
	Tray drying + microwave drying (90 W)	315	8.18×10^{-9}
	Tray drying + microwave drying (180 W)	237	3.27×10^{-8}
	Tray drying + microwave drying (270 W)	226	6.27×10^{-8}
	Freeze drying	2880	—
Pretreatment with dipping green tea extract	Tray drying	500	5.45×10^{-10}
	Tray drying + microwave drying (90 W)	380	5.45×10^{-9}
	Tray drying + microwave drying (180 W)	277	3.27×10^{-8}
	Tray drying + microwave drying (270 W)	266	6.54×10^{-8}
	Freeze drying	2880	—

due to higher microwave power resulting in enhanced rate of diffusion (Horuz et al. 2018). Thus, the samples dry faster leading to a shorter drying time (Vardin and Yilmaz 2018).

The energy required to break through the barrier and initiate the drying process is known as the activation energy. The logarithmic presentation of the effective diffusivity as an inverse function of temperature or power gives the activation energy (Tagnamas et al. 2022). Experiments were also carried out at 60°C and 80°C to calculate the activation energy of the tray drying samples (only for control group). The activation energy for tray drying was calculated as 10.92 kJ/mol; activation energy of apricot samples dried with different pretreatment methods were calculated as 6.47, 5.38, and 6.65 W/g for IR, ultrasound, and pretreatment with green tea extract, respectively. In literature, variable results were reported for different drying methods and fruits. Kipcak and Doymaz (2020) studied with 90, 180, and 360 W microwave power levels for black mulberry drying and the activation energy was calculated as 13.15 kW/kg. Macedo et al. (2020) calculated the activation energy as 41.43 kJ/mol by using hot air drying at 40°C, 60°C, and 80°C.

3.3 | Water Activity

Water activity is a function of the bond between food components and water and it is one of the most important factors affecting the stability of dried fruits. The high water activity shortens the storage period of the products (Holtz et al. 2010; Samoticha, Wojdyło, and Lech 2016). In this study, the water activity (a_w) value was measured as 0.955 ± 0.02 for fresh apricot samples and 0.842 ± 0.01 for control samples. As a result of different drying combinations, the water activity values of dried samples changed in the range of 0.200–0.773 (Table 3) and it was determined that the effect of drying process on a_w was statistically significant ($p < 0.05$). However, no effect was experienced due to pretreatment variation. The water activity results of the control group were higher than the pretreated samples which can be explained by heating mechanism of IR technology causing more free water to be removed and microscopic channels due to ultrasound waves facilitating the removal of water bound to solid matter and reducing water activity. Previous studies demonstrated that ultrasound pretreatment lead to a decrease in the water activity of samples similarly (Kowalski, Szadzińska, and Pawłowski 2015; Siucińska et al. 2016). When the a_w values of different dryings compared, freeze drying was found to be the best method causing the least values. Large ice crystals in the product which occurs during freeze drying process disrupt the structure of the sample causing a higher amount of free water (Serna-Cock, Vargas-Muñoz, and Aponte 2015; Aral and Beşe 2016).

3.4 | Rehydration Capacity

The rehydration capacity of a dried product is used as a quality index and shows the physical and chemical changes during drying, which are affected by the process conditions and the pretreatments applied to the sample (Maskan 2001). The decrease in the rehydration ability of dried products during drying is related to the physicochemical changes in the product. As a result of wrinkling and disintegration that occurs during drying, deterioration in the capillary structure and tissues occurs, and this deformation negatively affects the rehydration ability (Cemeroğlu, Yemencioğlu, and Özkan 2001).

