

Real-Time Colour Monitoring and Predictive Modelling of Shahani Date Slices during Electrohydrodynamic-Assisted Drying

S. S. Mohtasebi¹, M. Moradi^{2,3*}, M. Keramat-Jahromi^{3*}

1- Department of Agricultural Machinery Engineering, Faculty of Agricultural Engineering and Technology, University of Tehran, Karaj, Iran

2- Department of Biosystems Engineering, Faculty of Agriculture, Ferdowsi University of Mashhad, Mashhad, Iran

3- Department of Biosystems Engineering, Faculty of Agriculture, Shiraz University, Shiraz, Iran

(*- Corresponding authors Email: moradih@um.ac.ir, mahdikeramat@shirazu.ac.ir)

<https://doi.org/10.22067/jam.2026.100880.1527>

Abstract

This study investigated how drying temperature, air velocity, and drying time affect the colour evolution of Shahani date slices during electrohydrodynamic (EHD)-assisted drying integrated with forced convection. Drying experiments were conducted at 25, 35, and 60 °C and air velocities of 0.5, 1.0, and 1.5 m s⁻¹ until the moisture content reached approximately 12% (wet basis). An online machine vision system monitored the CIELAB coordinates (L*, a*, and b*), total colour difference (ΔE), Chroma, Hue angle, and browning index (BI) during drying. To facilitate comparison of colour changes relative to the initial state, relative values of lightness (L*/L₀), redness (a*/a₀), yellowness (b*/b₀), and browning index (BI/BI₀) were used. Linear mixed-effects models evaluated the main and interactive effects of the drying variables, while polynomial regression models were developed for prediction. Drying time decreased markedly with increasing temperature and air velocity, with the shortest duration obtained at 60 °C and 1.5 m s⁻¹. Colour evolution was time-dependent and parameter-specific: L*/L₀ and b*/b₀ generally decreased, whereas relative redness, ΔE , and BI/BI₀ increased. Significant interactions indicated that the effects of drying conditions on colour responses varied with the drying stage. The predictive models, based on MR, temperature, and air velocity, achieved validation-set R² values of 0.8717–0.9490, with corresponding RMSE and MAE values of 0.00292–0.06375 and 0.00226–0.05148, respectively. These results demonstrate the potential of combining online colour monitoring with interpretable models for non-destructive process monitoring and future optimisation of EHD-assisted drying.

Keywords: Colour evolution, Machine vision, Moisture ratio, Polynomial regression

Abbreviations and Nomenclature

Abbreviation	Definition	Abbreviation	Definition
EHD	Electrohydrodynamic	ΔE	Total colour difference
MR	Moisture ratio	C*	Chroma
M ₀	Initial moisture content (w.b.)	h°	Hue angle
M _t	Moisture content at time t	BI	Browning index
M _e	Equilibrium moisture content	BI ₀	Initial browning index
L*	Lightness	RGB	Red–green–blue colour space
T	Temperature (°C)	AR (1)	First-order autoregressive covariance structure
V	Air velocity (m s ⁻¹)	AIC	Akaike information criterion
t	Drying time (min)	BIC	Bayesian information criterion
a*	Redness–greenness coordinate	RMSE	Root mean square error
b*	Yellowness–blueness coordinate	MAE	Mean absolute error
L ₀	Initial lightness	R ²	Coefficient of determination
a ₀	Initial redness–greenness coordinate	R ² adj	Adjusted coefficient of determination
b ₀	Initial yellowness–blueness coordinate		

Introduction

Date palm (*Phoenix dactylifera* L.) fruit is an economically important agricultural commodity and a valuable source of carbohydrates, dietary fibre, minerals, and bioactive compounds. Depending on cultivar characteristics, climatic conditions, and market preferences, date fruits are harvested and consumed at different maturity stages, including the *khalal*, *rutab*, and *tamar* stages. At the *khalal* stage, fruits generally contain relatively high moisture contents and are therefore more susceptible to microbial deterioration and quality loss during storage. Consequently, dehydration is commonly used to reduce moisture content, extend shelf life, facilitate handling and transportation, and improve product stability. Drying, however, may induce substantial changes in the physical and sensory properties of date fruits (Kiumarsi Darbandi, Selahvarzi, Abedy, Kamali, & Sadrnia, 2025). Among these properties, colour is particularly important because consumers perceive it first and it strongly influences product acceptance and marketability (Lü, Chen, Li, Hu, & Bi, 2023). During drying, changes in lightness, redness, and yellowness may result from several simultaneous phenomena, including moisture removal, pigment degradation, enzymatic and non-enzymatic browning reactions, and structural modifications of the food matrix (Lü *et al.*, 2023; Tuly, Mahiuddin, & Karim, 2023). Therefore, monitoring the evolution of CIELAB colour parameters during drying is important for understanding quality deterioration and for identifying suitable drying conditions. Recent studies on food drying have increasingly emphasised the importance of achieving an appropriate balance between product quality retention, particularly colour and other quality attributes, and reductions in drying time and energy consumption (Bhattacharjee, Mohanty, Sahu, & Sahu, 2024; Nowacka, Matys, & Witrowa-Rajchert, 2024; Teymori-Omran, Askari Asli-Ardeh, Motevali, & Taghinezhad, 2026).

Conventional thermal drying methods can

effectively reduce the moisture content of agricultural products; however, exposure to elevated temperatures may accelerate undesirable quality changes, particularly discolouration and browning. In this context, electrohydrodynamic (EHD) drying has attracted considerable attention as an emerging drying technology. In EHD drying, a high-voltage electric field generates a corona wind that enhances heat and mass transfer near the product surface. This technology can operate under relatively mild thermal conditions and has been investigated for its potential to improve drying efficiency while maintaining product quality. Recent reviews have highlighted EHD drying's potential to improve energy efficiency while preserving sensory quality and heat-sensitive nutrients compared with conventional thermal drying (Martynenko, Bashkir, & Kudra, 2021; Onwude, Iranshahi, Martynenko, & Defraeye, 2021; Prakasha, Vinay, Pandey, & Bhoi, 2025). However, these reviews have also highlighted important research needs in EHD drying. These include a better understanding of coupled transport mechanisms, improved dryer design, and safe and efficient scale-up of EHD systems (Ham *et al.*, 2024; Onwude *et al.*, 2021). The drying behaviour and quality evolution of food products are influenced by several process variables, including drying temperature, air velocity, and drying time. These factors may affect not only the rate of moisture removal but also the progression of colour changes throughout the drying process. Different drying conditions can produce similar moisture states at different times. Thus, relating quality changes to the moisture state rather than drying time alone may provide a more meaningful basis for comparing drying processes.

These considerations highlight the need for approaches that can relate quality changes to the drying state. Mathematical modelling is an important tool for describing quality changes and predicting product behaviour under different drying conditions. However, few studies have modelled the continuous evolution of individual CIELAB parameters as a function

of drying conditions and MR. Such models can provide useful information for process monitoring, optimisation, and the development of intelligent drying systems. Previous studies have shown the potential of mathematical modelling to describe and predict colour changes in foods during drying (Chen & Pan, 2023; Tuly *et al.*, 2023). However, the coupling among drying conditions, moisture removal, and the evolution of individual colour attributes remains insufficiently understood. Further research is, therefore, needed to develop robust predictive models. Despite the growing interest in EHD-assisted food drying, the evolution of individual colour attributes in relation to both drying conditions and moisture removal has received comparatively limited attention. In particular, the independent and interactive effects of drying temperature, air velocity, and drying time on individual CIELAB colour coordinates and derived colour indices remain insufficiently explored. Their predictive modelling as a function of MR has also received limited attention. Therefore, the present study investigated the evolution of colour quality in date slices during drying under different temperatures and air-velocity conditions. The relative CIELAB coordinates, including lightness (L^*/L_0), redness (a^*/a_0), and yellowness (b^*/b_0), as well as total colour difference (ΔE), chroma (C^*), hue angle (h°), and relative browning index (BI/BI_0), were systematically evaluated. Statistical analysis quantified the individual and interactive effects of the drying variables. Mathematical modelling was used to develop predictive relationships between the selected colour parameters and MR under different drying conditions.

The novelty of this study lies in linking the continuous evolution of colour quality to the moisture state of the product during EHD-assisted drying. This approach goes beyond evaluating colour only at selected drying times or comparing initial and final colour values. By relating colour changes to moisture ratio under different drying conditions, the study provides an interpretable framework for predicting colour evolution during the drying process.

