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Optimization of red pepper drying conditions in a tray dryer with cross current air flow

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In this study, the effect of temperature, air velocity, and punching of the pods on the drying process of red pepper in a cross-flow tray dryer was investigated. Red pepper samples were dried at three temperatures (55, 65, and 75 °C), two air velocities (1 and 2 m/s), and three preparation methods: unpunched, punched with a 2-mm-diameter needle (needle No. 1), and punched with a 3.5-mm-diameter needle (needle No. 2). The qualitative indicators of the final product, including pungency, color, and moisture content, were evaluated. According to the experimental results and statistical analyses, the optimum drying conditions for red pepper in the cross-flow tray dryer were determined to be a drying temperature of 65 °C, a punch diameter of 2 mm, and an air velocity of 1 m/s. Under these conditions, the drying rate was 0.299 $kg_w/kg_{dm}.h$, the pungency was 0.427 wt.% total capsaicinoids, and the extracted color value, measured as absorbance at 458 nm, was 3.776. Furthermore, the results showed that the Page and Midilli nonlinear models provided a better fit for the drying kinetics of red pepper than the Newton model, as indicated by their higher coefficients of determination (R^2) and lower RMSE and χ^2 values.

1-Introduction

Red pepper, which belongs to the *Capsicum* genus, is one of the most widely consumed spices in the world and is used either in fresh or dried form[1, 2]. In the literature, the scientific names *Capsicum annuum* L. (including sweet and mildly pungent cultivars) and *Capsicum frutescens* L. (including pungent cultivars) are commonly used for this plant. The compounds responsible for pungency and color in red pepper are capsaicinoids and carotenoids, respectively. Depending on the cultivar, peppers exhibit considerable variation in shape, size, and color. The pods may range in shape from short and round to long and slender. Each pepper pod contains a number of flattened, yellowish-white seeds with diameters ranging from 1 to 5 mm. The number, color, and size of the seeds depend on the pepper species. In fresh fruits, the seeds are attached to the spongy central core (placenta) of the pod by individual seed stalks (funiculi). However, in dried fruits, the seeds are generally detached from the pod core and can move freely within the internal cavity of the pod. Capsaicinoids are the primary compounds responsible for pungency in Capsicum species and represent one of the distinguishing characteristics of the Capsicum genus compared with other plant groups. Their composition and concentration vary considerably among species; consequently, the pungency of red peppers exhibits a wide range of variation, from very mild to extremely hot. Among the capsaicinoids, the two major compounds, capsaicin and dihydrocapsaicin, account for 80–90% of the total capsaicinoid content of red peppers and are therefore responsible for most of their pungency. Therefore, they are responsible for the majority of the pungency perceived in peppers. Approximately 90% of the capsaicinoids are concentrated in the placenta, a white spongy tissue located in the center of the fruit to which the seeds are attached. Although the seeds are not a primary source of pungency, they absorb some capsaicinoids because of their location within the pod[3]. The pungency of peppers is classified according to the Scoville Heat Unit (SHU) system. In general, the smaller the pepper fruit, the higher its pungency. Peppers are considered low-acid foods and, depending on the cultivar, have a pH ranging from 4.8 to 6.0. Capsicum species, particularly *Capsicum annuum* L., are rich sources of carotenoid pigments. The major part of the color of Capsicum is attributed to the carotenoids capsanthin and capsorubin. Capsicum contains approximately 9–17% fat and 12–15% protein and is a rich source of vitamins C and A. The seeds of the fruit also contain vitamins A, B, and C. In addition to the above constituents, citric acid, palmitic acid, pentosans, and pectin are present in hot red peppers of *Capsicum frutescens* species. Volatile oils, present in trace amounts, consist of approximately 125 compounds, of which around 24 have been identified. Scopoletin, a coumarin compound, is also present in this plant. Coumarin is a white crystalline substance with the molecular formula $C_9H_6O_2$ and is known for its anticoagulant properties[4].

Red pepper is harvested at high moisture content and must be dried to a very low moisture level, typically 8–10% (w/w) for storage and 4–5% (w/w) for grinding[5]. In most pepper-producing regions, this crop is traditionally sun-dried. In the traditional method, after harvesting, red peppers are stored indoors (in small rooms, at field edges, or under straw or tarpaulins) for 1–3 days until uniform pod coloration is achieved. The crop is then spread out on rooftops, mountain slopes, roadsides, or agricultural fields. The semi-dried peppers are heaped at night and covered, and then spread out again during the day. In this way, depending on temperature and humidity conditions, the crop dries within 6–15 days. In some regions, the product remains exposed to ambient conditions throughout the entire drying period. In another traditional practice, peppers are tied into clusters weighing 5–12 kg and hung from house walls or supporting structures for drying; this process may take several weeks. Furthermore, the pods dry non-uniformly, and the outer portions that are more exposed to sunlight become discolored, while seeds may also fall out from damaged pods. In these methods, the product remains outdoors for an extended period while still having a relatively high moisture content, which may promote mold growth. During this time, it is exposed to various environmental factors, including dust, rainfall, insects, birds, and other animals, and is often placed on unsanitary surfaces, resulting in a product of inferior quality[6-8]. Therefore, in order to reduce the drying time of red pepper and improve product quality, the use of more advanced drying methods and mechanical dryers appears to be essential[1, 5, 9, 10].

In industrial drying processes, after entering the processing facility, the product is first sorted and inspected, washed with chlorinated water, and then passed through a vibrating machine to remove excess water and foreign materials. Following a final sorting stage, the product is fed into a cutting machine, a punching machine, or any other equipment used for pre-drying preparation. It is then loaded into the dryer and dried until the desired final moisture content is reached. The main advantages of industrial drying include improved product quality, shorter drying time, and higher processing efficiency. Numerous studies have been conducted on the drying of red pepper.

Pinar et al. investigated the effects of different drying methods, including sun drying, shade drying, greenhouse drying, microwave drying (300–600 W), hot-air convective drying (60–80 °C), and freeze-drying, on the drying kinetics, biochemical properties, rehydration ratio, color, and total phenolic content of pepper[11]. Wang et al. applied a novel thermal pretreatment technology, known as high-humidity hot-air impingement blanching (HHAIB), to red pepper and investigated its effects on drying behavior and the underlying mechanisms through analyses of microstructure, component contents, and composition. The results indicated that HHAIB is a promising alternative to chemical dipping treatments and can significantly improve the drying process of red pepper[10]. In another study, the drying of chili pepper was investigated using four methods: convective drying, microwave–convective drying, vacuum drying, and freeze-drying. The results showed that the Midilli model provided the best description of the drying kinetics. Freeze-drying at 40 °C resulted in the highest retention of color, carotenoids, capsaicinoids, and polyphenols, whereas microwave–convective drying at 60 °C caused the greatest quality degradation. Overall, increasing temperature led to a reduction in total flavonoid content, and both freeze-drying and vacuum drying produced the highest quality dried products[12].

The aim of this study was to investigate the effects of temperature, air velocity, and preparation method during mechanical drying on the final moisture content, drying rate, and quality attributes of red pepper, particularly pungency and color.

2 -Materials and Methods

2-1 Materials

Fresh red peppers were obtained from Davarzan (Sabzevar, Khorasan Province, Iran). In this study, a red pepper variety locally known as red chili, which is commonly used for the production of red pepper powder, was used. For the quality analyses of dried red pepper, acetone, chloroform, methanol, hydrochloric acid, sodium hydroxide, diethyl ether, and ethyl acetate (Merck, Germany) were used. Deionized distilled water was also used throughout the experiments.

Figure 1. Red pepper (*Capsicum annuum L.)* used in the experiment

2-2 Sample Preparation

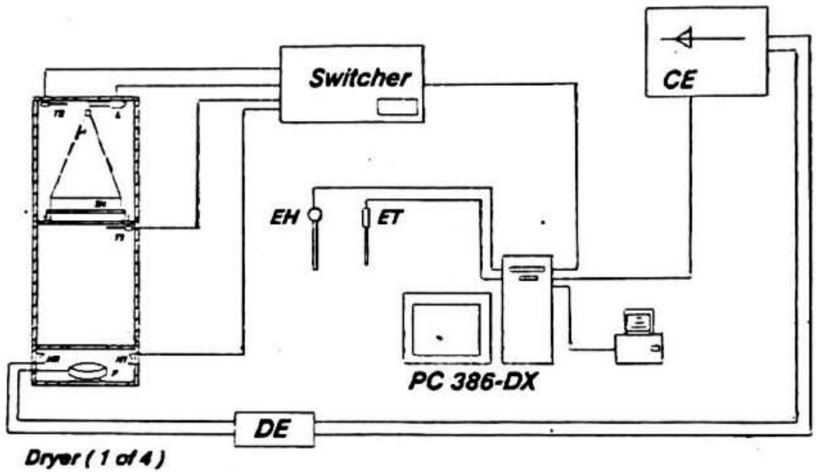
Fresh red pepper was randomly harvested from a field plot and transported to the laboratory after being packed in cartons. The samples were sorted and inspected, then divided into portions of 2–3 kg, wrapped in cotton cloths, and stored in a refrigerator at 4–5 °C. Prior to each experimental run, the initial moisture content of the samples was measured. Based on previous studies on different red pepper drying methods, pod punching was applied to accelerate the drying process. Compared with other methods such as surface scratching or cutting, this technique has the advantage of causing less effect on essential oils and volatile compounds of the fruit, while also preventing seed loss from the pods, thereby reducing both quantitative and qualitative losses. Therefore, the needle diameter of the punching device was considered as one of the important parameters affecting the drying process of red pepper, and the peppers were dried under both punched and unpunched conditions at the specified temperature and air velocity levels.

