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FREEZE-DRYING OF TEA LEAVES AT DIFFERENT PRESSURES: EFFECTS ON THE THIN-LAYER DRYING KINETICS, WATER ACTIVITY AND COLOR CHANGE

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ABSTRACT

The primary purpose of this study is to freeze-drying (FD) of tea leaves (*Camellia sinensis*) and determine the drying kinetics using six different drying models. For this intent, a nonlinear regression analysis was conducted to evaluate four different criteria (R^2, r, χ^2, RMSE) and determine the best-fitting model for each pressure level based on the highest R^2 and r values and the lowest χ^2 and RMSE values. Fresh tea leaves farm in Rize, Türkiye were placed in a laboratory-scale freeze dryer and dried until the product reached equilibrium moisture. FD experiments were performed at three different cabin pressures (0.008, 0.010, and 0.012 mbar) to examine the effect of pressure variation on drying time and quality parameters. After analyzing the experimental results, it was determined that the Alibas model best describes the drying process of tea leaves at 0.008 mbar and 0.010 mbar pressure, while the Improved Midilli-Kucuk model is the most suitable at 0.012 mbar pressure. As a consequence of the FD *process*, it has been noted that the hue angle changed between 86.98-87.38 depending on cabin pressure, i.e. there was a transition in the color of tea leaves from green to red. The a^* (Redness/Greenness) value changed from -6.2 in the fresh product to +1.3 in the final product. The highest drying rate of tea leaves occurred at the lowest cabin pressure. As a consequence of the FD experiment, the water activity of the tea leaves decreased (from 0.9800±0.0093 to 0.2901±0.0077) to a level where no microbial growth would occur.

Keywords: Tea, Drying, Freeze-Drying, Drying kinetics.

INTRODUCTION

Drying is the process of reducing the high water content of the product to a level where microbial growth will not occur, using various techniques (Addo *et al*., 2023; Zhao *et al*., 2023). Drying provides significant advantages not only in extending the shelf life of the product, but also during storage and transportation due to the reduction in the volume of the product (Bakhshipour *et al*., 2021; Pateiro *et al*., 2022). Drying can be done by many different methods, such as heat pump drying, superheated steam drying, fluidized bed drying, high electric field drying, microwave drying, and freeze-drying (FD) (Ren *et al*., 2025; Thamkaew *et al*., 2021). Among the mentioned methods, FD stands out with its advantages, such as minimizing the loss of quality parameters of the dried product such as color, flavor, and vitamins, retaining volatile compounds in the product, and preserving the dried products for a much longer period (Bhatta *et al*., 2020; Waghmare *et al*., 2022). FD is a drying process that occurs by sublimation at a relatively low temperature and vacuum pressure (0.01 °C, 612 Pa) (Chaurasiya and Singh, 2023). The FD technique, in which structural defects and quality losses such as color, odor, and shape are reduced due to the moisture contained in the food being first frozen and then removed by sublimation, stands out with its preservation period of up to twenty-five years, considering all the drying techniques available in the literature. The FD is widely used, especially in the food and pharmaceutical industries (Henry *et al*., 2022). In this study, FD of tea leaves was conducted to investigate its effects on drying rate, moisture content, water activity, and color change.