This framework may support non-destructive process monitoring and future optimisation of colour quality.

Materials and Methods

The experimental setup and operating conditions of the EHD-assisted drying system have been described in detail in previous studies (Keramat-Jahromi, Mohtasebi, Musazade, Ghasemi-Varnamkhasti, & Nasiri, 2018; Keramat-Jahromi, Mohtasebi, Mousazadeh, Ghasemi-Varnamkhasti, & Rahimi-Movassagh, 2021). The 2018 study investigated the drying kinetics and mathematical modelling of Shahani date slices under EHD, hot-air, and hybrid EHD–hot-air conditions, whereas the 2021 study focused on real-time estimation of moisture ratio from online image attributes using k-nearest neighbour and random forest regression models. In the present study, we used the same experimental platform to investigate colour evolution during drying, emphasising the effects of drying conditions and moisture removal on CIELAB colour parameters and derived colour indices.

Raw material and sample preparation

Fresh Shahani date fruits at the *Khalal* stage were harvested randomly from date palm orchards in Jahrom, Fars Province, Iran. The initial moisture content of the date samples was determined using the standard oven-drying method at 105 °C until a constant weight was reached and was approximately 60% on a wet basis (w.b.). Immediately after harvesting, the fruits were placed in polyethylene bags and stored under refrigerated conditions at approximately 5 °C to minimise physiological and biochemical changes before the experiments. Prior to each drying experiment, the samples were allowed to equilibrate at room temperature for approximately 3 h. The date fruits were then sliced with an electric deli meat slicer (Maysan, model MMS-275) to obtain thin, relatively uniform slices approximately 3 mm thick. Approximately 10 g of sliced date material was used in each experimental run.

Drying system and experimental procedure

The drying experiments were conducted using a laboratory-scale electrohydrodynamic (EHD)-assisted drying system integrated with forced convection (Fig. 1). The experimental setup consisted of an EHD chamber, a high-voltage DC power supply, a needle-to-plate electrode configuration, an airflow and temperature control system, an online machine vision system, and a data acquisition unit. The EHD chamber was constructed from 5-mm-thick Plexiglas sheets and had internal dimensions of $340 \times 270 \times 270 \text{ mm}^3$. A high-voltage DC power supply (Fanavaran Nanoscale, Iran), with an adjustable output range of 0–50 kV and a maximum output power of 35 W, was used to generate the electric field. The applied voltage was maintained at 50 kV throughout the drying experiments. The electrode system consisted of a needle discharge electrode positioned above a grounded copper plate. The discharge electrode comprised 25 chromium-coated stainless-steel needles, each 40 mm long, arranged in a square array with 25 mm centre-to-centre spacing. An $18 \times 18 \text{ cm}^2$ copper plate served as the grounded electrode. Airflow was generated using a centrifugal blower (Guangdong Shunde Electric Motor Co., Ltd.) with adjustable rotational speed. The blower was operated at 1400 rpm and 23 W and connected to a rectangular outlet duct measuring $25 \times 10 \text{ cm}^2$. A 1500 W heater ($198 \times 35 \times 38 \text{ mm}^3$) was installed downstream of the blower to provide the required drying-air temperature. Air velocity was measured using a hot-wire anemometer (Testo SE & Co. KGaA, Lenzkirch, Germany) with a resolution of 0.01 m s^{-1} and an accuracy of $\pm 0.1 \text{ m s}^{-1}$. Forced convection was supplied to the drying chamber at air velocities of 0.5, 1.0, and 1.5 m s^{-1} , while the drying-air temperature was controlled at 25, 35, and 60°C . Shahani date slices were placed in a single layer on the sample holder within the treatment zone. The variation in sample mass during drying was monitored using a high-precision electronic balance (GF-3000, A&D Co., Japan) with a measurement capacity of 610

g and a resolution of 0.001 g. The balance was interfaced with a computer for automatic acquisition and storage of mass data throughout the drying process. Sample mass was recorded at 300 s intervals and used to monitor moisture removal and determine the MR. Air conditions were monitored at the inlet and outlet regions of the drying chamber. Air temperature and relative humidity were measured using digital DHT22 (AM2302) sensors. Sensor signals were acquired through an Arduino MEGA 2560 microcontroller and transferred to a computer-based data acquisition system for real-time visualisation and storage. Air velocity was maintained at the prescribed experimental level throughout each drying run. The continuously recorded mass data were used to determine the moisture content and MR throughout the drying process. The moisture ratio (MR) was calculated on a wet basis as:

$$MR = \frac{M_t - M_e}{M_o - M_e} \quad (1)$$

where M_t is the moisture content at time t , M_o is the initial moisture content, and M_e is the equilibrium moisture content. Because the equilibrium moisture content was considered negligible relative to the initial moisture content under the experimental drying conditions, M_e was neglected. Therefore, the moisture ratio was simplified to (Moradi, Fallahi, & Mousavi Khaneghah, 2020; Yousefi, Niakosari, & Moradi, 2013):

$$MR = \frac{M_t}{M_o} \quad (2)$$

where both M_t and M_o were expressed on a wet basis. Under the present experimental conditions, the initial moisture content was approximately 60% (wet basis), and the drying process was terminated at approximately 12% (wet basis), corresponding to an MR of approximately 0.20. This definition should be considered when comparing the present MR values with those reported in conventional drying models, particularly when different moisture bases or non-negligible equilibrium moisture contents are used.

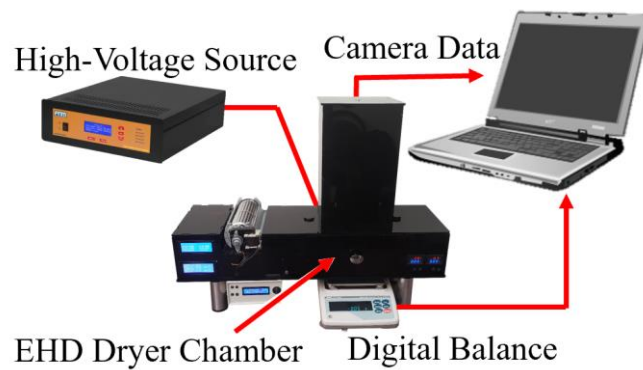


Fig. 1. Schematic of the drying system

Online image acquisition system

An online machine vision system was developed to monitor the samples during drying. The system consisted of a digital camera, an illumination system, a computer, and a custom-developed graphical user interface for image acquisition, data recording, and process monitoring. A Microsoft LifeCam camera (Microsoft Corporation, USA) with an image resolution of 960×544 pixels was positioned vertically above the centre of the sample tray at a distance of approximately 30 cm. The camera was connected to the computer through a USB interface and was used to acquire top-view images of the date slices during drying. To ensure consistent illumination among experimental runs, LED lamps were used as the light source. The illumination intensity was controlled using a pulse-width modulation system to maintain stable imaging conditions. The light source was positioned above the sample tray at an angle of approximately 45° relative to the horizontal plane. The developed software enabled automatic online image acquisition at predefined time intervals. Images were captured at 300-s intervals throughout the drying process and stored for subsequent processing and analysis. The graphical user interface simultaneously recorded image data and received mass measurements from the weighing system, enabling real-time monitoring of MR. Digital images of the samples were acquired in JPEG format with a resolution of 960×544 pixels.

Image preprocessing and sample segmentation

The acquired colour images were processed using custom-developed algorithms implemented in MATLAB R2024a. Before colour analysis, the images were preprocessed to isolate the date slices from the background and reduce the influence of irrelevant regions. Threshold values were determined from the image histograms and used to separate the sample from the background. Morphological opening and closing were then applied to remove small artefacts and fill holes in the segmented regions. The resulting binary mask was applied to the colour images to remove the background, and only pixels within the segmented date slices were retained for subsequent colour analysis.

Camera calibration and colour conversion

To improve the accuracy and consistency of image-derived colour values, the imaging system was calibrated using a 24-colour reference chart. The reference chart was imaged under the same camera position and illumination conditions used for the drying experiments. Colour values were extracted from the reference patches using the image-processing procedure and compared with the corresponding standard CIELAB values provided for the chart. Calibration relationships were then established to minimise the differences between the image-derived and reference colour values. The resulting calibration equations were subsequently applied to the date-slice images. The RGB image data were converted to the CIELAB colour space, which provides an approximately

perceptually uniform representation of colour and separates lightness from chromatic information. The three principal CIELAB coordinates were considered: L^* , representing lightness; a^* , representing the red–green chromatic coordinate; and b^* , representing the yellow–blue chromatic coordinate. For each image, the mean L^* , a^* , and b^* values of the segmented sample pixels were calculated and used for subsequent colour analysis.