The rehydration capacity of the control sample was determined as 2.40 ± 0.06 g wet product/g dry product. The rehydration capacity of the samples were given in Table 3. It was found that pretreatment type does not affect rehydration capacity. Moreover, it was found that applying a pretreatment to samples prior to drying did not make any difference with the control sample. On the other hand, another fact that was determined was dependency of effect of drying process on pretreatment type. Although, drying type was found to be insignificant on rehydration capacity for IR and ultrasound pretreatment, it was vice versa for treatment with green tea extract ($p < 0.05$). The highest rehydration capacity value was obtained for the samples treated with green tea extract and freeze dried, and this value was calculated as 3.09 ± 0.06 g wet product/g dry product. It can be explained by the fact that large ice crystals in the product form a porous structure and rehydrate the products more easily in the freeze drying process (Serna-Cock, Vargas-Muñoz, and Aponte 2015; Aral and Beşe 2016). The swelling of the samples due to water absorption during green tea treatment and the formation of ice crystals during the freezing step prior to freeze drying causes a more porous structure.

3.5 | Color Values

Color is one of the most important parameters that has an impact on consumer expectations of dried samples. The color values (L^*, a^*, and b^*) of dried apricots were given in Table 3. The results of color analysis showed that the effect of the drying type on color values of the samples was significant for all pretreatments ($p < 0.05$). In addition, it was determined that the pretreatment type was also effective on L^* values. Images of dried apricot fruits were given in graphical abstract of the manuscript. L^* values of fresh and control samples were measured as 61.79 ± 2.37 and 36.15 ± 1.06, respectively. The closest L^* value to the ones of the fresh samples was obtained by freeze drying. It is known that low temperatures during the freeze drying process enables higher quality products in terms of appearance and reducing the breakdown of thermolabile chemicals, many of which give fruits their distinct scents and nutritional worth (Silva-Espinoza et al. 2019). Moreover, ultrasound pretreatment resulted in products with highest L^* values. This can be explained by the enzyme inactivation capability of ultrasound treatment leading to control enzymatic browning (Baltacıoğlu 2022). The other color value examined in the study was a^* value. It was found that there was no significant effect of pretreatment type on a^* values ($p > 0.05$). On the other hand, drying type was effective significantly ($p < 0.05$). The a^* values of fresh and control samples were determined as 6.72 ± 1.46 and 10.91 ± 0.21, respectively.

The last color value investigated was b^* value. It is known that positive b* values indicates yellow color. In other words, the higher the b^* value, the closer the dried sample to fresh ones with respect to color. Drying type was found to be significantly effective on b^* values ($p < 0.05$). When the b^* values of the different pretreated samples were examined, the closest values to

TABLE 3 | The effect of different drying methods applied after different pretreatments on a_w, rehydration capacity, L^*, a^*, and b^* values of apricots.