The home of tea, a plant that can grow in many different areas such as India, Indonesia, Türkiye, Argentina, and Kenya, is China, which is now the largest producer and exporter (Shuai *et al*., 2022). Looking at the areas where tea is grown around the world, it can be said that tea cultivation is more efficient in semi-tropical climates (Su *et al*., 2017). Today, tea is classified into two main types based on the manufacturing process: fermented (black tea and oolong tea) and unfermented (white, green, and yellow tea) (Kumar *et al*., 2023). These teas, divided into fermented and unfermented teas, are known as the most consumed and non-herbal teas in the world (Tomou *et al*., 2023). The investigation of scientific studies has shown that tea is used in the treatment of cardiovascular diseases, Parkinson's disease, diabetes, cancer, and neurological diseases, and has many benefits for human health (Fadhlina *et al*., 2023; Rafique *et al*., 2023). In addition, many different cosmetic products can be obtained from tea, which is the most consumed drink after water (Koch *et al*., 2019; Thammarat *et al*., 2021). Tea goes through a series of processes such as withering, rolling, and drying until it is packaged and ready for brewing. It is believed that the quality of tea is improved by FD instead of the traditional techniques commonly used in the tea industry. Freeze-dried tea leaves exhibit superior quality compared to those dried using traditional methods, particularly in terms of antioxidant content (Roslan *et al*., 2020), color attributes(Różyło, 2020), and vitamin C retention (Roshanak *et al*., 2016). In the FD method, the quality characteristics of the dried product, such as aroma, color, and flavor, are minimally lost, and structural defects are also minimized (Liu *et al*., 2022). In this regard, it is important to widely use the FD method to eliminate the hygiene problem caused by other drying methods, increase the potential of environmental sustainability, and improve the drying process. The situation in which the ambient air acts completely on the product during the drying process is called thin film drying. Numerous models can be found in the literature to describe the drying process and to determine the ideal drying method, which are called thin film models. In this study, various drying models and evaluation criteria were used to describe the time-dependent drying of tea leaves. Drying of tea leaves using traditional methods is a topic that has been extensively studied. In this section, some studies in the literature on tea drying have been compiled, but none of them have examined FD drying kinetics. For example, Okur *et al*., (2023) carried out the drying of tea leaves using a simultaneously swirling flow-fluidized bed-infrared drying system. They analysed the drying kinetics by applying thin film drying models based on experiments conducted at infrared power levels of 100 W, 250 W, 500 W, 750 W and 1000 W. As a result, they determined that the most appropriate infrared power level was 500 W and identified the Aghbashlo *et al*. model as the most appropriate thin film drying model. (Sharma and Dutta, 2022), conducted the low-temperature solar drying of tea leaves in their study. To describe the drying process and analyze the drying kinetics, they employed seven different thin-layer drying models: Lewis, Henderson and Pabis, Logarithmic, Page, Two-term, Midilli and Kucuk, and Wang and Singh. The drying experiments were performed at three different temperatures (23 °C, 27 °C, and 32 °C), and the results indicated that the fastest drying process occurred at 32 °C. They concluded that as the temperature increased, the drying time decreased. Furthermore, they determined that the Two-term model (R^2=0.9977) was the most suitable for describing the drying process. Köse *et al*., (2024)investigated the drying kinetics of tea leaves using a hybrid drying system (microwave-integrated rotary flow fluidized bed). They conducted drying experiments at microwave power levels of 100 W, 300 W, 600 W, and 800 W, calculating critical drying parameters such as dimensionless moisture ratio, moisture content, and drying rate. As a result, they determined that the Improved Midilli-Kucuk model was the best fit for describing the drying process across all microwave power levels. Mathematical models are widely used to analyse and optimise drying processes and, as these studies show, they play a crucial role in characterising the drying process for different drying techniques. Upon examining studies in the literature on tea dried with various methods such as microwave drying, fluidized bed drying, oven drying, and solar-assisted drying, it was found that research focused on mathematical modeling (Sharma and Dutta, 2022; Zeng *et al*., 2024), color change (Chung and Youn, 2020; Li *et al*., 2024), and different quality parameters (Lee *et al*., 2019; Ni *et al*., 2020; Okur *et al*., 2023). Whilst the extant literature concerning the subject of tea drying is chiefly focused on conventional methods such as hot air and microwave drying, there is a paucity of studies that utilise freeze-drying techniques. However, the effect of cabin pressure on the drying process has never been investigated in these studies. The present study aims to provide a comprehensive evaluation of the drying kinetics, moisture content variation, drying rate changes, colour change, and water activity variation of tea leaves dried at different cabin pressures.

This study experimentally investigated the freeze-drying of tea leaves at different cabin pressures (0.008 mbar, 0.010 mbar, and 0,012 mbar), applying the obtained data to six thin-layer mathematical models (Aghbaslo, Alibas, Balbay&Şahin, Improved Midilli Kucuk, Newton, and Page) to determine drying kinetics, while also evaluating the effects of pressure on moisture content, drying rate, color change, and water activity change.

MATERIALS AND METHODS

Plant materials: The fresh tea leaves used as samples for the FD experiments were harvested in June 2023 in Rize, Türkiye (41.01450° N, 40.53251° E). Tea leaf samples were visually selected based on color and freshness, ensuring that only vibrant green leaves with minimal oxidation were used. Leaves exhibiting yellowing or browning were excluded. Additionally, freshness was assessed based on texture and moisture content, with tender and flexible leaves being preferred, while wilted or dried-out leaves were discarded. Tea leaves were frozen (-40 °C, 24 hours) before the FD process and prepared for the experiments.

Drying experiments: The FD experiments were carried out using the Labconco Freezone 2.5 Manual Laboratory

Scale Freeze Dryer. The experimental setup in which the drying process is carried out is shown in Fig. 1.

The frozen tea leaves were placed in the freeze dryer and dried until the product reached equilibrium moisture. FD experiments were carried out at different pressures (0.008, 0.010, and 0.012 mbar) to investigate the effect of pressure variation on drying time. To observe the mass changes of the tea samples during the experiments, a precision balance of OHAUS PR 224 with an accuracy of 10^{-4} grams was used. Operating pressure and collector temperature were read on the digital displays of the freeze dryer. The operating temperature was measured with a digital thermometer. Mass measurements were conducted using a precision balance at consistent intervals (every two hours) to assess the changes in mass of the tea leaf samples during the freeze-drying process. The drying experiment was terminated after the product reached its equilibrium moisture content.