2-3 Drying Procedure

Drying experiments were conducted using a laboratory-scale cross-flow tray dryer. The dryer consisted of four completely identical and independent units, each equipped with a computerized control system (Figure 2).

Figure 2. Four laboratory tray-type cross-flow air dryers

Each system consists of three main parts. In the lower section, the heating elements and blower fan are located. An air inlet vent is installed on the lower surface of this section. Airflow in each unit is drawn through this vent by a turbine-type fan located below the heating elements and rotating around a vertical axis. Before switching on the electrical heaters, the air velocity is measured using an anemometer (Lutron, model AM-4201) with an accuracy of ±0.1 m/s. The induced airflow, after passing over the heating system, enters the middle section. During operation, the air temperature inside the system is maintained at the desired set point using the control software. The boundary between the middle and upper sections is defined by the carrier system surface. Above this section, a weighing system is installed which connected to the carrier system via supporting arms. Two temperature sensors are installed at the bottom and top of the drying tray to record air temperature before and after contact with the product, with an accuracy of ±0.1 °C. An outlet vent is installed 400 mm above the tray through which humid air is discharged to prevent an increase in relative humidity inside the dryer. The lower surface of the carrier system is mesh-type (4 mm mesh size), allowing the passage of hot air through the material bed. Forced ventilation within the system is provided by identical fans installed in each dryer unit. Relative humidity of the surrounding air is measured using a digital hygrometer with an accuracy of ±1%.



ET: Ambient air temperature sensor around the dryer system
CE: Electronic control system
T_1: Air temperature sensor before the carrier system
T_2: Air temperature sensor after the carrier system
DE: Dryer electronic system
SH: Sample holder system
H_1: Manual heating source
H_2: Automatic heating source
L: Load cell
F: Fan
EH: Environmental humidity sensor

Figure 3. Schematic diagram of a laboratory drying system with an electronic control system

To eliminate errors in weight measurement caused by airflow during drying, the control software automatically switches off the fans during data acquisition. After a 20-min stabilization period, allowing complete cessation of airflow within the system, sample weight is measured with an accuracy of ±0.01 g. Equal amounts of the prepared samples were uniformly spread in a single layer on the trays and placed inside the dryers. The samples were removed after reaching the desired moisture content, and the corresponding process conditions were recorded. The dried samples were allowed to cool to ambient temperature and were then ground using a laboratory mill. To prevent moisture absorption, the ground samples were packaged in cellophane bags and sealed using a heat-sealing machine.

2-4 Experimental Design and Statistical Analysis

The drying experiments were conducted using a D-optimal factorial design. The factors considered were drying air temperature, airflow velocity, and pod punching diameter. The factors and their corresponding levels are presented in Table 1. A total of 19 treatment combinations were evaluated in three replications. Statistical analysis of the experimental data was performed using analysis of variance (ANOVA) in Design-Expert software (Version 13).

Table 1. Factors used in the experiments along with their corresponding levels

Factor	Level 1	Level 2	Level 3
A: Air velocity (m/s)	1	2	–
B: Puncher diameter (mm)	٠	2	3.5
C: Drying temperature (°C)	55	65	75

2-5 Moisture Content Determination

According to the Iranian National Standard No. 1196, the moisture content of red pepper was determined by drying 5–10 g of the sample in an atmospheric oven at 100–105 °C until a constant weight was achieved. The moisture content of the sample was calculated using Eq. (1):

$$\mathit{Moisture\ percentage\ on\ wet\ basis} = \frac{(M_1 - M_2)}{M_0} \times 100 \qquad (1)$$

where:

M_0: weight of the wet sample (g)

M_1: weight of the container and sample before drying (g)

M_2: weight of the container and sample after drying (g)

2-6 Determination of Red Pepper Pungency

The pungency of red peppers plays an important role in their consumption level and applications. To determine the pungency of the dried samples, the total capsaicinoid content was measured by spectrophotometry according to ISO 7543-1. This method requires decolorization with activated carbon. In some cases, the extracted capsaicinoid solution may not be sufficiently decolorized during the analysis; under such conditions, capsaicinoid determination should be performed using high-performance liquid chromatography (HPLC). In the present study, the solutions were adequately decolorized, and therefore the use of HPLC was not required. This method is based on extracting dried red pepper powder using tetrahydrofuran, followed by measurement of the absorbance of the methanolic extract solution at wavelengths of 248 and 296 nm. The mass percentage of total capsaicinoids at a wavelength of 248 nm (W_{248})was calculated using the following equation:

$$W_{248} = \frac{(A_s - A_b) \times d}{314 \times m} \qquad (2)$$

The mass percentage of total capsacinoids at a wavelength of 296 nm is also obtained through the following equation[13]:

$$W_{296} = \frac{(A_s - A_b) \times d}{127 \times m} \qquad (3)$$

Where:

A_s: Absorbance of the sample solution

A_b: Absorbance of the blank solution

d: Dilution factor, which under the conditions specified in the standard is equal to 100×25

m: Sample mass (g)

2–7 Color Determination

The color of dried red pepper samples was determined according to ISI Standard No. 9345. Color compounds were extracted with acetone using a Soxhlet apparatus, and the extractable color was subsequently measured by spectrophotometry at a wavelength of 458 nm. This method, which is based on the measurement of color derived from chemical compounds rather than visual appearance, is important for evaluating the quality of spices and dried products.

2–8 Drying Kinetics Analysis

To evaluate the drying behavior of red pepper, three commonly used mathematical models, namely the Newton, Page, and Midilli models, were selected. For this purpose, the moisture content of the samples was determined on a dry basis (d.b.) over time. The moisture ratio (MR) was calculated using the following equation:

$$MR = \frac{M(t) - M_e}{M_0 - M_e} \quad (4)$$

where M(t) is the moisture content at time t, M_0 is the initial moisture content, and M_e is the equilibrium moisture content.

$$MR = \exp(-kt) \quad (5) \quad Nawoton\ model$$

$$MR = \exp(-kt^n) \quad (6) \quad Page\ model$$

$$MR = a\exp(-kt^n) + bt \quad (7) \quad Midilli\ model$$

where a, b, k and n are the model parameters.

To evaluate the accuracy of the models, three statistical indicators were calculated. Model parameters were estimated using nonlinear regression analysis in Excel Solver.

$$R^2 = 1 - \frac{\sum(MR_{exp} - MR_{pred})^2}{\sum(MR_{exp} - \bar{MR}_{exp})^2} \quad (8)$$

$$RMSE = \sqrt{\frac{\sum(MR_{exp} - MR_{pred})^2}{N}} \quad (9)$$

$$x^2 = \frac{\sum(MR_{exp} - MR_{pred})^2}{N - p} \quad (10)$$

3 -Results and Discussion

In evaluating the parameters affecting the drying process, the effects of drying air temperature, airflow velocity inside the dryer, and pod punching diameter, as well as their interaction effects, on drying time, drying rate, pungency, color, and moisture content were investigated.

3-1 Drying Time and Drying Rate

Drying is a process in which the water activity of a food material is reduced through the removal of most of its water content by evaporation, sublimation, or a mechanical process. By reducing the moisture content of the food material, microbial spoilage is prevented and the rate of other undesirable reactions is also reduced. In addition to its preservative effect, drying significantly decreases the weight and volume of the product and consequently reduces transportation and storage costs. Since the drying process affects the aroma, flavor, and nutritional value of food materials, moisture removal should be carried out in a manner that minimizes adverse effects on product quality. To select appropriate drying conditions, it is necessary to evaluate the drying rate of the food material. Such data are not available for all food products and therefore must be obtained experimentally by plotting free moisture content as a function of drying time. The drying rate curve can then be obtained by differentiating this curve with respect to time[14].

Table 2 presents the drying time and drying rate required to reach the final moisture content (8–10%) under the investigated treatments. The average initial moisture content was 83.4% on a wet basis.