Pretreatment	Drying method	a_w	Rehydration capacity	L^*	a^*	b^*
Control	Tray drying	0.842 ± 0.01^{a}	2.40 ± 0.06^{a}	36.15 ± 1.06^{a}	10.91 ± 0.21^{bc}	25.50 ± 1.84^{a}
Infrared pretreatment	Tray drying	0.762 ± 0.04^{b}	2.79 ± 0.05^{a}	33.12 ± 0.68^{ab}	10.46 ± 0.15^{c}	22.86 ± 0.89^{ab}
	Microwave drying (90 W)	0.676 ± 0.01^{c}	2.79 ± 0.34^{a}	29.89 ± 1.66^{bc}	12.03 ± 0.68^{ab}	19.17 ± 2.60^{b}
	Microwave drying (180 W)	0.628 ± 0.04^{cd}	2.77 ± 0.01^{a}	29.35 ± 0.77^{c}	12.26 ± 0.54^{a}	18.99 ± 2.49^{b}
	Microwave drying (270 W)	0.588 ± 0.03^{d}	2.88 ± 0.45^{a}	31.05 ± 3.22^{bc}	11.87 ± 0.80^{ab}	20.38 ± 4.68^{ab}
	Freeze drying	0.487 ± 0.03^{e}	2.63 ± 0.17^{a}	29.58 ± 0.96^{bc}	10.25 ± 0.64^{c}	18.45 ± 1.62^{b}
Control	Tray drying	0.842 ± 0.01^{a}	2.40 ± 0.06^{a}	36.15 ± 1.06^{b}	10.91 ± 0.21^{bc}	25.50 ± 1.84^{bc}
Ultrasound pretreatment	Tray drying	0.773 ± 0.02^{b}	2.83 ± 0.19^{a}	36.78 ± 1.31^{b}	12.62 ± 0.61^{ab}	30.27 ± 2.02^{b}
	Tray drying + Microwave drying (90 W)	0.724 ± 0.01^{c}	2.88 ± 0.26^{a}	29.94 ± 1.32^{c}	11.58 ± 0.89^{abc}	20.08 ± 1.72^{c}
	Tray drying + microwave drying (180 W)	0.627 ± 0.02^{d}	2.87 ± 0.15^{a}	$35.01 \pm 1,91^{b}$	12.91 ± 0.55^{a}	28.03 ± 2.76^{b}
	Tray drying + microwave drying (270 W)	0.638 ± 0.02^{d}	2.92 ± 0.17^{a}	34.16 ± 2.15^{b}	13.02 ± 0.43^{a}	26.01 ± 2.88^{bc}
	Freeze drying	0.200 ± 0.02^{e}	2.50 ± 0.08^{a}	66.04 ± 2.10^{a}	9.92 ± 1.64^{c}	47.86 ± 3.96^{a}
Control	Tray drying	0.842 ± 0.01^{a}	2.40 ± 0.06^{b}	36.15 ± 1.06^{b}	10.91 ± 0.21^{b}	25.50 ± 1.84^{b}
Pretreatment with dipping green tea extract	Tray drying	0.753 ± 0.01^{b}	2.55 ± 0.20^{b}	32.37 ± 1.98^{bc}	14.03 ± 0.76^{b}	25.09 ± 1.22^{b}
	Tray drying + microwave drying (90 W)	0.690 ± 0.03^{c}	2.58 ± 0.21^{b}	25.73 ± 1.45^{d}	9.46 ± 1.48^{b}	14.38 ± 2.02^{c}
	Tray drying + microwave drying (180 W)	0.609 ± 0.01^{d}	2.43 ± 0.10^{b}	26.34 ± 2.76^{d}	10.79 ± 1.96^{b}	15.92 ± 3.41^{c}
	Tray drying + microwave drying (270 W)	0.622 ± 0.03^{d}	2.65 ± 0.26^{ab}	28.19 ± 0.97^{cd}	11.31 ± 0.34^{b}	17.60 ± 1.44^{c}
	Freeze drying	0.226 ± 0.00^{e}	3.09 ± 0.06^{a}	65.72 ± 4.50^{a}	18.75 ± 4.39^{a}	51.65 ± 1.31^{a}

Note: Different lowercase letters indicate differences between samples subjected to different drying methods ($p \leq 0.05$) for three different pretreatments.

the fresh samples were obtained for ultrasound treated samples. This can also be found to be associated with the enzymatic inactivation provided by the ultrasound treatment, as stated before. Browning was observed for all apricots processed by conventional methods without sulfur application, which is considered as a quality defect for some consumers. Moreover, ultrasound and green tea extract pretreated and freeze dried samples were found to be the closest to the fresh sample. This is mostly due to low process temperatures of these applications. Similar to our results, in pineapple drying (Izli, Izli, and Taskin 2018), turmeric drying (Taskın and Izlı 2019), and Japanese quince fruit drying (Turkiewicz et al. 2019) studies, b^* values of freeze dried samples had smallest changes.

3.6 | SEM

SEM images are used to investigate the structural changes in the cell walls of the dehydrated samples. The structural changes during drying are important as they give information about the drying quality (Lombraña, Rodríguez, and Ruiz 2010). SEM images of the microwave dried samples at 270 W after different pretreatments and the control samples were given in Figures 1 and 2. In the 400× and 600× magnified SEM images, the uniformity of green tea extract pretreated and control group was remarkable. The reason for this were thought to be the fragmentation in the tissues during drying process. The SEM images also showed that IR and ultrasound pretreated samples had a few nonhomogeneous pores which may be due to the cell wall rupture ability of these waves.