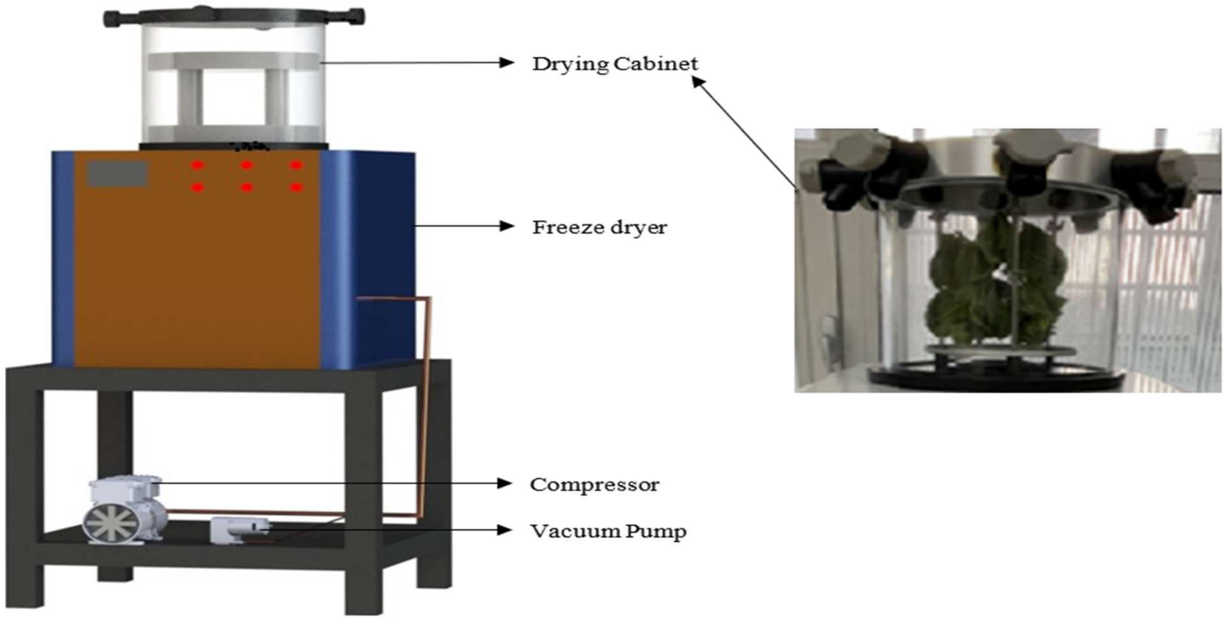

Fig. 1. Laboratory scale freeze dryer

ANALYSIS METHODS

Determination of moisture ratio (MR): To determine the moisture content of the product, the dry mass must first be determined before the beginning of the FD experiment. Before starting the experiment, preliminary studies were conducted with fresh tea leaves to determine the exact dry weight of the product. Fresh tea leaves provided for the experiment were cleaned and placed in a drying oven operating at constant temperature (105°C) and the moisture content of the product was determined after 24 hours. The initial moisture content (M_i) of the product was determined from the ratio between the mass of the product before it was placed in the oven and after the drying process. The most important parameter in the mathematical modeling phase, which is performed using the data obtained during the drying tests, is the dimensionless moisture ratio (MR). The dimensionless moisture ratio is determined using Eq. 1.

$$MR = \frac{M_t - M_e}{M_i - M_e} \qquad (1)$$

Depending on the moisture ratio during the drying process of the product, mathematical modeling of the entire drying process is performed, and the most appropriate model is selected to describe the process.

Determination of water activity (AW): It is very important to reduce water activity to prevent food spoilage and extend storage time (İlhan Dincer and Temiz, 2023). The water activity of product plays a very important role in the development of microorganisms. When water activity is high, there is a greater increase in the number of microorganisms. To prevent this, the water activity of the food is supposed to be reduced to relatively low levels. One of the most important methods for reducing water activity is FD. In this study, the products were dried using the FD method to prevent the deterioration of the tea leaves and losses in quality properties. A water activity meter (Aqualab Dew Point Water Activity Meter 4TE) was used to observe the change in water activity. The water activity of the product was determined by using a 5-gram tea sample and the measurements were taken both before and after the FD experiments.

Color analysis: The color of the tea leaves used in the experiments was measured on fresh and dried samples using a colorimeter (Color Reader CR -10). Eq. 2 (Topal *et al*., 2024) was used to describe the color change between fresh tea and the dried product.

$$\Delta E = \sqrt[2]{(\Delta L^*)^2 + (\Delta a^*)^2 + (\Delta b^*)^2} \qquad (2)$$

(ΔL^*: Lightness difference, Δa^*: Redness/greenness difference, Δb^*: Yellowness/blueness difference)

Eq. 3 (Borucu and Doymaz, 2025) was used to calculate the color of the dried product after the FD process. Here, h is called the hue angle used to determine the color of the product.

$$h = \tan^{-1}\left(\frac{b^*}{a^*}\right) \qquad (3)$$

Mathematical modeling of drying data: During the FD experiments, the mass of the tea leaves was recorded and the dimensionless mass ratio was determined. The obtained data were applied to the thin film models given in Eq. 4-9. Thin film drying models or mathematical drying models are equations used to estimate the amount of moisture contained in the product at each time in the drying process. Six drying models that are commonly used in the literature are listed in Table 1.

Table 1. Models used in drying tea leaves.

Model Name	Model No	Model Equation	Eq.	Ref.
Aghbaslo	1	$MR = \exp\left(-\frac{k_1 t}{1 + k_2 t}\right)$	(4)	(Midilli and Kucuk, 2023)
Alibas	2	$MR = a\exp(-kt^n) + bt + g$	(5)	(Alibaş, 2012)
Balbay&Şahin	3	$MR = (1 - a)\exp(-kt^n) + b$	(6)	(Balbay and Şahin, 2012)
Improved Midilli Kucuk	4	$MR = a\exp(-k_1 t^n) - \exp(-k_2 t^n) - bt^n$	(7)	(Midilli and Kucuk, 2023)
Newton	5	$MR = \exp(-kt)$	(8)	(Onwude *et al*., 2016)
Page	6	$MR = \exp(-kt^n)$	(9)	(Onwude *et al*., 2016)