Table 2. Drying time and rate to achieve final moisture content in the product

Temperature (°C)	Air velocity (m/s)	Unpunched		Punched with needle 1		Punched with needle 2	
		Drying time (h)	Average drying rate ($kg_w/kg_{dm}.h$)	Drying time (h)	Average drying rate ($kg_w/kg_{dm}.h$)	Drying time (h)	Average drying rate ($kg_w/kg_{dm}.h$)
55	1	23.625	0.1935	22.375	0.2150	15.625	0.3065
55	2	23.125	0.1995	21.875	0.2190	15.500	0.3095
65	1	18.625	0.2450	15.500	0.3035	15.125	0.3810
65	2	17.625	0.2575	15.125	0.3130	12.500	0.3880
75	1	14.875	0.2975	13.875	0.3485	11.000	0.4225
75	2	15.375	0.2990	14.500	0.3315	10.875	0.4295

As shown in Table 2, the treatment at 75 °C, an air velocity of 2 m/s, and pod punching with a 3.5 mm needle diameter resulted in the shortest drying time and the highest drying rate. In contrast, the treatment at 55 °C, an air velocity of 1 m/s, and without punching exhibited the longest drying time and the lowest drying rate. Therefore, increasing the drying temperature, air velocity, and punching needle diameter reduced the drying time by 53.97% and increased the drying rate by 122%. The free moisture content versus drying time curves and the drying rate curves are discussed below.

3-1-1 Effect of Punching

Figure 4 shows the moisture content of red peppers punched with four different punching needle diameters (1.5, 2, 3, and 3.5 mm) and dried at a constant temperature and airflow velocity (65 °C and 1 m/s), plotted as a function of drying time. As can be seen in the figure, increasing the punching needle diameter causes the product moisture content to approach its final value more rapidly. This can be attributed to the easier and faster evaporation of moisture through the larger openings created by punching. Considering the similarity in drying times between the 1.5 and 2 mm punching diameters, as well as between the 3 and 3.5 mm punching diameters, the 2 mm (Needle 1) and 3.5 mm (Needle 2) diameters were selected for the drying experiments.

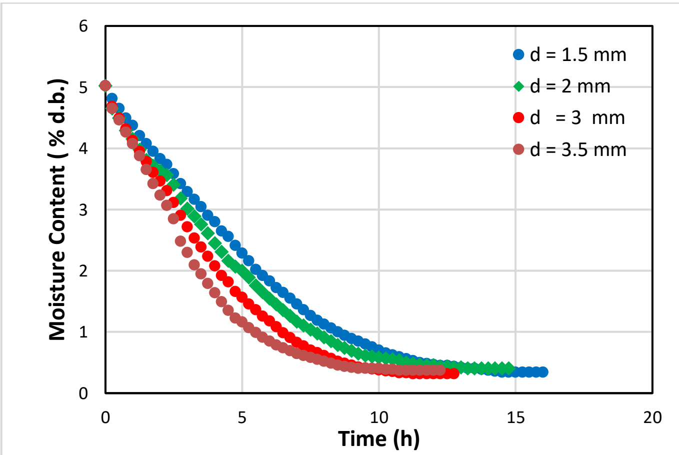


Figure 4. Drying curve of punched red peppers with four different punching needle diameters

Figures 5–7 illustrate the effect of punching on the drying behavior of red pepper pods at temperatures of 55, 65, and 75 °C and air velocities of 1 and 2 m/s. As can be seen, the punching treatment reduced the drying time. The slope of the drying curve for unpunched pods was the lowest, followed by those of pods punched with Needle 1 and Needle 2, respectively.

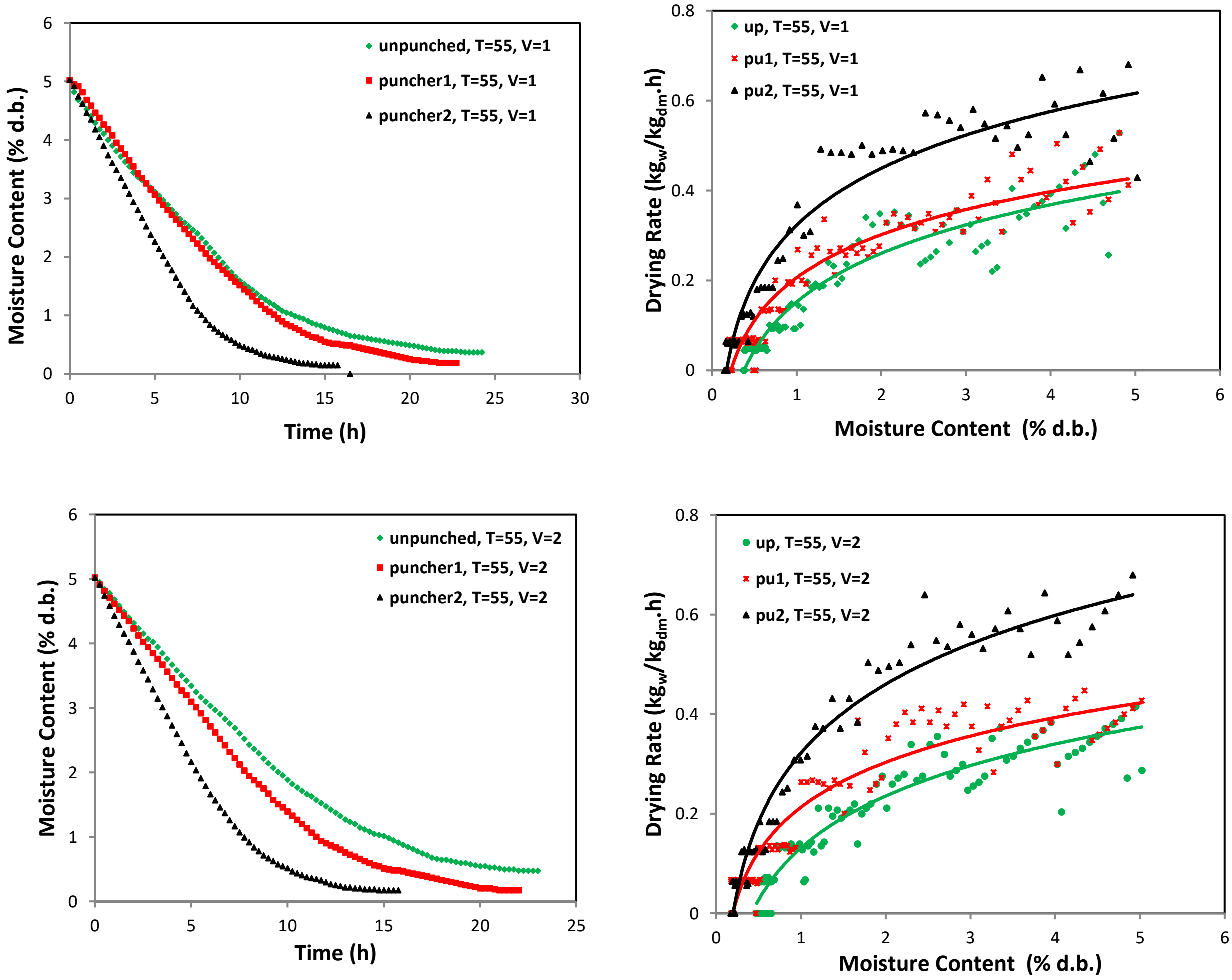
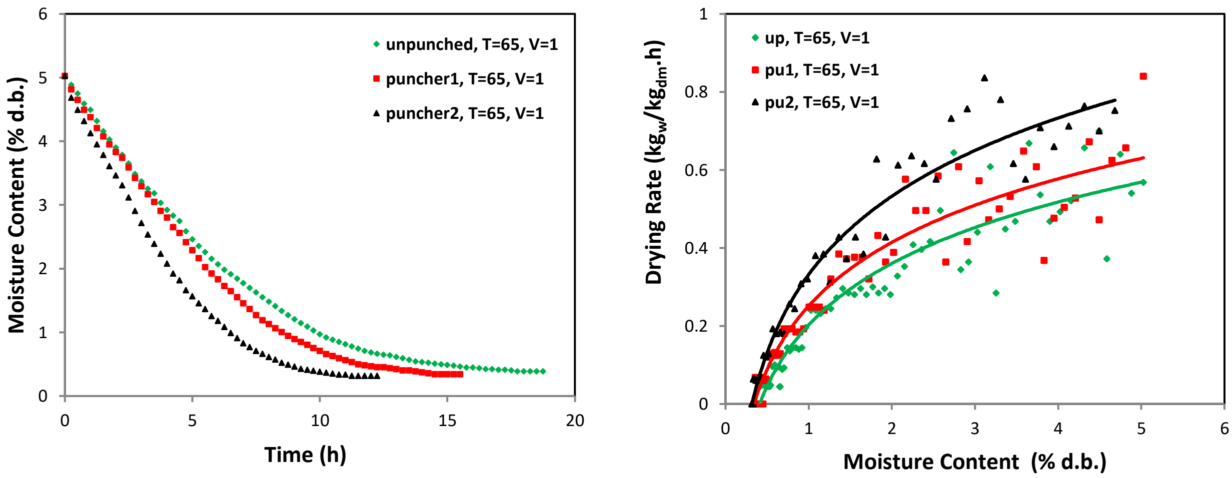