The damage on cell wall make them collapse and merge. This causes significant changes in the cell during drying. As it was mentioned before, a more porous structure was observed for ultrasound treated samples than the ones treated with green tea extract. This was found to be correlated with rehydration capacity results, since the porous structure of the products leads to higher amount of water to be absorbed. When the literature was examined, it was seen that similar results were reported (Aral and Beşe 2016; Çağlayan and Barutçu Mazı 2018; Yılmaz et al. 2019).

3.7 | Nuclear Magnetic Resonance (NMR)

The signal amplitude curve of T_2 provides information about the activity of hydrogen protons and reflects the state of water. If the signal amplitudes of T_2 are large, the water molecules are much more active, which is due to the presence of free water (Lv et al. 2017). The variation in T_2 values with respect to different drying methods and pretreatments were given in Table 4. The T_2 value of control was determined as 40.50 ms and it was observed to be the highest value when compared with all other samples. This result shows that more free water was removed in the drying process with different pretreatments.

It was observed that three pretreatment methods were significantly different from each other. T_2 values of green tea extract treated samples were shorter than those of other samples. It may be due to the presence of paramagnetic ions in green tea, that gain magnetic properties when exposed to an external magnetic field (Kirtil et al. 2017). Based on this information, it can be said that the dipping process of green tea extracts was applied effectively.

3.8 | pH and Titratable Acidity (TA)

Acidity is one of the most important criteria to determine appropriate process to be applied to foods (Yıldız et al. 2021). The

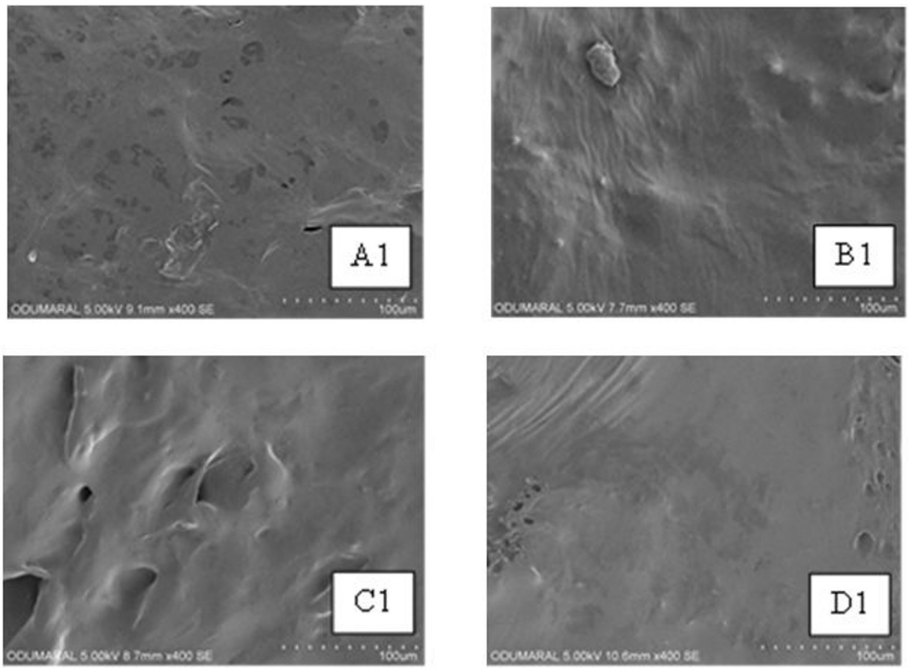


FIGURE 1 | SEM analysis images of dried apricots. (A1) Control; (B1) Infrared pretreatment and microwave drying (270 W); (C1) Ultrasound pretreatment and tray drying + microwave drying (270 W); (D1) Green tea extract pretreatment and tray drying + microwave drying (270 W) indicates 400× magnification SEM analysis images of dried apricots.