(MR: Dimensionless mass loss ratio; k, k_1, k_2, a, b, c, g: Drying Constants; n: Number of drying constants; t: Time)

Statistical analysis: Experimental data obtained during FD experiments of tea leaves were applied to six different mathematical models listed in Table 1. A nonlinear regression analysis was performed to analyze all experimental data and determine the model that best describes the drying process. The evaluation criteria given in Eq. 10-13 used to demonstrate the compatibility of the mathematical models with the real experimental system are given below. The most suitable model to describe the FD of tea leaves was determined by the evaluation criteria. When evaluating the data obtained from the FD experiments, it is desirable that the correlation coefficient (r) and coefficient of determination (R^2) have the highest value and the reduced chi-square (χ^2) and root mean square error (RMSE) have the lowest value (Sahoo *et al*., 2022; Zalpouri *et al*., 2023).

$$\chi^2 = \frac{\sum_{i=1}^{N}(MR_{exp,i} - MR_{pre,i})^2}{N-n} \qquad (10)$$

$$RMSE = \sqrt{\frac{\sum_{i=1}^{N}(MR_{pre,i} - MR_{exp,i})^2}{N}} \qquad (11)$$

$$r = \frac{N\sum_{i=1}^{N}(MR_{pre,i})(MR_{exp,i}) - (\sum_{i=1}^{N} MR_{pre,i})(\sum_{i=1}^{N} MR_{exp,i})}{\sqrt{N\left(\sum_{i=1}^{N} MR_{pre,i}^2 - (\sum_{i=1}^{N} MR_{pre,i})\right)\left(N\sum_{i=1}^{N} MR_{exp,i}^2 - (\sum_{i=1}^{N} MR_{exp,i})\right)}} \qquad (12)$$

$$R^2 = 1 - \frac{\sum_{i=1}^{N}(MR_{exp,i} - MR_{pre,i})^2}{\sum_{1}^{n}(MR_{exp,i} - MR_{avg})^2} \qquad (13)$$

Uncertainty analysis: During experimental studies, an uncertainty analysis is performed using Eq. 14 to determine the accuracy of the experiment, taking into account many factors such as the sensitivity of the measurement instruments, the environmental conditions under which the experiment is performed (Gilago and Chandramohan, 2022; Mugi and Chandramohan, 2021). The sensitivity values of the devices used in the experiments are given in Table 2.

Table 2. Sensitivity of equipment used in experiments.

Equipment	Uncertainty	Sensitivity
Freezer temperature	w_1	±1 °C
Precision balance	w_2	±10-4 g
Freeze dryer temperature	w_3	±0.1 °C
Freeze dryer pressure	w_4	±0.001 mbar
Drying oven temperature	w_5	±1 °C
Digital thermometer	w_6	±0.1 °C
Water activity meter	w_7	±0.01
Color meter	w_8	±0.1

$$W_R = \left[\left(\frac{\partial R}{\partial x_1} w_1\right)^2 + \left(\frac{\partial R}{\partial x_2} w_2\right)^2 + \left(\frac{\partial R}{\partial x_3} w_3\right)^2 + \cdots + \left(\frac{\partial R}{\partial x_n} w_n\right)^n\right]^{\frac{1}{2}} \qquad (14)$$

In Eq. 14, W_R represents the uncertainty in the results, R is the outcome as a function of the independent variables x_1, x_2, x_3, and x_n, and w_1, w_2, w_3, and w_n are the uncertainties associated with these independent variables.

As a result of the calculations performed depending on the sensitivity of the measuring devices used in experimental studies, $W_R = 1.42\%$ was obtained. The uncertainty value of 1.42% indicates a high level of measurement precision, suggesting that the experimental results are reliable and reproducible. This low uncertainty has a minimal impact on the overall findings and does not alter the observed trends in drying kinetics, water activity, or color change. Additionally, the uncertainty is not significant enough to affect the comparison of different drying conditions or the validity of the mathematical models used. Therefore, the conclusions drawn from this study remain robust despite the minor measurement uncertainties.

RESULTS AND DISCUSSION

Effect of freeze-drying process on moisture content and drying rate: The change in moisture content in the product after the tea samples, whose moisture content was determined before the FD experiments, were subjected to the FD process is shown in Fig. 2. As a result of the FD experiments conducted depending on the freeze-dryer cabin pressure (0.008, 0.010, and 0.012 mbar), the moisture content of dried products was determined as 6.18%, 6.33%, and 6.47%, respectively. Upon investigating the FD data, it was observed that lower cabin pressure resulted in lesser moisture content in the final product.

In reviewing the moisture content-time chart generated with the data obtained from the experimental study, it was found that the decrease in moisture content of the product over time was consistent with studies in the literature. The moisture content of the product decreases over time due to sublimation and mass loss during the drying process, and it has been observed that it remains approximately constant after a certain time.