Figure 5. Effect of punching on moisture content and drying rate at 55°C and 1 m/s (top row), 2 m/s (bottom row)



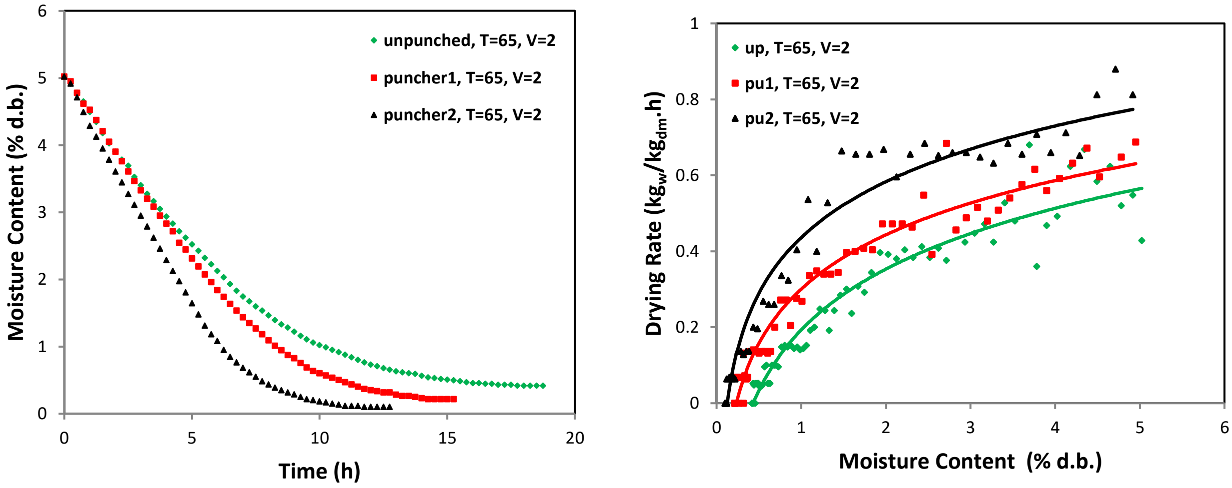


Figure 6. Effect of punching on moisture content and drying rate at 65°C and 1 m/s (top row), 2 m/s (bottom row)

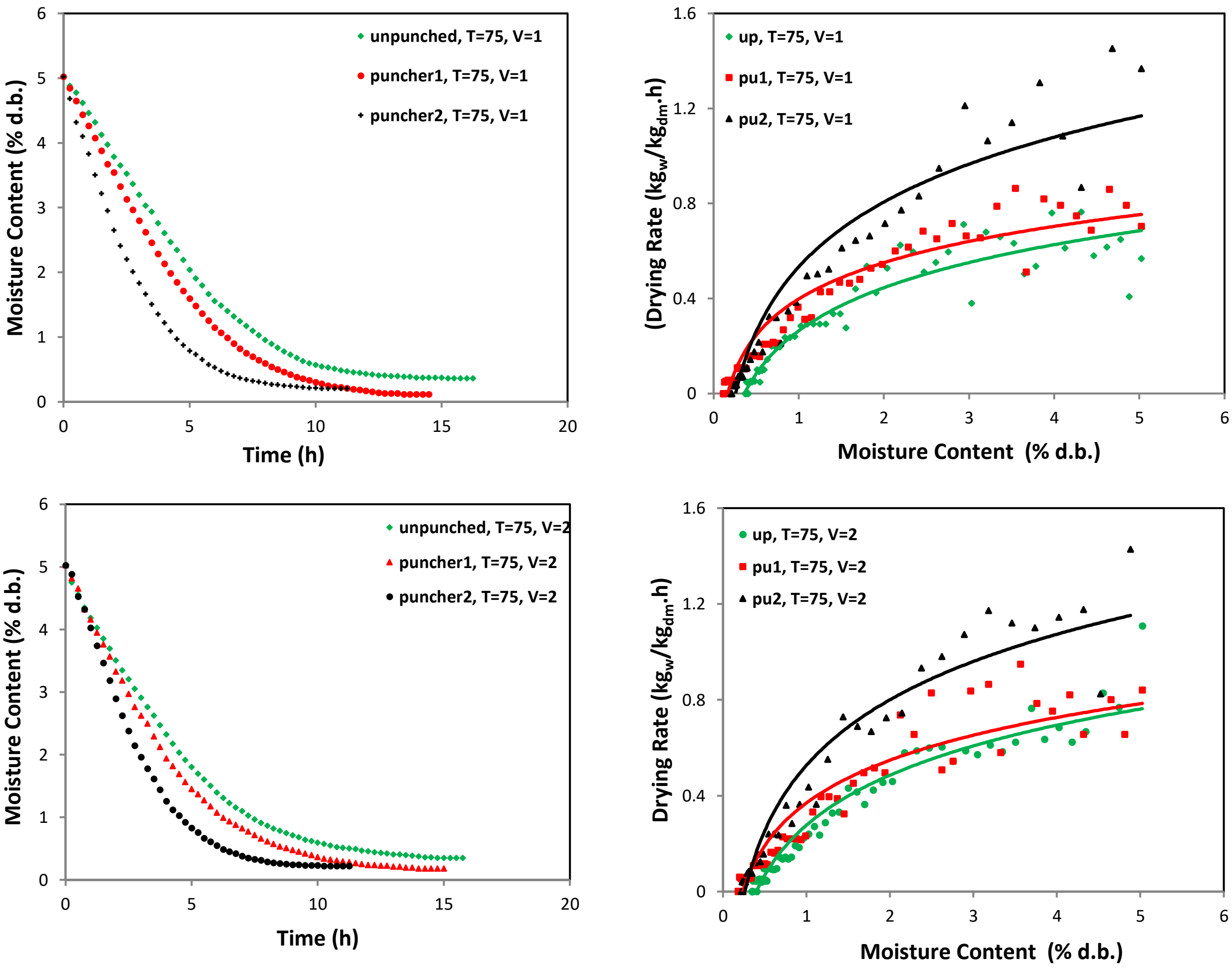


Figure 7. Effect of punching on moisture content and drying rate at 75°C and 1 m/s (top row), 2 m/s (bottom row)

3-1-2 Effect of Drying Air Temperature

The effect of temperature was evaluated by comparing the drying curves (Figures 8–10) and the corresponding mean values. As the drying air temperature increased, the drying time decreased. This behavior can be attributed to the faster evaporation of moisture at higher temperatures. A statistically significant difference was observed among all three temperature levels.