Colour measurement and calculation of colour indices

The evolution of colour during drying was evaluated using the CIELAB colour coordinates L^* , a^* , and b^* . To reduce the influence of the initial colour variability among samples and experimental replicates, the CIELAB coordinates were normalised to their initial values: L^*/L_0 , a^*/a_0 , and b^*/b_0 , representing relative lightness, relative redness, and relative yellowness, respectively. Accordingly, 1 represents the initial colour, whereas values above or below 1 indicate increases or decreases, respectively. In addition to the individual CIELAB coordinates, several derived colour indices were calculated to provide a more comprehensive characterisation of colour changes. The ΔE was calculated as:

$$\Delta E = \sqrt{(L^* - L_0^*)^2 + (a^* - a_0^*)^2 + (b^* - b_0^*)^2} \quad (3)$$

C^* was calculated as:

$$C^* = \sqrt{a^{*2} + b^{*2}} \quad (4)$$

The h° was calculated as:

$$h^\circ = \tan^{-1}\left(\frac{b^*}{a^*}\right) \quad (5)$$

with appropriate quadrant correction where required.

The browning index (BI) was calculated according to the standard CIELAB-based relationship:

$$BI = \frac{100(x-0.31)}{0.172} \quad (6)$$

where:

$$x = \frac{a^* + 1.75L^*}{5.645L^* + a^* - 3.012b^*} \quad (7)$$

All colour parameters were determined from the mean values obtained from the segmented sample regions.

Experimental design and statistical analysis

Drying experiments were conducted at three drying-air temperatures (25, 35, and 60 °C) and three air velocities (0.5, 1.0, and 1.5 m s⁻¹), with three independent replicates for each treatment combination. The experiments conducted at 60 °C were considered a hybrid electrohydrodynamic–hot-air drying process. The effects of drying temperature, air velocity, and drying time on the relative CIELAB colour parameters were evaluated using linear mixed-effects models. Drying temperature and air velocity were treated as fixed experimental factors, whereas drying time was treated as a repeated within-unit factor because colour measurements were repeatedly obtained from the same experimental unit throughout the drying process. A unique subject identifier was assigned to each experimental unit to account for the correlation among repeated observations obtained under the same drying condition and experimental replication. The fixed-effects structure included the main effects of drying temperature, air velocity, and drying time, as well as all possible two-way and three-way interactions among these factors. The general model structure was expressed as:

$$Y = \mu + T + V + t + (T \times V) + (T \times t) + (V \times t) + (T \times V \times t) + u + \varepsilon \quad (8)$$

where Y represents the response variable, T , V , and t denote drying temperature, air velocity, and drying time, respectively; u represents the random effect associated with the experimental unit; and ε is the residual error. Several covariance structures were evaluated, and the first-order autoregressive [AR (1)] structure was selected based on the lowest information criteria (AIC and BIC). The significance of fixed effects was evaluated using Type III tests. Statistical significance was set at $p < 0.05$. All statistical analyses were performed using IBM SPSS Statistics 16.0.

Mathematical modelling and prediction of colour evolution

Mathematical modelling was performed to describe and predict the evolution of colour parameters during drying as a function of the drying conditions and moisture removal.

Regression-based modelling was selected because it provides explicit mathematical relationships between the response variables and the processing variables, thereby facilitating the interpretation and practical application of the developed models. The primary response variables considered for model development were the relative CIELAB colour parameters, including relative lightness, relative redness, and relative yellowness. Drying temperature, air velocity, and MR were considered as predictor variables. For model development, the experimental responses were first averaged over the three replicates at each drying condition and sampling time. The resulting observations were randomly divided into training (80%) and validation (20%) datasets. Several regression structures, including linear, quadratic, cubic, and reduced cubic models, were developed using the training dataset. The candidate models were compared based on their predictive performance on the validation dataset, goodness of fit, and model parsimony. The best-performing model structure was selected for each response and subsequently refitted using the complete dataset to obtain the final regression coefficients.

Candidate model development and selection

Several regression structures with different levels of complexity were evaluated to identify suitable relationships between the colour parameters and the predictor variables. The candidate models included linear, quadratic, cubic, and interaction terms involving drying temperature, air velocity, and MR. Model structures were simplified by removing terms that provided limited improvement in predictive performance. The final model for each response was selected by balancing goodness of fit, predictive performance, and parsimony. Model selection considered R^2 , adjusted R^2 , RMSE, MAE, predictive performance on the validation dataset, and the number of retained terms. This approach was used to obtain accurate, simple, and interpretable equations for describing colour evolution as a function of the drying variables.

Model performance evaluation

The performance of the selected model structures was evaluated separately using the training and validation datasets before final refitting. The R^2 , R^2_{adj} , RMSE, and MAE were used to assess model fit and predictive accuracy. The R^2 value was used to quantify the proportion of variation explained by the model and was calculated as follows (Sharifi, Hafezi, & Aghkhani, 2025):

$$R^2 = 1 - \frac{\sum_{i=1}^N (y_i - \hat{y}_i)^2}{\sum_{i=1}^N (y_i - \bar{y})^2} \quad (9)$$

The adjusted coefficient of determination was considered during model selection to account for the number of predictor terms included in the regression equation. The RMSE was calculated as follows (Sharifi et al., 2025):

$$RMSE = \left[\frac{1}{N} \sum_{i=1}^N (y_i - \hat{y}_i)^2 \right]^{0.5} \quad (10)$$

The MAE was calculated according to Namjoo, Moradi, Nematollahi, and Golbakhshi (2025):

$$MAE = \frac{1}{N} \sum_{i=1}^N |y_i - \hat{y}_i| \quad (11)$$

where y_i , $\hat{y}_i$, and $\bar{y}$ represent the observed value, predicted value, and mean observed value, respectively, and N is the number of observations. The training dataset was used to establish the candidate regression relationships, whereas the validation dataset was used to assess the predictive performance of the candidate model structures. The final regression coefficients and corresponding mathematical equations are presented in the Results and Discussion section.

Results and Discussion

Effect of drying temperature and air velocity on drying time

Figure 2 illustrates the drying time required to reach the target MR (0.2) under the investigated conditions. Drying time decreased substantially as air temperature and air velocity increased. At 25 °C, increasing air velocity from 0.5 to 1.5 m s⁻¹ reduced drying time from 155 to 110 min, while at 35 °C it decreased from 125 to 95 min. The shortest drying times were obtained at 60 °C, decreasing from 55 min

at 0.5 m s^{-1} to 40 min at 1.5 m s^{-1} .

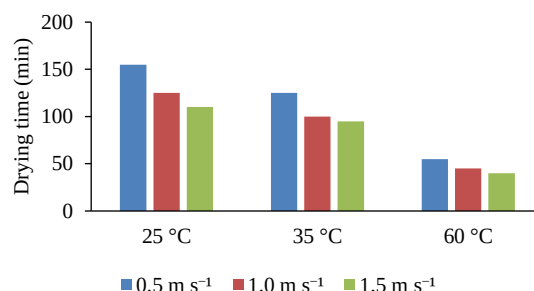


Fig. 2. Effect of air temperature and air velocity on the drying time required to reach an MR of 0.2

Temperature had the strongest effect on drying duration. Increasing the temperature from 25 to 60 °C reduced drying time by approximately 65% at 0.5 m s^{-1} and 64% at 1.5 m s^{-1} . Higher temperatures increased the driving force for moisture removal, whereas higher air velocity enhanced convective mass transfer at the product surface. These results highlight the combined role of thermal and convective conditions in controlling drying duration. These trends align with previous findings for convective and EHD-assisted drying systems. Corona wind can enhance external heat and mass transfer, while drying performance depends on the drying environment and the interaction between electrically induced and mechanically imposed airflow (Anukiruthika, Moses, & Anandharamakrishnan, 2021; Ham *et al.*, 2024). Comparable behaviour has also been reported for hybrid drying systems. Meng *et al.* (2022) reported that integrating EHD with hot-air drying reduced the drying time of fruit and vegetable slices compared with hot-air drying alone. Although direct quantitative comparisons are limited by differences in product characteristics, sample geometry, initial moisture content, electrode configuration, electric-field intensity, and drying endpoint, the overall trend is consistent with the present results: stronger thermal and convective driving forces accelerate moisture removal and shorten drying time. Differences in drying duration also affect product quality. Shorter drying times may reduce exposure to drying conditions, whereas higher temperatures

may simultaneously intensify undesirable colour changes. Therefore, Figure 2 provides an important basis for interpreting the subsequent evolution of CIELAB colour parameters and evaluating the trade-off between drying efficiency and colour preservation.