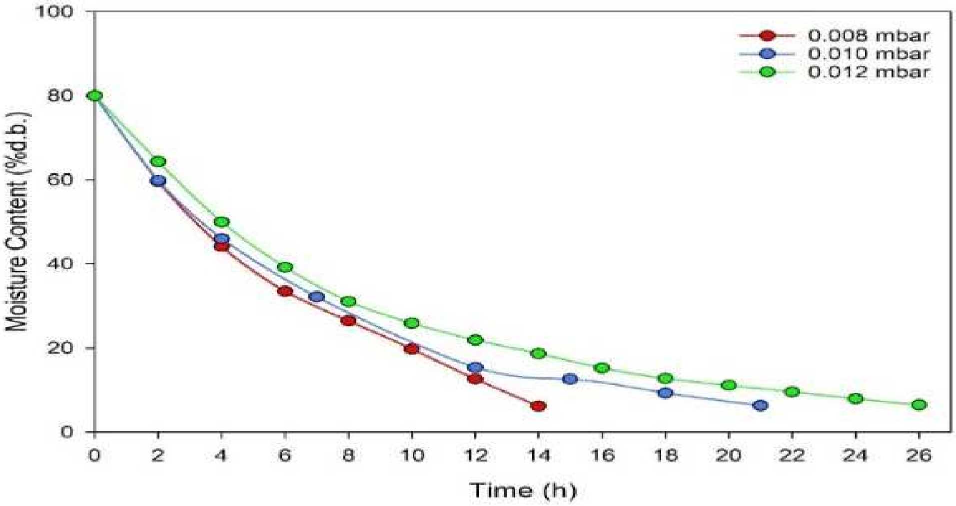

Fig. 2. Change in the moisture content of tea leaves depending on cabin pressure

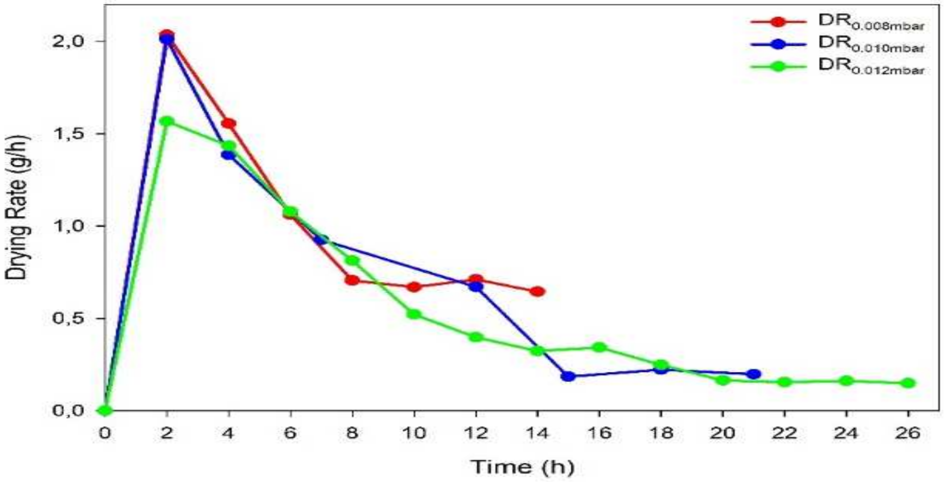

Fig. 3. Drying rate-time curves depending on cabin pressure

Fig. 3 shows the drying rate depending on cabin pressure obtained from FD experiments. Initially, the high moisture content of the fresh product led to a high drying rate. However, as the moisture content of the product decreased over time, the drying rate subsequently decreased. Upon examining Fig. 3, it is clear that lower cabin pressure results in higher drying rates.

Effect of freeze-drying process on water activity: In food preservation methods, reducing water activity is the most important process to extend the shelf life and storage period of a product. By reducing the water activity of the product through FD, very long storage times can be achieved. While high water activity can lead to the microorganisms' growth and poor quality characteristics, too low water activity can cause excessive energy consumption (Lertworasirikul and Tipsuwan, 2008). Once the water activity falls below 0.6, microbial growth stops, and product spoilage is prevented (Al-Saadi *et al*., 2023). In the analysis conducted on fresh tea leaves before the FD process, the water activity was found to be 0.9800±0.0093. The water activities of the dried tea leaves resulting from the FD experiments are shown in Fig. 4. As observed in Fig. 4, the water activity values of the freeze-dried tea leaves range from 0.2901±0.0077 (0.008 mbar) to 0.3422±0,0113 (0.012 mbar). These values indicate that the final water activity levels of the products are well below the 0.6 threshold accepted for preventing microbial spoilage (Barbosa-Cánovas *et al*., 2020), leading to the conclusion that the storage life of the product is extended. In the literature, Atalay and Erge, (2017) reported that the water activity of dried tea leaves ranged between 0.333 ± 0.017 and 0.369 ± 0.005, while (Topuz *et al*., 2014) found values between 0.31 and 0.35. The results obtained in our study, ranging from 0.2901 ± 0.0077 to 0.3422 ± 0.0113, are largely consistent with those reported in the literature. However, the slightly lower water activity observed in our study highlights the impact of low-pressure drying conditions, which result in a further reduction in water activity. This finding suggests that the low-pressure drying method facilitates more effective moisture removal, offering a significant advantage in terms of long-term stability. Additionally, the water activity of the dried tea varies in direct proportion to the cabin pressure.

Effect of freeze-drying process on color change: The change in color of food products after drying is a critical quality parameter. As a result of the FD process, a significant change in the color of the tea leaves occurred, as seen in Fig. 5.