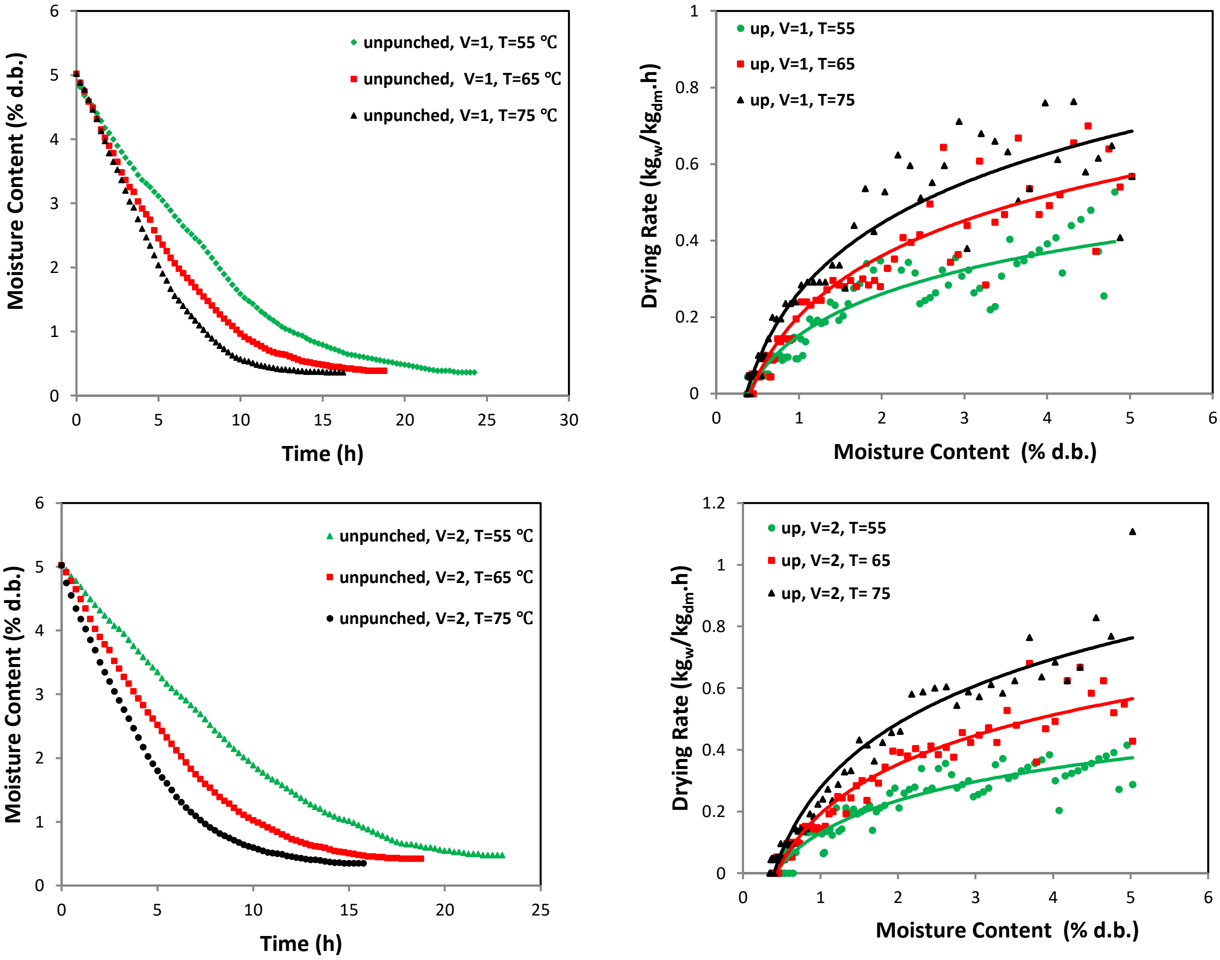
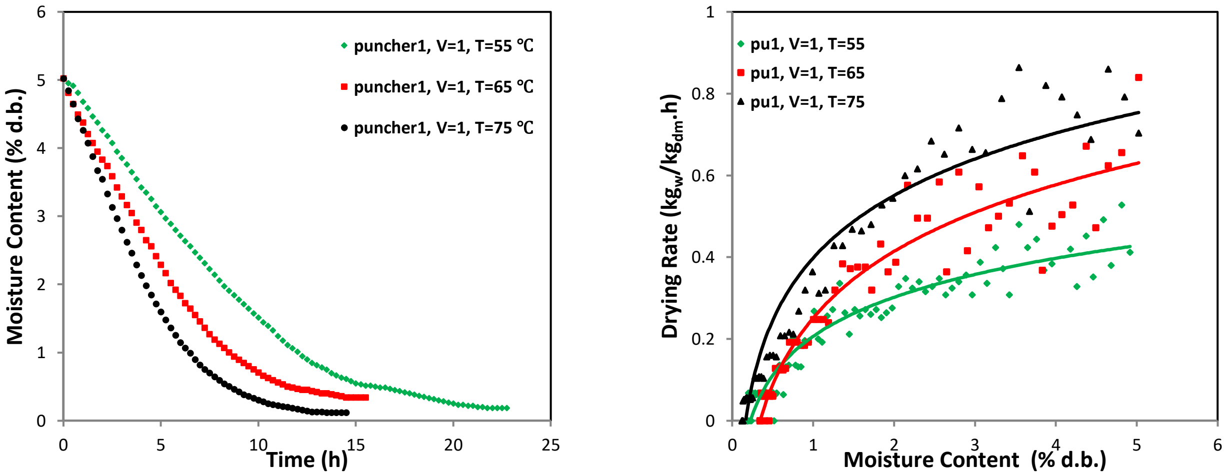


Figure 8. Effect of temperature on moisture content and drying rate in the unpunched pepper and air velocity of 1 m/s (top row), 2 m/s (bottom row)



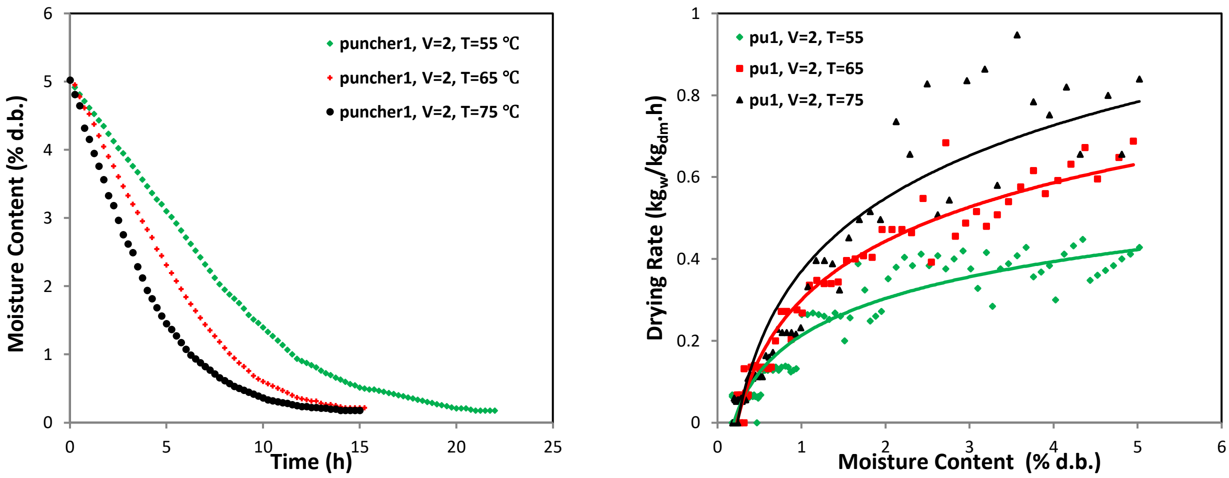


Figure 9. Effect of temperature on moisture content and drying rate in punched pepper with needle 1 and air velocity of 1 m/s (top row), 2 m/s (bottom row)

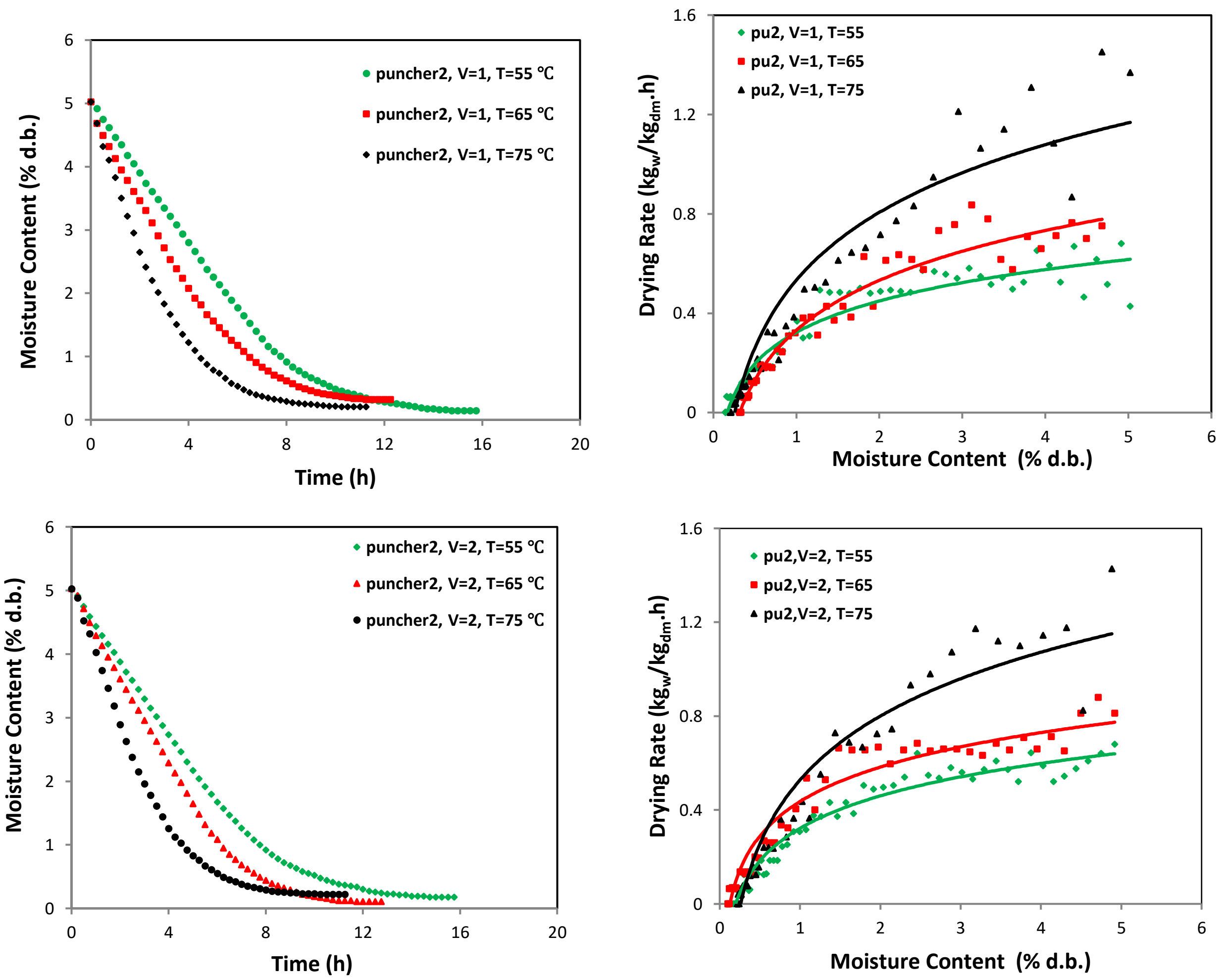


Figure 10. Effect of temperature on moisture content and drying rate in punched pepper with needle 2 and air velocity of 1 m/s (top row), 2 m/s (bottom row)