Effects of drying conditions on CIELAB colour parameters

The effects of drying temperature, air velocity, drying time, and their interactions on the relative CIELAB coordinates and derived colour indices are summarised in Table 1. The linear mixed-effects analysis showed that the responses differed in their sensitivity to the drying variables. Overall, drying time was the most consistently significant factor, affecting all three relative CIELAB coordinates, total ΔE , C^* , and browning index (BI), whereas h° was not significantly affected by any of the investigated factors or interactions. For relative lightness (L^*/L_0), neither temperature nor air velocity had a significant main effect ($p > 0.05$), whereas the temperature $\times$ time interaction was significant ($p < 0.001$). Thus, the effect of temperature on lightness was expressed primarily through its temporal trajectory rather than through a uniform difference in mean L^*/L_0 values. Similarly, relative yellowness (b^*/b_0) was significantly affected by drying time and by its interactions with temperature and air velocity, despite the absence of significant main effects of these two variables. These results indicate that drying conditions affected the temporal evolution of lightness and yellowness rather than their overall mean

levels. This behaviour is consistent with the dynamic nature of colour development during dehydration. Changes in moisture content and product structure may alter the optical properties of the material and, consequently, the measured colour parameters. As noted in a recent critical review, colour changes during fruit and vegetable drying can be associated with concurrent changes in moisture content and product structure, although the underlying mechanisms and their relative contributions depend on the drying conditions (Tuly *et al.*, 2023). Relative redness (a^*/a_0) showed the most complex response among the primary CIELAB coordinates. Temperature and drying time had significant effects, and significant temperature $\times$ time, velocity $\times$ time, and three-way interactions were also observed. These findings indicate that the evolution of redness depended on both the drying stage and the specific combination of temperature and air velocity. Notably, although air velocity had no significant main effect, it significantly modified the temporal evolution of relative redness. This suggests that the effect of air velocity on colour trajectory may be related partly to differences in drying kinetics and process duration. Similar behaviour has been reported in drying studies, where changes in drying conditions did not produce uniform responses across individual CIELAB coordinates, reflecting the different kinetics of colour evolution during drying (Lamadrid De Vela & Recidocruz Elepaño, 2024). Among the derived indices, ΔE was significantly affected by temperature and drying time, with additional significant temperature $\times$ time and three-way interactions. Because ΔE integrates simultaneous changes in L^*/L_0 , a^*/a_0 , and b^*/b_0 , these results indicate that the overall deviation from the initial colour developed differently according to both the drying environment and the drying stage. Consistent with this observation, Jia, Liu, and Xiao (2024) showed that drying conditions significantly affected colour kinetics in apple slices, with changes in colour responses observed across different drying temperatures and humidity-control conditions. Chroma

exhibited a comparatively simple response and was significantly affected only by drying time, suggesting that changes in colour saturation were more closely associated with drying progression than with the individual effects of temperature or air velocity within the investigated ranges. In contrast, h° was unaffected by any of the investigated variables or interactions. Therefore, although the magnitude of individual colour components changed during drying, the overall hue remained relatively stable. This difference between C^* and h° further demonstrates the value of evaluating multiple colour descriptors rather than relying on a single parameter. The BI/BI_0 was significantly affected by temperature and drying time, as well as their interaction, indicating that browning development depended on both the drying environment and process progression. This pattern is consistent with previous evidence that thermal exposure and drying conditions can contribute to discolouration during the dehydration of fruit and vegetable products (Lü *et al.*, 2023). However, because the underlying chemical changes were not directly measured in the present study, the observed changes in BI should be interpreted as colour responses rather than direct evidence of specific browning mechanisms. Overall, colour evolution during drying was both time-dependent and parameter-specific. Drying time exerted the most consistent influence, whereas temperature affected several responses, either directly or through its interaction with time. Although air velocity showed no significant main effect, its interactions with drying time significantly influenced relative redness and yellowness. These findings support previous research indicating that colour preservation depends on the combined effects of drying intensity and exposure duration rather than on individual operating variables alone. Gonçalves *et al.* (2023) similarly reported that drying time had a greater overall effect on product quality than temperature, while CIELAB colour parameters changed progressively during drying.

Table 1- Results of the mixed-model analysis of the effects of drying variables on colour parameters
Panel A. Relative CIELAB colour coordinates

Source of variation	F (L*/L ₀)	p (L*/L ₀)	F (a*/a ₀)	p (a*/a ₀)	F (b*/b ₀)	p (b*/b ₀)
T	1.083	0.359	8.740	0.002	0.427	0.659
V	0.871	0.435	1.750	0.199	0.646	0.536
t	8.409	<0.001	16.465	<0.001	5.791	<0.001
T × V	0.416	0.795	0.211	0.929	0.320	0.861
T × t	2.222	<0.001	5.134	<0.001	1.659	0.012
V × t	1.177	0.209	1.793	0.002	1.430	0.040
T × V × t	1.035	0.413	1.576	0.008	1.142	0.239

Panel B. Derived colour indices

Source of variation	F (ΔE)	p (ΔE)	F (C*)	p (C*)	F (h°)	p (h°)	F (BI/BI ₀)	p (BI/BI ₀)
T	8.308	0.002	0.491	0.62	1.687	0.201	5.939	0.010
V	0.077	0.926	0.984	0.392	1.211	0.311	0.697	0.510
t	15.846	<0.001	1.728	0.011	0.761	0.819	9.687	<0.001
T × V	0.9	0.48	0.281	0.887	1.610	0.195	0.241	0.912
T × t	4.885	<0.001	1.022	0.439	1.089	0.340	8.241	<0.001
V × t	0.664	0.956	1.125	0.275	0.833	0.775	1.259	0.129
T × V × t	1.737	0.002	0.753	0.902	1.358	0.055	1.051	0.384

T, V, and t denote drying temperature, air velocity, and drying time, respectively.

Interactive effects of drying temperature and time on relative CIELAB colour parameters

Figure 3 presents the temporal evolution of relative CIELAB colour parameters under different drying temperatures. Overall, relative lightness and yellowness decreased during drying, whereas relative redness increased. Because the target MR was reached at different times under each temperature condition, the curves illustrate both the magnitude and rate of colour evolution.

Relative lightness

As shown in Figure 3a, relative lightness generally decreased during drying at all temperatures, indicating progressive darkening relative to the initial state. The decline was most rapid at 60 °C, whereas changes occurred more gradually at 35 and 25 °C. At 25 °C, the decrease extended over the longest drying period and reached comparatively low values toward the end of drying. A localised increase in relative lightness was observed at an intermediate stage under the 25 °C condition. The measurements were rechecked and retained because no data processing or recording error was identified. Because the mechanisms

underlying this fluctuation were not directly investigated, its precise origin cannot be established. It may reflect transient changes in the optical properties of the sample surface during moisture removal. Despite this local variation, the overall trend remained downward. The reduction in lightness agrees with previous studies reporting substantial colour changes in fruit tissues during drying. [Dajbych, Kabutey, Mizera, and Herák \(2023\)](#) observed marked changes in the lightness of apple slices under different drying conditions, while alterations in the colour characteristics of dried date fruits have also been reported by [Elwakeel *et al.* \(2023\)](#) and [Hadibi *et al.* \(2024\)](#), with the extent of change depending on the drying method and operating conditions.

Relative redness

Figure 3 b shows the relative redness profiles. In contrast to lightness, a*/a₀ increased during drying at all temperatures. The increase was most rapid at 60 °C, exceeding 1.06 within about 50 min, whereas increases were more gradual at 35 and 25 °C. These results indicate that higher drying temperatures accelerated changes in the red–green colour component.

However, the different process durations should also be considered when comparing treatments, as lower-temperature conditions involved substantially longer exposure times. Previous studies likewise indicate that a^* can be particularly sensitive to drying conditions, although the direction and magnitude of the change are product-dependent. Variations in a^* during drying have been reported for apple and other plant materials under different drying methods, temperatures, and processing durations (Dajbych *et al.*, 2023; Getahun & Ebissa, 2024).