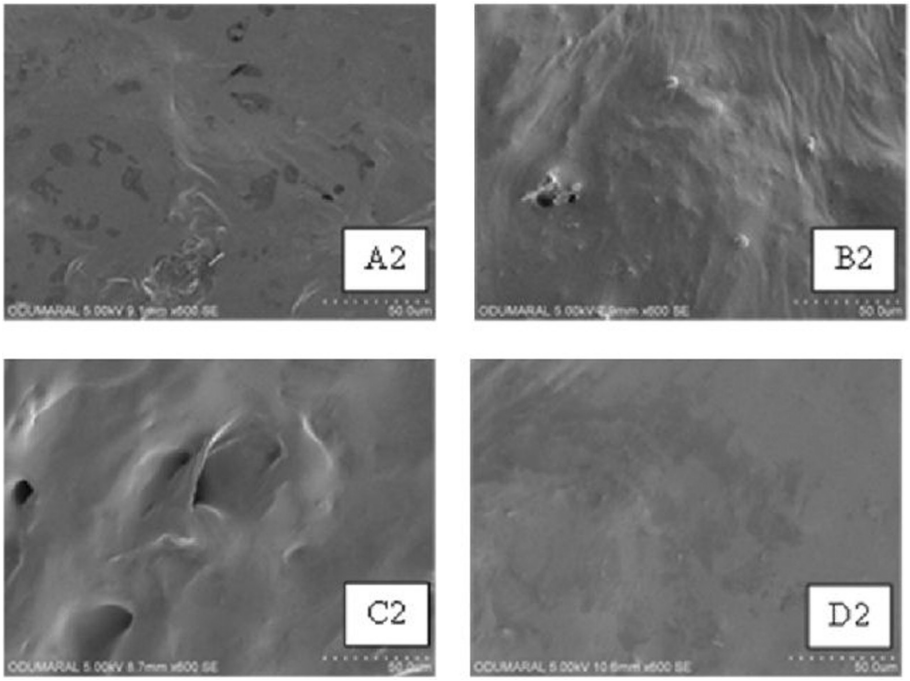


FIGURE 2 | SEM analysis images of dried apricots. (A2) Control; (B2) Infrared pretreatment and microwave drying (270 W); (C2) Ultrasound pretreatment and tray drying + microwave drying (270 W); (D2) Green tea extract pretreatment and tray drying + microwave drying (270 W) indicates 600× magnification SEM analysis images of dried apricots.

pH and titratable acidity which gives information about acidity of the samples were given in Table 4. The pH and titration acidity values of the fresh apricots were measured as 4.49 ± 0.01 and 2.41 ± 0.00 g citric acid/100 g dry matter, respectively. Although there was no effect of pretreatment type on pH, it was vice versa for drying method ($p < 0.05$). It can be seen from Table 4 that pH and titration acidity values of dried samples changed in the range of 4.61–5.01 and 1.19–1.89 g citric acid/100 g dry matter, respectively. The highest pH value was obtained for the green tea extract pretreated and microwave dried (270 W) sample and the highest titratable acidity value was obtained for IR pretreated and tray dried sample. This may be an advantage for the storage duration since these acidity values may prevent the sample form spoilage.

3.9 | Total Phenolic Content (TPC) and Antioxidant Activity (AA)

Total phenolic contents of samples were given in Table 4. TPC of fresh apricot was found as 203.36 ± 5.90 mg GAE/100 g dry matter. It was observed that all kinds of drying methods resulted in a decrease in TPC of the samples. It is known that phenolics are heat sensitive matters and additionally, long drying time affect the phenolic content negatively (Kaur, Kaur, and Ahluwalia 2020; Pashazadeh, Redha, and Koca 2024). When the effect of pretreatment types was examined, as it was expected, TPC of green tea extract treated samples were found to be the highest due to the penetration of phenolics of green tea to the apricots during dipping procedure. Moreover, IR was found to be the second highest TPC resulting pretreatment: it was a surprising result due to long treatment times and high temperatures applied. The authors thought that the Maillard reactions during heat treatments may be the reason for this finding by leading to form new phenolic compounds (Sultana, Ashraf, and Saari 2012).