As can be seen from the drying rate curves, the slope of the drying curve at 55 °C is considerably lower than those at 65 and 75 °C. As the drying temperature increases, the samples dry more rapidly due to the increase in the mass transfer driving force within the pepper tissue. Comparison of the three curves also shows that the slope of the drying curve for unpunched pods is noticeably lower than that for punched pods. This indicates that the creation of mechanical openings in the pods facilitates moisture migration pathways and reduces the diffusion resistance of the pod skin. Consequently, the drying rate increases and the time required to reach the final moisture content decreases.

3-1-3 Effect of Airflow Velocity

The results of the analysis of variance showed that the effect of airflow velocity on drying time was not statistically significant. Due to its waxy and relatively impermeable skin, red pepper allows only limited penetration of the drying air into its internal tissues; therefore, the effect of airflow velocity on moisture removal is negligible. As shown in Figure 11, at each drying temperature and under each pod punching condition, the drying curves obtained at air velocities of 1 and 2 m/s almost overlap. The air velocity of 2 m/s resulted in only a very slight reduction in drying time compared with 1 m/s.

From a practical standpoint, these findings highlight the greater importance of drying temperature and sample preparation method (pod punching) compared with increasing airflow velocity; Increasing the airflow velocity, contrary to expectations, did not produce a significant reduction in drying time and only increased the energy consumption of the fans. Therefore, optimization of the red pepper drying process should focus on temperature control and modification of the pod structure (e.g., punching) in order to reduce drying time while preserving product quality in terms of color and pungency.

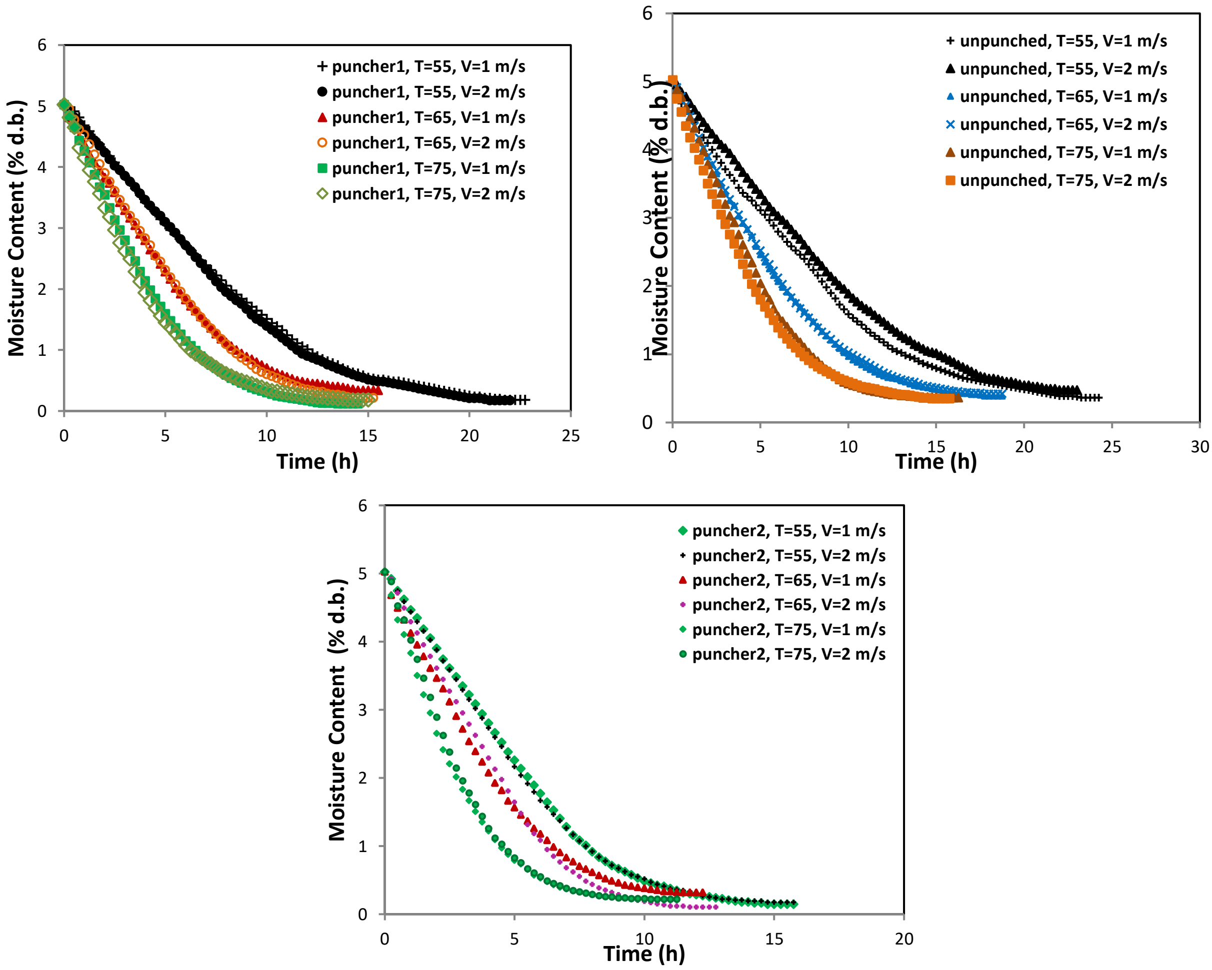


Figure 11. Effect of air velocity and temperature on moisture content and drying rate in the following cases: a) Unpunched b) Punched with needle 1 c) Punched with needle 2

3-1-4 Statistical Analysis of the Drying Process

The effects of punching, drying temperature, and airflow velocity, as well as the interaction effects among these factors, on drying time and drying rate were evaluated through statistical comparison of the treatment means. The variations observed among the three replications were mainly attributed to uncontrollable factors such as differences in the size and geometric shape of the raw material, degree of maturity, initial moisture content, and other inherent characteristics, which prevented complete agreement among the replicates of a given experiment. Therefore, the statistical analyses were performed using the mean values of the replications.

According to the results, factor A (airflow velocity) and its interaction effects with the other two factors were not statistically significant. However, factor B (punching), factor C (temperature), and their interaction effects were statistically significant at a probability level of less than 0.01. Both increasing the drying temperature and increasing the punching diameter reduced the drying time. The combined effect of temperature and punching diameter had a greater influence on drying time than their individual effects. Increasing the temperature accelerated moisture evaporation, while increasing the punching diameter facilitated moisture vapor removal from the tissue. The combination of these two factors therefore resulted in a substantial reduction in the overall drying time. From an industrial perspective, these findings highlight the importance of selecting appropriate drying temperatures and sample preparation methods. Thus, the combination of higher drying temperatures and punching can accelerate the drying process while reducing energy consumption and improving the quality of the final product in terms of color retention and pungency.

Regarding the drying rate, both temperature and punching diameter had significant individual effects; however, their interaction effect on drying rate was not significant. In many drying processes, temperature is the dominant factor, whereas mechanical factors (such as hole diameter or product thickness) tend to exert a more linear influence. Similarly, in a study by Nasrnia et al. (2024) on rice drying, temperature and drying method had significant effects on the total drying time, whereas the drying rate was primarily governed by temperature and the interaction effects were reported to be weak and statistically insignificant[15]. Similarly, Adeyeye et al. (2025), in their review of drying processes for various food products, reported that drying time is often significantly influenced by the interaction between temperature and physical characteristics (such as thickness, diameter, and airflow conditions). However, drying rate is frequently described more accurately by linear or semi-empirical models, and interaction effects are often less significant[16].