Relative yellowness

Figure 3c shows the evolution of relative yellowness during drying. The b^*/b_0 values generally decreased at all temperatures. The decline was rapid at 60 °C, reaching approximately 0.985 by the end of drying, whereas changes occurred more gradually at 35 °C. Under the 25 °C condition, the reduction extended over the longest drying period and reached the lowest values among the temperature treatments. A temporary increase was also observed at an intermediate stage at 25 °C. As with relative lightness, the measurements were verified and retained. Because this study did not directly investigate the underlying physical or chemical changes,

we cannot provide a definitive explanation for this localised variation. The overall decrease in relative yellowness is consistent with previous observations that the b^* coordinate can change considerably during dehydration, although its response depends strongly on product characteristics and drying conditions (Dajbych *et al.*, 2023; Elwakeel *et al.*, 2023). Overall, Figure 3 demonstrates that drying temperature influenced the temporal evolution of all three relative CIELAB coordinates. Higher temperatures accelerated the observed colour changes but also substantially shortened the drying period, whereas lower temperatures produced slower changes over longer exposure times. This highlights the trade-off between drying intensity and process duration: increasing the temperature may accelerate both moisture removal and colour evolution, while lower temperatures reduce the instantaneous rate of change but prolong the drying process. Similar trade-offs between drying efficiency and quality retention have been reported in fruit drying studies (Getahun & Ebissa, 2024; Hadibi *et al.*, 2024). Therefore, the complete temporal profiles provide more informative evidence of colour evolution than considering drying temperature or drying time independently.

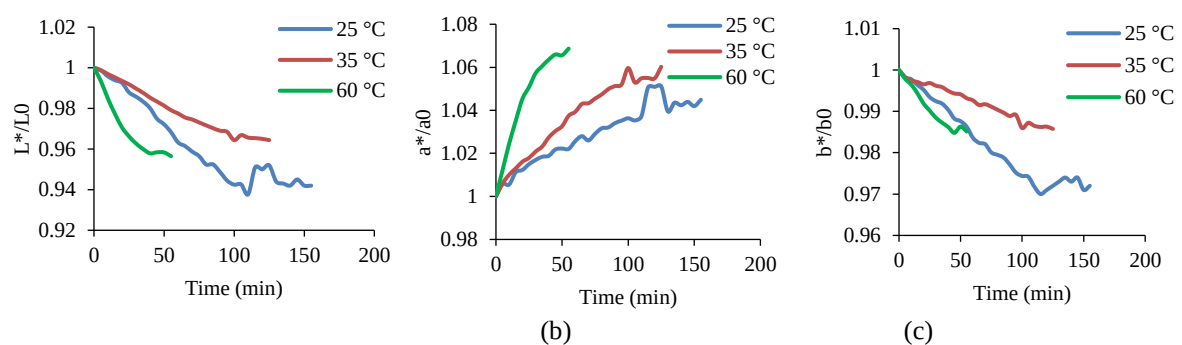


Fig. 3. Interaction between drying temperature and drying time on the relative CIELAB colour parameters: (a) relative lightness (L^*/L_0), (b) relative redness (a^*/a_0), and (c) relative yellowness (b^*/b_0)

Interactive effects of air velocity and drying time on relative CIELAB colour parameters

The interactive effects of air velocity and drying time on relative redness and relative

yellowness are presented in Figure 4. The results show that the influence of air velocity on colour development depended on the stage of drying rather than producing a uniform

response throughout the process.

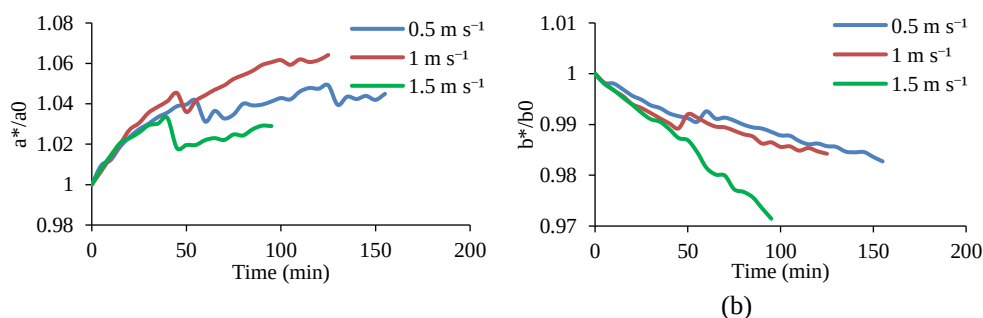


Fig. 4. Interactive effects of air velocity and drying time on the relative CIELAB colour parameters: (a) relative redness (a^*/a_0) and (b) relative yellowness (b^*/b_0)

Relative redness

As shown in Figure 4a, relative redness generally increased during drying at all air velocities, although its magnitude and temporal pattern differed among treatments. The trajectories were relatively similar at the beginning of drying, with clearer differences emerging later. The intermediate air velocity of 1.0 m s^{-1} generally produced the highest relative a^* values during the later stages, whereas the responses at 0.5 and 1.5 m s^{-1} followed different trajectories. The absence of a monotonic relationship between air velocity and relative redness indicates that airflow intensity alone did not determine the observed response. Instead, changes in air velocity altered the drying history by modifying external moisture transfer and the time required to reach successive drying stages. The resulting colour response therefore reflected the combined effects of airflow and drying progression. Direct comparison with studies specifically examining air-velocity effects should, nevertheless, be made cautiously. Polat (2024a) maintained the air velocity at 1.5 m s^{-1} while varying temperature, electric-field strength, and drying method, and therefore did not directly quantify the effect of air velocity on redness. However, the study showed that individual CIELAB coordinates responded differently to EHD, hot-air, and hybrid EHD-hot-air treatments. Similarly, Polat (2024b) reported higher a^* values for strawberry slices under combined EHD-hot-air drying than under EHD or hot-air drying alone. Although the operating conditions differed from those investigated

here, these findings support the interpretation that redness is not necessarily proportional to the intensity of a single processing variable. Accordingly, the increase in relative redness observed in the present study should be interpreted as a condition- and time-dependent colour response rather than being attributed to a specific chemical mechanism that was not directly measured.

Relative yellowness

As illustrated in Figure 4b, relative yellowness decreased progressively under all air-velocity conditions, although the trajectories diverged during the later stages of drying. The decline in b^*/b_0 was most pronounced at 1.5 m s^{-1} , whereas the reductions at 0.5 and 1.0 m s^{-1} were more gradual. This pattern indicates that the highest air velocity accelerated the temporal reduction in the yellow colour component under the investigated conditions. However, because higher air velocity also enhanced convective mass transfer and shortened drying time, the response cannot be attributed to airflow intensity alone. Rather, the observed b^* trajectories reflected the different moisture-removal histories associated with each air-velocity condition. In the peach study of Polat (2024a), air velocity was fixed at 1.5 m s^{-1} , but b^* varied significantly with other processing variables. Specifically, b^* decreased with increasing electric-field strength during EHD drying, whereas the relationship with temperature differed under hot-air drying. These results demonstrate that increasing the intensity of a

drying treatment does not necessarily produce a uniform response in yellowness across different drying configurations. Comparable complexity was reported by Moradi, Raeesi, Rashidi, and Keramat-Jahromi (2026) for apple slices, where drying temperature and sample thickness significantly affected colour-related quality. However, the shortest drying time at the highest temperature did not necessarily produce the greatest overall colour deterioration. One high-temperature condition resulted in the lowest ΔE . This finding supports the interpretation that colour quality depends on the balance between drying intensity and exposure duration rather than on a single processing variable. Comparable product-dependent responses have also been reported for other dried fruits. Han et al. (2025), for example, observed an increase in Δb^* during hot-air–infrared drying of banana slices. This contrasts with the progressive reduction in relative b^* observed here and further demonstrates that the direction of yellowness changes depends on the product and drying technology. Overall, Figure 4 demonstrates that air velocity modified the temporal evolution of relative redness and yellowness, but the responses were not proportional to airflow intensity. The intermediate velocity produced comparatively higher relative redness during the later stages of drying, whereas the highest velocity was associated with the greatest reduction in relative yellowness.