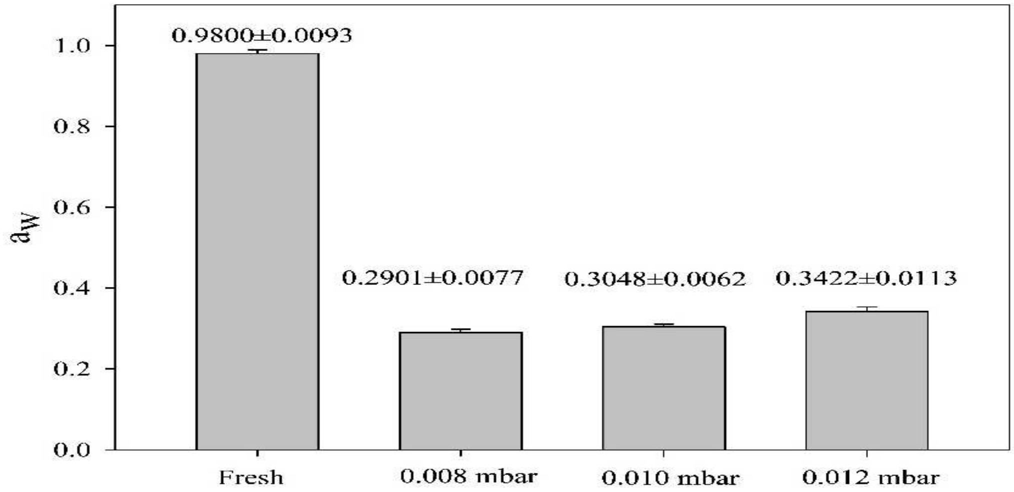

Fig. 4. Water activities of tea leaves dried at different cabin pressures

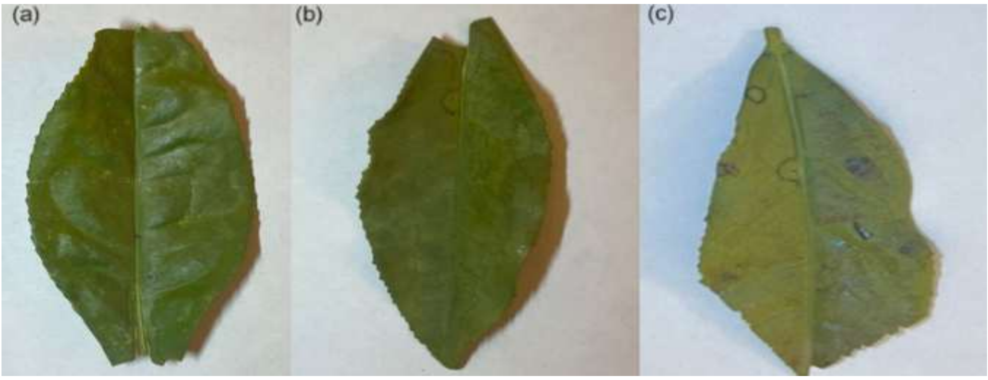

Fig. 5. Dried tea leaves. (a) 0.008 mbar, (b) 0.010 mbar, (c) 0.012 mbar

The results of the color measurement of the tea leaves before and after drying and color difference are shown in Fig. 5. The a^* and b^* parameters of the colorimeter determine the color of the product. A negative a^* value indicates greenness, while a positive value indicates redness.