The other important parameter examined through the scope of study was the antioxidant capacity. The analysis was performed for fresh samples, control group, and for the samples of which total phenolic content was the highest (MW drying at 270 W) (Table 5). The antioxidant activity of fresh and control sample was calculated as 1.64 ± 0.10 mg TE/g dry matter and 0.71 ± 0.05 mg TE/g dry matter, respectively. This was correlated with the phenolic results. Since the drying procedure decreased the TPC of the samples, the antioxidant capacity was found to be less which is due to low TPC (Yang et al. 2024). Moreover, AA of control sample was significantly less than MW dried samples after different pretreatment procedures ($p < 0.05$). This may depend on the effect of long drying time and high temperature of procedure which disrupts the cell matrix and provides an extractability and bioaccessibility of total phytochemicals (Valadez-Carmona et al. 2016). On the other hand, the highest antioxidant activity values were obtained for the green tea extract pretreated samples due to higher TPC results.

4 | Conclusion

In this study, it was determined that drying at 270 W microwave power decreased drying time dramatically while increasing the product quality. Morever, ultrasound pretreatment had facilitated the drying process as compared to other pretreatment methods. Midilli equation was the best model to explain drying kinetics. Another important observation of the study was negative effect of IR pretreatment on physical and chemical properties of samples due to long pretreatment times and high

TABLE 4 | The effect of different drying methods applied after different pretreatments on T_2 (ms), pH and titratable acidity (g citric acid/100 g dry matter), and total phenolic content values of apricots.

Pretreatment	Drying method	T_2 (ms)	pH	Titratable acidity (g citric acid/100 g dry matter)	Total phenolic content (mg GAE/100 g dry matter)
Control	Tray drying	40.50 ± 0.76^{a}	4.82 ± 0.04^{b}	1.19 ± 0.14^{b}	99.24 ± 5.12^{d}
Infrared pretreatment	Tray drying	13.54 ± 0.61^{b}	4.61 ± 0.05^{d}	1.89 ± 0.43^{a}	112.36 ± 2.61^{d}
	Microwave drying (90 W)	14.15 ± 0.51^{b}	4.74 ± 0.09^{bcd}	1.31 ± 0.09^{ab}	153.41 ± 4.99^{c}
	Microwave drying (180 W)	12.86 ± 0.38^{b}	4.64 ± 0.06^{cd}	1.47 ± 0.02^{ab}	185.23 ± 7.64^{ab}
	Microwave drying (270 W)	13.59 ± 0.06^{b}	4.78 ± 0.03^{bc}	1.20 ± 0.09^{b}	194.18 ± 9.04^{a}
	Freeze drying	—	4.97 ± 0.03^{a}	1.25 ± 0.13^{b}	169.41 ± 2.52^{bc}
Control	Tray drying	40.50 ± 0.76^{a}	4.82 ± 0.04^{ab}	1.19 ± 0.14^{a}	99.24 ± 5.12^{d}
Ultrasound pretreatment	Tray drying	35.85 ± 0.24^{b}	4.99 ± 0.05^{a}	1.32 ± 0.13^{a}	124.86 ± 3.42^{c}
	Tray drying + microwave drying (90 W)	16.06 ± 0.28^{c}	4.73 ± 0.08^{b}	1.19 ± 0.09^{a}	149.15 ± 7.23^{b}
	Tray drying + microwave drying (180 W)	10.09 ± 0.51^{d}	4.80 ± 0.11^{ab}	1.53 ± 0.57^{a}	164.49 ± 0.80^{b}
	Tray drying + microwave drying (270 W)	11.61 ± 0.26^{d}	4.74 ± 0.09^{b}	1.39 ± 0.27^{a}	166.10 ± 6.87^{b}
	Freeze drying	—	4.75 ± 0.05^{b}	1.36 ± 0.19^{a}	203.26 ± 1.90^{a}
Control	Tray drying	40.50 ± 0.76^{a}	4.82 ± 0.04^{bc}	1.19 ± 0.14^{b}	99.24 ± 5.12^{c}
Pretreatment with dipping green tea extract	Tray drying	12.57 ± 0.30^{b}	4.70 ± 0.09^{c}	1.68 ± 0.10^{a}	218.61 ± 4.62^{b}
	Tray drying + microwave drying (90 W)	10.13 ± 00^{bc}	4.82 ± 0.02^{bc}	1.32 ± 0.06^{ab}	215.63 ± 4.02^{b}
	Tray drying + microwave drying (180 W)	8.17 ± 1.88^{c}	4.87 ± 0.15^{ab}	1.66 ± 0.20^{a}	237.64 ± 16.67^{b}
	Tray drying + microwave drying (270 W)	2.91 ± 0.48^{d}	5.01 ± 0.05^{a}	1.57 ± 0.03^{a}	247.44 ± 1.21^{b}
	Freeze drying	—	4.74 ± 0.09^{bc}	1.67 ± 0.21^{a}	512.60 ± 38.51^{a}