Table 3. Analysis of variance (ANOVA) for drying time (min)

Source	Sum of Squares	df	Mean Square	F-value	p-value	
Model	9.349E+05	8	1.169E+05	58.58	< 0.0001	significant
B-Puncher Diameter (mm)	3.218E+05	2	1.609E+05	80.66	< 0.0001	
C-Temperature (°C)	5.307E+05	2	2.654E+05	133.02	< 0.0001	
BC	68672.69	4	17168.17	8.61	0.0028	
Residual	19950.00	10	1995.00			
Lack of Fit	19921.88	9	2213.54	78.70	0.0873	not significant
Pure Error	28.13	1	28.13			
Cor Total	9.548E+05	18				

Std. Dev.	44.67	**R^2**	0.9791
Mean	985.66	**Adjusted R^2**	0.9624
C.V. %	4.53	**Predicted R^2**	0.9454

		Adeq Precision	24.2755

P-values less than 0.05 in the analysis of variance (ANOVA) for drying time indicate that the model terms are statistically significant. The coefficient of determination (R^2) value of 0.9791 indicates that the variability of the data is well explained by the model. The close agreement between the adjusted coefficient of determination (Adjusted R^2) and the predicted coefficient of determination (Predicted R^2), with a difference of less than 0.2, confirms the adequacy of the selected model. Adeq Precision measures the signal-to-noise ratio, and values greater than 4 indicate an adequate signal and the ability of the model to distinguish among factors and identify the important variables affecting the process. The Adeq Precision value obtained for the drying time response was 24.2755, which is substantially higher than the minimum required value, demonstrating the adequacy and reliability of the model for screening the influential factors. The following equation, expressed in terms of coded factors, was obtained for drying time and can be used to predict the drying behavior of red pepper under different operating conditions:

Drying Time (min)=993.06+139.44*B[1]+39.44*B[2]+228.19*C[1]−40.14*C[2]+41.81*B[1]C[1]+66.81*B[2]C[1]−4.86*B[1]C[2]−73.61*B[2]C[2] (11)

Table 4. ANOVA for Drying Rate (Kg $_{w}$/Kg $_{dm}$.h)

Source	**Sum of Squares**	**df**	**Mean Square**	**F-value**	**p-value**	
Model	0.0938	4	0.0234	305.65	< 0.0001	significant
B-Puncher Diameter (mm)	0.0516	2	0.0258	336.51	< 0.0001	
C-Temperature (°C)	0.0403	2	0.0202	262.72	< 0.0001	
Residual	0.0011	14	0.0001			
Lack of Fit	0.0011	13	0.0001	16.06	0.1932	not significant
Pure Error	5.120E-06	1	5.120E-06			
Cor Total	0.0949	18				

Std. Dev.	0.0088	**R²**	0.9887
Mean	0.3072	**Adjusted R²**	0.9854
C.V. %	2.85	**Predicted R²**	0.9788
		Adeq Precision	52.8768

According to the results of the drying rate analysis of variance, P-values lower than 0.05 indicate that the model is statistically significant. The coefficient of determination (R^2) value of 0.9887 demonstrates that the variability of the data is well explained by the model. The close agreement between the Adjusted R^2 and Predicted R^2 values indicates that the selected model has high accuracy and reliability for predicting the drying rate. The F-value for lack of fit was 16.06, indicating that the lack of fit was not significant relative to the pure error. Therefore, the proposed model was able to adequately describe the actual behavior of the data. The following equation, expressed in terms of coded factors, was obtained for the drying rate:

Drying Rate (kg$_{(w)}$/kg$_{(dm)}$·h) = 0.3030 − 0.0544*B[1] − 0.0146*B[2] − 0.0625*C[1] + 0.0108*C[2] (12)

3-2 Pungency

The effects of temperature, airflow velocity, punching treatment, and their interaction effects on pungency were investigated. The parameter W_{248} is more sensitive to the overall absorption of aromatic compounds and may be more affected by residual pigments in cases of incomplete decolorization. In contrast, W_{296} exhibits greater selectivity toward capsaicinoids and is generally less susceptible to interference from colored compounds. Since complete decolorization was achieved and the differences between the values obtained at wavelengths of 248 and 296 nm were negligible, the average of the two measurements was reported.

The results showed that the pungency of unpunched peppers was significantly higher than that of punched peppers. This can be attributed to the loss of a portion of the pungency-related compounds through the openings created during the punching process. Comparison of the treatment means indicated that the unpunched samples retained the highest level of pungency, followed by peppers punched with 2 mm (Needle 1) and 3.5 mm (Needle 2) needles, respectively. All three treatments were significantly different from each other. In addition, increasing the drying temperature led to an increase in the measured pungency of the product. This effect can be attributed to the greater removal of water from the product and the consequent concentration of pungency-related compounds. Capsaicinoids are generally non-volatile and therefore do not evaporate during the drying process; instead, they remain within the tissue, and their concentration increases as moisture is removed. Comparison of the treatment means showed that drying at 75 °C had the greatest effect on the pungency level, followed by 65 °C and 55 °C, respectively. Airflow velocity did not have a significant effect on pungency. Similar findings were reported by Wu et al. (2025), who showed that hot-air drying effectively preserved the capsaicinoid content of red pepper, whereas shade drying and sun drying resulted in substantial losses of these compounds[17].

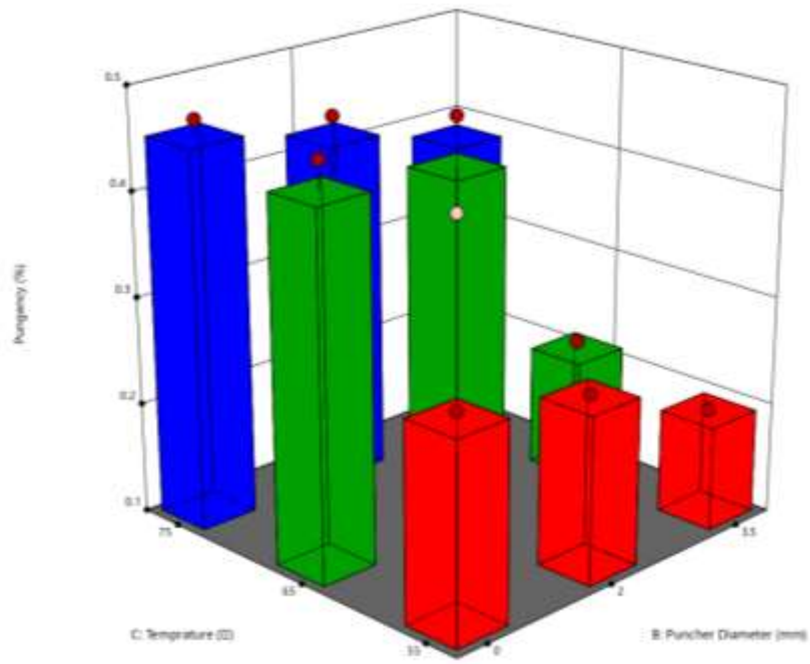


Figure 12. Effect of drying parameters on the pungency of red pepper

3-3 Color

According to the statistical analysis, airflow velocity did not have a significant effect on color. Pigments, particularly carotenoids, exhibit low volatility and, under hot-air drying conditions, tend to remain within the product or undergo degradation rather than evaporate[18]. In contrast, both punching and temperature had highly significant effects on the color parameter ($P < 0.0001$). The results showed that color retention was higher in unpunched peppers than in punched peppers. Furthermore, increasing the punching diameter resulted in a reduction in color. This effect can be attributed to the greater penetration of heat and airflow into the product, which adversely affects the pigment compounds. The unpunched treatment exhibited the highest color retention, followed by punching with a 2 mm needle and a 3.5 mm needle, respectively. The mean color value at 65 °C was higher than those obtained at the other two temperatures. Under the drying conditions of 65 °C, a punching diameter of 2 mm, and an airflow velocity of 2 m/s, the extracted color value was determined to be 3.776 based on absorbance at 458 nm. At lower temperatures, carotenoid degradation increased due to the longer exposure time to heat, whereas at higher temperatures, degradation was accelerated by the greater thermal stress imposed on the pigments. Because of the low volatility of the pigments, airflow velocity did not exert a noticeable effect on color. Similar results were reported by Krzykowski et al. (2024), who found that increasing the drying temperature promoted carotenoid degradation and reduced color-related indices in red pepper, whereas drying at lower temperatures provided better color preservation. They reported extracted color absorbance values ranging from 3.5 to 4.2[12].