Interactive effects of drying temperature and time on total colour difference

The interactive effects of drying temperature and time on ΔE are presented in Figure 5. ΔE increased progressively at all temperatures, indicating an increasing deviation from the initial colour; however, both the rate and magnitude of this change depended on temperature. The most rapid increase was observed at 60 °C, where ΔE reached approximately 0.98 within about 55 min. At 35 °C, ΔE increased more gradually and reached approximately 0.87 after about 125 min,

whereas at 25 °C it developed most slowly, reaching approximately 0.76 at the end of drying. Thus, increasing temperature accelerated the overall colour change despite substantially shortening the drying period. Under the present conditions, the greater drying intensity at 60 °C appeared to outweigh the potential benefit of reduced exposure time. A similar temperature-dependent deterioration of colour was reported by Getahun and Ebissa (2024) for red chilli peppers dried in a hot-air cabinet dryer at 40–60 °C. They reported greater colour deterioration with increasing drying temperature, with a ΔE value of 4.1 under the optimum condition of 50 °C and 35% relative humidity. In the present study, ΔE increased progressively during drying and reached approximately 0.76, 0.87, and 0.98 at 25, 35, and 60 °C, respectively. Both studies showed greater colour changes at higher drying temperatures. However, the magnitude of ΔE cannot be directly compared because the products, drying methods, and experimental conditions differed. The present results further demonstrate the temporal evolution of colour change rather than only the final colour difference.

Nowicka, Lech, and Wojdyło (2025) reported substantial differences in ΔE among conventionally dried peach samples, with prolonged hot-air treatments producing markedly greater colour differences than freeze drying. Similarly, Hadibi et al. (2024) showed that drying temperature and airflow jointly influenced both drying performance and ΔE in date fruits. Together, these findings indicate that the colour change reflects the combined effects of drying intensity and exposure duration, with their relative importance depending on the product and drying configuration. Overall, Figure 5 shows that shortening drying time does not necessarily ensure better colour preservation. Within the investigated conditions, the higher temperature was associated with a faster and greater increase in ΔE despite the shorter drying time.

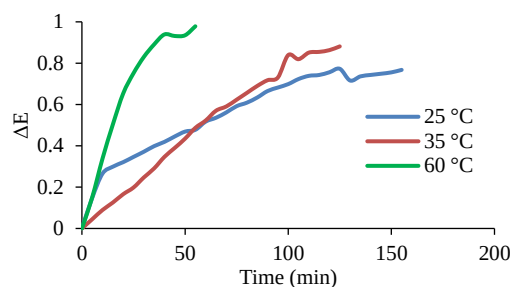


Fig. 5. Interactive effects of drying temperature and time on ΔE

Interactive effects of drying temperature and time on browning index

The interactive effects of drying temperature and time on the BI/BI_0 are presented in Figure 6. BI/BI_0 increased under all temperature conditions, although both the rate and magnitude of the increase differed among treatments. At 60 °C, BI/BI_0 increased rapidly to approximately 1.05 during the relatively short drying period. At 35 °C, browning developed more gradually but reached approximately 1.04 by the end of drying. In contrast, BI/BI_0 remained close to 1.02 at 25 °C despite the substantially longer drying duration. These results indicate that prolonged exposure at the lowest temperature did not produce browning comparable to that observed under the higher-temperature conditions. These trajectories provide a practical illustration of the significant temperature $\times$ time interaction identified by the mixed-effects analysis. Temperature influenced not only the final extent of browning but also the rate at which it developed. Under the present conditions, the greater thermal intensity at 60 °C appeared to outweigh the shorter processing time, whereas the prolonged drying period at 25 °C resulted in only limited changes in BI/BI_0 . Similar interactions between drying intensity and exposure time have been reported previously.

Sun, Wang, Wang, and Ren (2024) showed that the CIELAB colour response of Hami melon slices depended on both drying temperature and duration, with more pronounced colour changes occurring under conditions of higher thermal intensity or prolonged exposure. Likewise, Bulantekin and Kuşçu (2024) reported greater colour changes during the relatively prolonged hot-air drying of apple compared with faster microwave-vacuum treatments. Guan *et al.* (2024) reported that EHD drying better preserved the surface colour of apricot abalone mushrooms than hot-air and natural-air drying. Although these studies differ in product and drying technology, they support the present finding that browning cannot be explained by temperature or drying duration alone. Instead, it reflects their combined influence on the drying history of the product. Nevertheless, because the chemical pathways responsible for browning were not directly measured, the present results should not be interpreted as evidence of a specific reaction mechanism. The increase in BI/BI_0 should therefore be regarded primarily as an instrumental indication of progressive browning. Overall, Figure 6 shows that higher drying temperatures accelerated browning development, whereas drying time alone did not determine its magnitude.

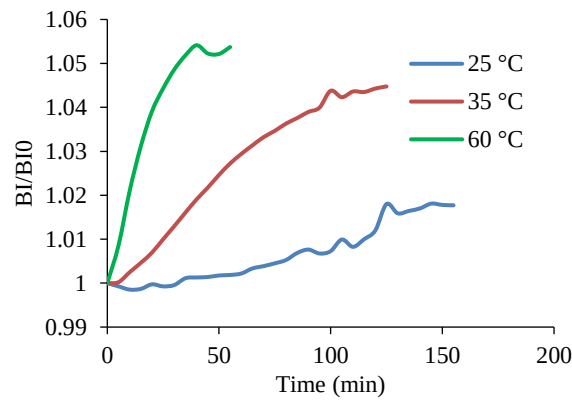


Fig. 6. Interactive effects of drying temperature and drying time on the BI/BI₀

Mathematical modelling of colour responses

Polynomial regression models were developed to predict the normalised CIELAB coordinates (L^*/L_0 , a^*/a_0 , and b^*/b_0), ΔE , C^* , h° , and BI/BI₀ as functions of MR, drying temperature, and air velocity. After model

selection and validation, the selected models were refitted using the complete dataset. The resulting regression coefficients are presented in Table 2. The predictive performance of the models is summarised in Table 3.

Table 2- Regression coefficients of the selected polynomial models for predicting normalised CIELAB colour parameters and colour indices

Term	L^*/L_0	a^*/a_0	b^*/b_0	ΔE	C^*	h°	BI/BI ₀
Intercept	0.866	0.983	0.962	0.702	0.960	-0.662	0.966
MR	0.266	—	0.135	-0.841	0.017	-0.419	—
T	0.001	0.002	—	0.023	0.002	0.058	0.003
V	—	0.134	-0.041	1.159	—	1.911	0.033
MR ²	—	—	-0.014	—	—	—	—
T ²	—	—	—	—	-2.473×10^{-5}	—	—
V ²	-0.136	—	-0.062	—	0.053	—	—
MR $\times$ T	-0.010	-0.001	-0.005	-0.016	—	0.007	-0.002
MR $\times$ V	—	-0.136	—	—	—	0.316	-0.059
T $\times$ V	0.008	-0.004	0.005	-0.079	-0.002	-0.083	—
MR ³	-0.011	0.022	—	0.246	—	0.065	0.072
T ³	—	-7.613×10^{-8}	2.369×10^{-8}	-3.370×10^{-6}	—	-7.192×10^{-6}	-3.235×10^{-7}
V ³	-0.004	-0.066	—	—	0.008	-0.250	-0.058
MR ² $\times$ T	—	—	—	—	-9.252×10^{-5}	—	-0.002
MR ² $\times$ V	-0.033	-0.022	-0.008	—	—	—	-0.029
MR $\times$ T ²	1.246×10^{-4}	1.612×10^{-5}	6.906×10^{-5}	—	-9.614×10^{-6}	—	6.056×10^{-5}
MR $\times$ T $\times$ V	-0.002	-0.001	-0.001	—	0.001	-0.006	-0.002
MR $\times$ V ²	0.065	0.117	0.036	0.106	-0.037	—	0.105
T ² $\times$ V	-1.297×10^{-4}	—	-6.866×10^{-5}	0.001	4.086×10^{-5}	0.001	-2.491×10^{-5}
T $\times$ V ²	0.002	0.002	0.001	—	-0.001	0.015	0.002

Table 3- Predictive performance of the selected polynomial models for normalised CIELAB colour parameters and

Response variable	No. of terms	colour indices						
		R ² (Train)	R ² (validation)	R ² (Total)	RMSE (train)	RMSE (validation)	MAE (Train)	MAE (validation)
L*/L ₀	14	0.8882	0.8717	0.8872	0.00733	0.00777	0.00593	0.00614
a*/a ₀	14	0.9710	0.9490	0.9682	0.00344	0.00349	0.00269	0.00282
b*/b ₀	14	0.8757	0.8837	0.8790	0.00349	0.00353	0.00266	0.00269
ΔE	10	0.9243	0.8995	0.9220	0.07656	0.06375	0.06014	0.05148
C*	13	0.8882	0.8781	0.8860	0.00235	0.00292	0.00179	0.00226
h°	13	0.8584	0.9031	0.8675	0.03492	0.02844	0.02417	0.02293
BI/BI ₀	15	0.9430	0.9279	0.9402	0.00476	0.00520	0.00393	0.00445

Model performance and prediction of CIELAB responses

The selected polynomial models provided satisfactory predictive performance for all investigated colour responses (Table 3). Validation-set R² values ranged from 0.8717 for L*/L₀ to 0.9490 for a*/a₀. The relatively small differences between training and validation performance indicate a limited but apparent overfitting under the adopted data partition. Cubic polynomial structures were selected for most responses, whereas ΔE was adequately described by a reduced cubic model, indicating nonlinear relationships among MR, temperature, and air velocity within the investigated experimental range. Among the normalised CIELAB coordinates, a*/a₀ showed the highest predictive accuracy, with training and validation R² values of 0.9710 and 0.9490, respectively. The corresponding validation-set R² values for L*/L₀ and b*/b₀ were 0.8717 and 0.8837.