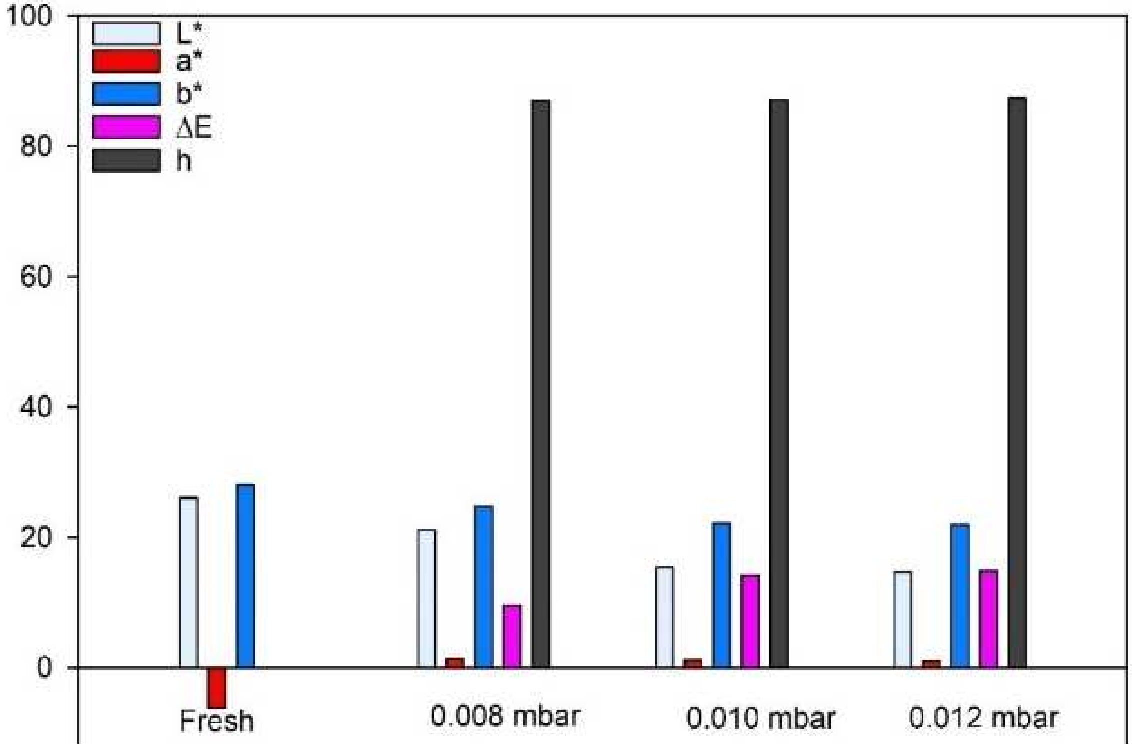

Fig. 6. Color measurement results of tea leaves

Fig. 6 shows the color change in tea leaves as a result of FD experiments performed at three different cabin pressures. After analyzing the obtained data, it was found that as cabin pressure increased, L^* and b^* decreased, while a^* increased. The changes in the L^*, a^*, and b^* values of the freeze-dried final product align with the results reported by Udomkun *et al*., (2018) and Topal *et al*., (2024). Hue angle values of dried tea samples vary between 86.98 and 87.38. It was concluded that the product turned brown during the drying process. As the cabin pressure increased, a significant rise in the total color difference between the fresh and final product was observed. Color and visual appearance are among the most critical factors influencing consumer preferences. In this context, tea leaves dried at 0.008 mbar, where color changes were minimal, can be considered more advantageous in terms of visual quality. Therefore, lower pressure conditions appear to be more suitable for preserving the visual attributes of the tea leaves. Although the freeze-drying method has certain disadvantages, such as longer drying time and higher cost compared to traditional drying techniques, it offers several advantages in the tea drying industry. Apart from the water activity and color change results presented in this study, previous research has demonstrated that products dried using this method exhibit better preservation of aromatic compounds (Cifte *et al*., 2024), higher antioxidant capacity (Roslan *et al*., 2020), and lower losses in vitamin C content (Mazár *et al*., 2025) compared to other drying techniques. Considering these findings, the freeze-drying method may be a suitable option for producing high-quality tea. However, its large-scale commercial implementation is hindered by the significantly higher initial investment and operational costs compared to alternative drying techniques. Nevertheless, the superior quality of the final product could influence consumer preferences in favor of freeze-dried tea, making this method an attractive alternative for premium tea production.

Mathematical modeling and statistical analysis results of freeze-drying process: After the experimental studies, six models used in the literature for thin-layer FD of tea leaves and the evaluation criteria used were investigated. When the data obtained from the FD experiments were evaluated, the r and R^2 values were the highest (close to 1), while the $\chi 2$ and RMSE values were the lowest (a value close to 0 is targeted). While the R^2 varies between 0 and 1, the mathematical model that yields results closest to 1 is the most suitable model for explaining the behavior and conditions of thin-layer FD of tea leaves.

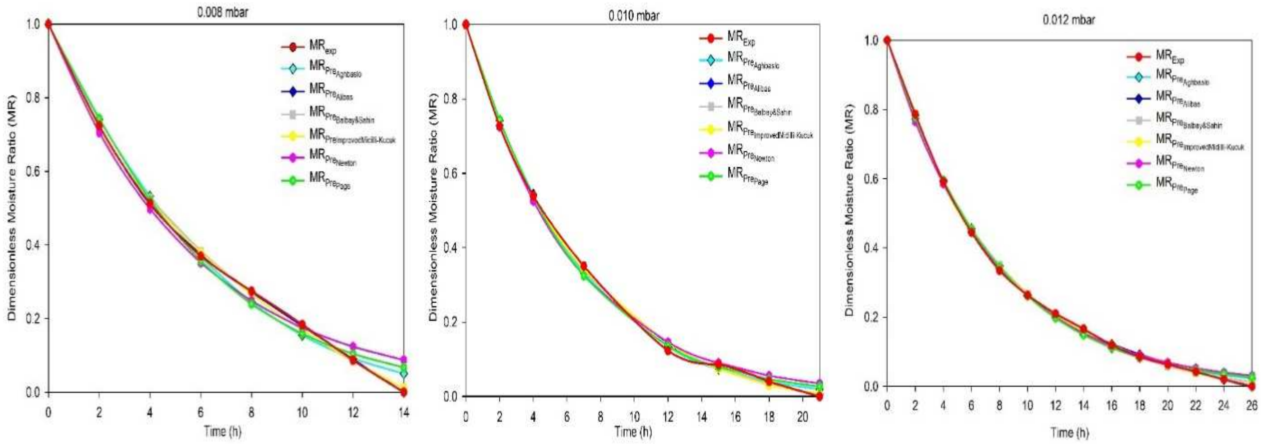

Fig. 7. MR variations of drying time depending on cabin pressure

Fig. 7 shows the MR-drying time curves, which change depending on the freeze-dryer cabin pressure. Upon examination of Fig. 7, it was found that lower cabin pressure resulted in shorter FD time for the product. The results of the evaluation criteria used to determine the mathematical model that best describes the FD process are shown in Table 3.