Note: Different lowercase letters indicate differences between samples subjected to different drying methods ($p \leq 0.05$) for three different pretreatments.

TABLE 5 | The effect of different drying methods applied after different pretreatment on antioxidant activity values of apricots.

Pretreatment	Drying method	Antioxidant activity (mg TE/g dry matter)
Control	Tray drying	0.71 ± 0.05^{c}
Infrared pretreatment	Microwave drying (270 W)	1.12 ± 0.08^{b}
Ultrasound pretreatment	Tray drying + microwave drying (270 W)	1.20 ± 0.37^{b}
Pretreatment with dipping green tea extract	Tray drying + microwave drying (270 W)	1.85 ± 0.01^{a}

Note: Different lowercase letters indicate differences between samples subjected to different pretreatments methods ($p \leq 0.05$).

temperatures. Pretreatment with green tea extract led the samples' enrichment in terms of phenolic compounds and enhanced the antioxidant activity. Rehydration capacity of dried samples obtained by ultrasound pretreatments for each drying methods were superior than others. As a final conclusion, it can be declared that dipping green tea extract and ultrasound pretreatments may be suggested as a promising alternative to traditional sulfur treatment since they resulted in better quality dried products. And also microwave technology was found to be the best method for apricot drying.

Nomenclature

$a, b, c, g, h, k, n, k_0, k_1$	empirical constants, and coefficients
D_{eff}	effective moisture diffusivity (m^2/s)
D_0	constant diffusivity at infinite temperature (m^2/s)
E_A	activation energy (kJ/mol)
K	slope
L	slice thickness (m)
MR	moisture ratio
M	moisture content at time t
M_0	initial moisture content
M_e	equilibrium moisture content
MW	microwave
R	universal gas constant (kJ/mol K)
RMSE	root mean square error
R^2	correlation coefficient
Adj-R^2	adjusted R-squared
T	temperature (K)
exp	experimental
P	microwave power
pre	predicted
π	pi number

Author Contributions

Merve Silanur Yilmaz: formal analysis, investigation, methodology, writing – original draft. **Ozge Sakiyan:** conceptualization, methodology, supervision, funding acquisition, resources, project administration, writing – review and editing. **Asli Isci:** conceptualization, methodology, supervision, writing – review and editing. All the authors have read and agreed to the published version of the manuscript.

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Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

The data that support the findings of this study are available on request from the corresponding author. The data are not publicly available due to privacy or ethical restrictions.

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Supporting Information

Additional supporting information can be found online in the Supporting Information section.