Prediction of derived colour indices and graphical validation

The derived colour indices were also

predicted satisfactorily. The validation-set R² values were 0.8995 for ΔE, 0.8781 for C*, 0.9031 for h°, and 0.9279 for BI/BI₀ (Table 3). BI/BI₀ showed particularly strong predictive performance, with training and validation R² values of 0.9430 and 0.9279, respectively, together with low validation RMSE (0.00520) and MAE (0.00445). The agreement between predicted and experimental values is illustrated in Figure 7. Most observations were distributed close to the 45° reference line, indicating good agreement between model predictions and measurements. Some deviations were observed at the extremes of the experimental ranges, but no pronounced systematic deviation from the 45° reference line was visually apparent. Thus, the graphical assessment supports the statistical indicators reported in Table 3.

For some responses, the validation dataset yielded slightly lower RMSE and MAE values than the training dataset. These differences can arise from the random 80/20 data partition and the different compositions and variability of the two subsets. Therefore, a lower validation error than the training error does not by itself indicate overfitting or model instability.

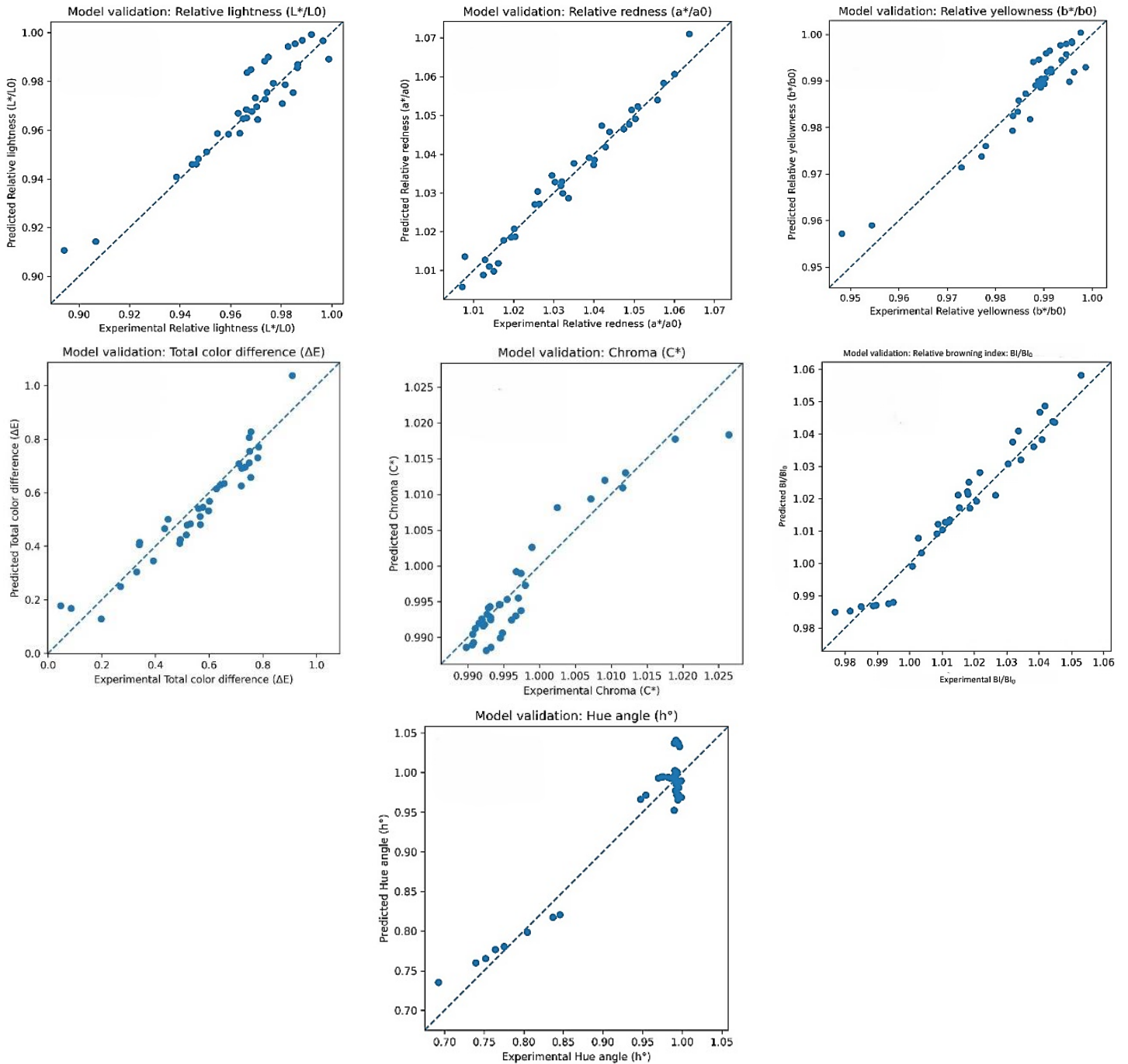


Fig. 7. Predicted versus experimental values for the modelled colour responses

Comparison with previous modelling approaches

Mathematical modelling in drying research has traditionally focused on MR or moisture content as functions of drying time and operating conditions. For example, [Al Faik et al. \(2024\)](#) compared conventional and semi-empirical models mainly for describing drying

kinetics and moisture removal. In contrast, the present study directly predicts multiple quality-related colour responses using MR together with temperature and air velocity. This approach accounts for both the drying state and processing conditions rather than relying solely on drying time. Recent studies have

increasingly combined predictive modelling with non-destructive quality monitoring. [Yu, Zheng, Wilson, Yu, and Young \(2024\)](#) integrated image analysis with multivariate and machine-learning methods to predict MR and evaluate appearance-related characteristics during kiwifruit drying. Similarly, [Azizi Ishkooh, Zareiforoush, and Bakhshipour \(2025\)](#) combined machine vision with response surface methodology to monitor and optimise colour change and other quality attributes. These studies demonstrate the potential of integrating image-based monitoring with predictive models for drying-process control. More complex machine-learning approaches can provide higher predictive accuracy but generally involve greater model complexity. [Rodríguez-Ortíz, García-Moreira, Vidaña, Alanis, and Moreno \(2026\)](#), for example, applied optimised neural-network models to predict CIELAB colour changes in solar-dried fruit and reported a very high predictive accuracy. The polynomial models developed in the present study provide a more explicit and interpretable alternative. Their analytical equations can be directly incorporated into process calculations and monitoring systems. The present findings also complement recent research on date drying. [Hadibi et al. \(2024\)](#) investigated hot-air drying of date fruit under different temperatures and airflow conditions and combined drying analysis with colour evaluation and response-surface optimisation. Their study integrated drying kinetics, colour evaluation, and process optimisation, whereas the present study focused on explicit predictive equations for the evolution of multiple image-derived colour parameters.

Practical implications

The developed equations can estimate colour attributes within the investigated ranges of MR, temperature, and air velocity. Combined with online machine vision, the proposed framework may support non-destructive process monitoring and future optimisation by considering colour quality alongside drying time and energy consumption.