Table 3. Evaluation criteria of FD of tea leaves depending on cabin pressure

Pressure	Model No	Constant	r	R^2	χ^2	RMSE
0.008 mbar	1	k_1=0.142570, k_2=-0.02368	0.99699	0.99684	0.00082	0.02485
	2	**a=0.372410, k=0.264515, n=1.378291, b=-0.044821, g=0.627456**	**0.99996**	**0.99996**	**0.00002**	**0.00271**
	3	a=-0.600294, k=0.115070, n=0.806182, b=-0.598369	0.99936	0.99934	0.00026	0.01134
	4	a=2.000029, k_1=0.000547, k_2=1.868470, n=0.264710, b=0.976507	0.99964	0.99963	0.00019	0.00845
	5	k=0.174186	0.99472	0.99323	0.00151	0.03637
	6	k=0.134394, n=1.136402	0.99563	0.99536	0.00121	0.03011
0.010 mbar	1	k_1=0.146193, k_2=-0.01055	0.99936	0.99918	0.00021	0.01246
	2	**a=1.263034, k=0.133425 n=0.932566, b=0.006688, g=-0.263574**	**0.99962**	**0.99952**	**0.00024**	**0.00947**
	3	a=-0.057493, k=0.149322 n=0.967474, b=-0.058635	0.99960	0.99950	0.00019	0.00966
	4	a=1.999936, k_1=-0.23792 k_2=0.929752, n=0.449587, b=-1.28782	0.99957	0.99946	0.00027	0.01004
	5	k=0.160580	0.99897	0.99816	0.00039	0.01859
	6	k=0.141342, n=1.065855	0.99907	0.99875	0.00031	0.01535
0.012 mbar	1	k_1=0.127186, k_2=-0.00460	0.99934	0.99921	0.00014	0.01090
	2	a=0.737945, k=0.138929, n=1.154972, b=-0.010287, g=0.262976	0.99991	0.99990	0.00002	0.00395
	3	a=-0.036054, k=0.130835, n=0.978864, b=-0.030623	0.99953	0.99945	0.00012	0.00909
	4	**a=1.999946, k_1=0.494499 k_2=1.266569, n=0.565071 b=0.013477**	**0.99992**	**0.99990**	**0.00002**	**0.00386**
	5	k=0.133839	0.99932	0.99889	0.00018	0.01291
	6	k=0.121934, n=1.041982	0.99931	0.99916	0.00015	0.01123

The results of the evaluation criteria in Table 3, the models that best describe the drying process of tea leaves are the Alibas model at 0.008 mbar and 0.010 mbar pressure, and the Improved Midilli-Kucuk model at 0.012 mbar pressure.

The equations of the experimental drying curve depend on cabin pressure are given in Eq. 20-22.

$$MR_{0.008mbar} = 0.37241 \text{ x } \exp(-0.264515 \text{ x } t^{1.378291}) - 0.044821 \text{ x } t + 0.627456 \quad (20)$$

$$MR_{0.010mbar} = 1.263034 \text{ x } \exp(-0.133425 \text{ x } t^{0.932566}) + 0.006688 \text{ x } t - 0.263574 \quad (21)$$

$$MR_{0.012mbar} = 1.999936 \text{ x } \exp(0.23792 \text{ x } t^{0.449587}) - \exp(-0.929752 \text{ x } t^{0.449587}) + 1.28782 \text{ x } t^{0.449587} \quad (22)$$

In this study, tea leaves were dried under different cabin pressures, and the drying kinetics were analyzed using six different mathematical models, while changes in color and water activity were also examined. However, to enhance the efficiency of the freeze-drying process and enable more comprehensive analyses, future studies could focus on optimizing various parameters of the freeze-drying process for tea leaves. First, the effects of different pre-treatment methods (such as enzyme inactivation and osmotic dehydration) on drying time and product quality could be investigated. Additionally, in-depth analysis of the relationship between different cabin pressure levels and the chemical composition of tea leaves (e.g., polyphenol and caffeine content) with drying kinetics could be conducted. In determining drying kinetics, data-driven modeling approaches such as artificial neural networks (ANNs) could be employed, and the results could be compared with conventional thin-layer drying models to identify the most suitable prediction method. From a modeling perspective, advanced ANN structures or multi-criteria optimization techniques could be utilized to improve prediction accuracy. Finally, testing laboratory-scale findings at pilot and industrial scales would be crucial for enhancing energy efficiency and assessing the applicability of the process.

Conclusion: In this study, a comprehensive analysis was conducted using various mathematical models best suited for modeling tea drying, based on data obtained from FD fresh tea leaves. To determine the constants used in the models, nonlinear regression analysis was conducted, and the constants in each model were determined. The freeze-drying experiment with the lowest cabin pressure was completed in the shortest time compared to the others. When cabin pressure increases, drying time also increases. The highest drying rate of tea leaves occurred at the lowest cabin pressure. As cabin pressure increases, the drying rate decreases. Considering the four different evaluation criteria (R^2, r, χ^2, and RMSE), the models that best describe the drying process of fresh tea leaves at three different cabin pressure were determined to be the Alibas model (for 0.008 mbar and 0.010 mbar cabin pressure), and Improved Midilli-Kucuk model (for 0.012 mbar cabin pressure). As a result of the FD process, it was found that the color of tea leaves changed from green to red, i.e., brown. As the cabin pressure decreases, the L^* and b^* values of the final product increase. The least color change in the tea leaves was carried out at the lowest cabin pressure. As cabin pressure increases, color change also increases. The lowest water activity value of the dried tea occurred at the lowest cabin pressure. The water activity of the tea leaves decreased (from 0.9800±0.0093 to 0.2901±0.0077) to a level where no microbial growth would occur.

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