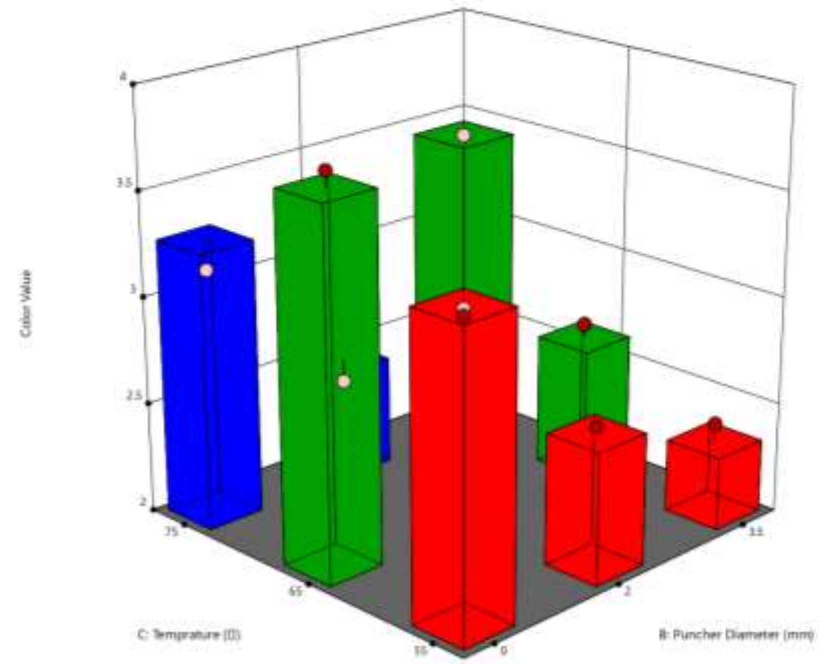


Figure 13. Effect of drying parameters on the color of red pepper

3-4 Final moisture content

Statistical analysis showed that punching and temperature had a significant effect on the moisture content of red pepper ($p < 0.0001$); however, air velocity and the interaction effects of various factors did not have a significant effect on moisture content. Furthermore, as the diameter of the created pores increased, the moisture content decreased, which can be attributed to more effective penetration of heat and airflow into the product tissue. Additionally, the average moisture content at 65°C fell within the standard range, indicating that this condition can be considered an optimal temperature for achieving desirable moisture content in the red pepper drying process.

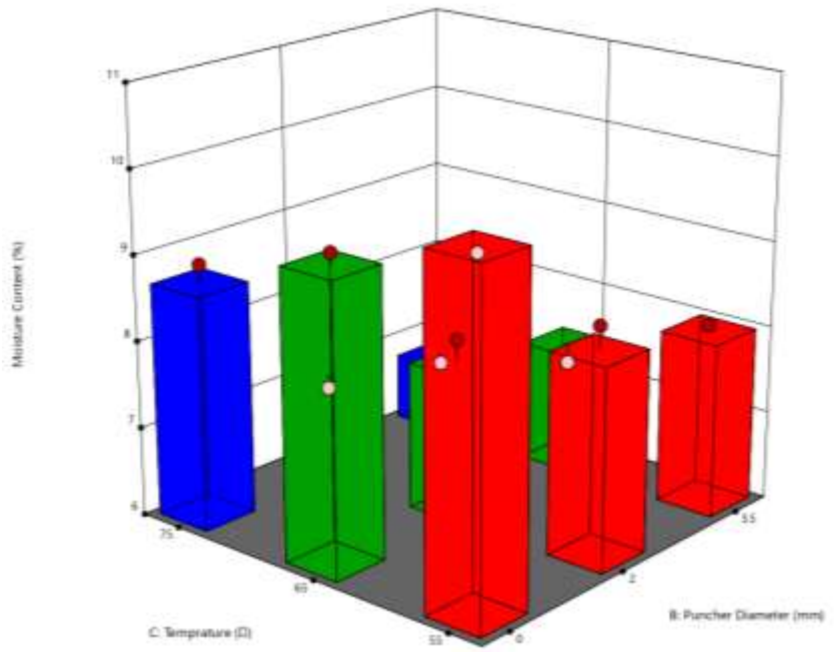


Figure 14. Effect of drying parameters on the moisture content of red pepper

3-5 Evaluation of model fitting

To describe the drying behavior of red pepper, three mathematical models, namely Newton, Page, and Midilli, were fitted to the experimental moisture ratio (MR) data. The performance of each model was evaluated using statistical indices including the coefficient of determination (R^2), chi-square (χ^2), and root mean square error (RMSE). The results of the model parameters and goodness-of-fit indices are presented in Table (5). Based on the results, the Midilli model exhibited the best fit to the experimental data, achieving the highest R^2 value and the lowest χ^2 and RMSE values. This indicates a very strong agreement between the predicted values and the observed data. The Page model also performed well and provided higher accuracy compared to the Newton model. In contrast, despite its structural simplicity, the Newton model showed lower R^2 values and higher errors (χ^2 and RMSE), indicating its limitation in describing the drying kinetics of red pepper under the experimental conditions. Overall, the results confirm that nonlinear models such as Page and Midilli possess greater capability in describing the moisture reduction behavior during the drying process. Among them, the Midilli model, due to its high flexibility and accuracy, is recommended as the best option for simulation and future optimization studies. In the study by Krzykowski et al. (2024), nonlinear models, particularly Midilli, were also introduced as the most accurate models[12]. Furthermore, the study by Wisdom (2023) confirms that the Midilli model has greater capability in describing red pepper drying kinetics compared to simpler models such as Newton[19]. Therefore, the present results, while confirming previous studies, demonstrate the superiority of the Midilli model in simulating the drying process of red pepper.

Table 5. Comparison of drying models based on fitting parameters and statistical indices

Model	Parameters (k, n, a, b)	R^2	χ^2	RMSE
Newton model	k = 0.2792	0.9613	0.012506986	0.110866354

Page model	k = -0.1027, n = 1.3692	0.996108637	0.000376019	0.019053944
Midilli model	a = 0.9563, k = -0.0867, n = 1.4043, b = -0.0022	0.998927265	0.0001075	0.010004151

4- Conclusion

In this study, the drying process of red pepper in a cross-flow tray dryer was investigated under the influence of three factors: drying temperature, airflow velocity, and sample preparation method (pod punching). Drying curves and drying rate curves were developed to analyze moisture removal behavior, and product quality attributes, including pungency, color, and final moisture content, were evaluated. The resulting data were analyzed using Design-Expert 13 software. The results showed that drying time was significantly affected by temperature and sample preparation, whereas the effect of airflow velocity was negligible. The shortest drying time was obtained at 75 °C, an airflow velocity of 2 m/s, and punching with Needle 2 (3.5 mm). In contrast, the longest drying time was observed at 55 °C, an airflow velocity of 1 m/s, and in the unpunched condition. Based on the statistical optimization results, a drying temperature of 65 °C, an airflow velocity of 1 m/s, and punching with a 2-mm-diameter needle were identified as the optimum drying conditions for red pepper. This treatment minimized the drying time while maintaining desirable product quality in terms of pungency, color, and final moisture content. Furthermore, fitting the experimental data to several mathematical models demonstrated that the Midilli model provided the most accurate prediction of drying behavior, exhibiting the highest coefficient of determination (R^2) and the lowest error values among the models evaluated. Therefore, the Midilli model is recommended for simulation and optimization of red pepper drying processes under industrial conditions.

Conflict of Interest

There are none to declare.

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Author Contributions

All authors have contributed to the design, analysis, writing, and approval of the final manuscript in this manner

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بهینه‌سازی شرایط خشک‌کردن فلفل قرمز در خشک‌کن سینی‌دار با جریان متقاطع هوا

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چکیده

در این پژوهش اثر دما، سرعت جابجایی هوا و پانچ کردن نیام‌ها بر فرایند خشک‌کردن فلفل قرمز در خشک‌کن سینی‌دار با جریان متقاطع هوا، مورد بررسی قرار گرفت. نمونه های فلفل قرمز در سه دمای ۵۵، ۶۵ و $75°C$، دو سرعت هوای ۱ و ۲m/s و با سه روش آماده‌سازی پانچ نشده، پانچ شده توسط سوزن با قطر ۲ mm (سوزن شماره ۱) و پانچ شده توسط سوزن با قطر ۳/۵ mm (سوزن شماره ۲) خشک شده و شاخص‌های کیفی محصول نهایی شامل تندی، رنگ و رطوبت اندازه‌گیری گردیدند. با توجه به نتایج آزمایشات و تجزیه‌های آماری صورت گرفته، شرایط بهینه برای خشک کردن فلفل قرمز در خشک‌کن سینی‌دار با جریان متقاطع هوا، دمای °C ۶۵، قطر پانچ ۲ mm، سرعت هوای ۱m/s بود که سرعت خشک کردن در این شرایط ۰/۲۹۹ $kg_w/kg_{dm}.h$، میزان تندی ۰/۴۲۷ درصد جرمی کاپسائی‌سینوئیدهای تام و میزان رنگ استخراج‌شده بر اساس جذب نوری در طول موج ۴۵۸ نانومتر، ۳/۷۷۶ بود. همچنین نتایج نشان داد که مدل‌های غیرخطی پیج و میدیلی با مقادیر بسیار پایین RMSE و χ^2 و ضریب تعیین بالا، برازش دقیق‌تری نسبت به مدل نیوتن ارائه کردند و بنابراین برای توصیف سینتیک خشک‌کردن فلفل قرمز مناسب‌تر هستند.