Limitations and future research

The models were developed within a limited range of MR, temperature, and air velocity, and therefore require validation before application beyond these conditions. Averaging replicate observations reduced random variability but removed replicate-level variation from the modelling dataset. In addition, the random 80/20 split may not fully account for statistical dependence among observations from the same drying trajectory. Condition-wise, trajectory-wise, or leave-one-condition-out validation could provide a stronger assessment of model transferability. Finally, the models are empirical and do not explain the physicochemical mechanisms of colour change. Future studies should combine colour modelling with pigment, structural, and other physicochemical measurements and compare the present polynomial models with advanced machine-learning approaches using the same dataset. As suggested by [Li, Malvandi, Feng, and Shao \(2025\)](#), more flexible and uncertainty-aware methods may be beneficial with larger and more diverse datasets, although improvements in accuracy should be weighed against increased model complexity.

Conclusion

This study showed that colour evolution in Shahani date slices during EHD-assisted drying was strongly influenced by drying conditions and progress. Increasing temperature and air velocity reduced the time required to reach the target MR, with temperature having the strongest effect. Relative lightness and yellowness generally decreased, whereas relative redness, ΔE , and BI/BI_0 increased during drying. Mixed-effects analysis identified drying time as the most consistently significant factor, with several colour responses also showing significant interactions between drying conditions and time. Polynomial models based on MR, temperature, and air velocity provided satisfactory predictions, with validation-set R^2 values of 0.8717–0.9490 and the highest accuracy for relative redness. The integration of online machine vision, statistical analysis, and interpretable modelling provides a potential basis for non-destructive monitoring

and future process optimisation. However, the models should be applied only within the investigated experimental domain. Further validation under independent drying conditions, together with trajectory-based validation and physicochemical measurements, is needed to improve model transferability and clarify the mechanisms underlying colour changes.

Author Contributions

S. S. Mohtasebi: Supervision, Technical advice, Conceptualization, Methodology
M. Moradi: Software services, Text mining, Review and editing services, Statistical analysis Numerical/computer simulation
M. Keramat-Jahromi: Data acquisition, Data pre- and post- processing, Methodology

References

1. Al Faik, M. A., Roy, M., Azam, M. S., Ahmmed, R., Hoque, M. M., & Alam, M. M. (2024). Comprehensive study on potato drying in convective air dryer: Experimental observations, mathematical modeling, and model validation. *Measurement: Food*, 14, 100170. <https://doi.org/10.1016/j.meaf00.2024.100170>
2. Anukiruthika, T., Moses, P. J., & Anandharamakrishnan, P. C. (2021). Electrohydrodynamic drying of foods: Principle, applications, and prospects. *Journal of Food Engineering*, 295, 110449. <https://doi.org/10.1016/j.jfoodeng.2020.110449>
3. Azizi Ishkooh, S. A., Zareiforush, H., & Bakhshipour, A. (2025). Towards smart fruit dryers: Integrating machine vision and response surface methodology for multi-objective monitoring and optimization of kiwifruit drying process. *Applied Food Research*, 5(1), 100988. <https://doi.org/10.1016/j.afres.2025.100988>
4. Bhattacharjee, S., Mohanty, P., Sahu, J. K., & Sahu, J. N. (2024). A critical review on drying of food materials: Recent progress and key challenges. *International Communications in Heat and Mass Transfer*, 158, 107863. <https://doi.org/10.1016/j.icheatmasstransfer.2024.107863>
5. Bulantekin, Ö., & Kuşçu, A. (2024). Evaluation of microwave vacuum drying combined with explosion puffing drying and compared with microwave vacuum drying and hot-air drying by the quality of the dried apple slices. *Cogent Food & Agriculture*, 10(1), 2404699. <https://doi.org/10.1080/23311932.2024.2404699>
6. Chen, C., & Pan, Z. (2023). An overview of progress, challenges, needs and trends in mathematical modeling approaches in food drying. *Drying Technology*, 41(16), 2586–2605. <https://doi.org/10.1080/07373937.2023.2207636>
7. Dajbych, O., Kabutay, A., Mizera, Č., & Herák, D. (2023). Investigation of the effects of infrared and hot air oven drying methods on drying behaviour and colour parameters of red delicious apple slices. *Processes*, 11(10), 3027. <https://doi.org/10.3390/pr11103027>
8. Elwakeel, A. E., Wapet, D. E. M., Mahmoud, W. A. E. M., Abdallah, S. E., Mahmoud, M. M., Ardjoun, S. A. E. M., & Tantawy, A. A. (2023). Design and implementation of a PV-integrated solar dryer based on internet of things and date fruit quality monitoring and control. *International Journal of Energy Research*, 2023(1), 7425045. <https://doi.org/10.1155/2023/7425045>
9. Getahun, E., & Ebissa, D. T. (2024). Investigation of optimal drying conditions of red chili peppers in a hot air cabinet dryer. *Case Studies in Thermal Engineering*, 59, 104586. <https://doi.org/10.1016/j.csite.2024.104586>
10. Gonçalves, E. M., Pereira, N., Silva, M., Alvarenga, N., Ramos, A. C., Alegria, C., & Abreu, M. (2023). Influence of air-drying conditions on quality, bioactive composition and sensorial attributes of sweet potato chips. *Foods*, 12(6), 1198. <https://doi.org/10.3390/foods12061198>
11. Guan, P., Ding, C., Lu, J., Bai, W., Liu, J., Lian, J., ... & Jia, Y. (2024). Influence of electrohydrodynamics on the drying characteristics, microstructure and volatile composition of apricot abalone mushroom (*Pleurotus eryngii*). *Current Research in Food Science*, 9, 100856. <https://doi.org/10.1016/j.crfs.2024.100856>

12. Hadibi, T., Mennouche, D., Boubekri, A., Arıcı, M., Wang, Y., Li, M., ... & Shirkole, S. S. (2024). Experimental investigation, performance analysis, and optimization of hot air convective drying of date fruits via response surface methodology. *Renewable Energy*, 226, 120404. <https://doi.org/10.1016/j.renene.2024.120404>
13. Ham, J. C., Alawi, A., Rizki, Z., Boom, R. M., Garbin, V., Padding, J. T., & Schutyser, M. A. (2024). A multi-scale analysis on electrohydrodynamic drying technology for bio-based & food products. *Trends in Food Science & Technology*, 151, 104634. <https://doi.org/10.1016/j.tifs.2024.104634>
14. Han, G., Luo, C., Liu, X., Li, Y., Cheng, Y., Huang, S., & Huang, D. (2025). Drying characteristics and process optimization of banana slices using hot air-infrared combined drying. *Frontiers in Heat and Mass Transfer*, 23(6), 1981–1999. <https://doi.org/10.32604/fhmt.2025.074593>
15. Jia, Z., Liu, Y., & Xiao, H. (2024). Deep learning prediction of moisture and color kinetics of apple slices by long short-term memory as affected by blanching and hot-air drying conditions. *Processes*, 12(8), 1724. <https://doi.org/10.3390/pr12081724>
16. Keramat-Jahromi, M., Mohtasebi, S. S., Musazade, H., Ghasemi-Varnamkhasti, M., & Nasiri, A. (2018). Study and simulation drying kinetics of date fruit slices in a hybrid electrohydrodynamic-convective dryer. *Iranian Journal of Biosystem Engineering*, 49(3), 489–500. [in Persian]. <https://doi.org/10.22059/ijbse.2018.246556.665013>
17. Keramat-Jahromi, M., Mohtasebi, S. S., Mousazadeh, H., Ghasemi-Varnamkhasti, M., & Rahimi-Movassagh, M. (2021). Real-time moisture ratio study of drying date fruit chips based on on-line image attributes using kNN and random forest regression methods. *Measurement*, 172, 108899. <https://doi.org/10.1016/j.measurement.2020.108899>
18. Kiumarsi Darbandi, F., Selahvarzi, Y., Abedy, B., Kamali, M., & Sadrnia, H. (2025). Evaluating the Effects of Grape Harvest Time and Vacuum Drying on the Physicochemical Properties of White Seedless Quchan Raisin Cultivar. *Journal of Agricultural Machinery*, 15(4). [in Persian]. <https://doi.org/10.22067/jam.2024.87715.1241>
19. Lamadrid De Vela, R. J., & Recidocruz Elepaño, A. R. N. O. L. D. (2024). Drying and colour kinetics of decorticated queen pineapple (*Ananas comosus* L.) fibre bleached with a hydrogen peroxide solution. *Research in Agricultural Engineering*, 70(2), 73–81. <https://doi.org/10.17221/47/2023-RAE>
20. Li, S., Malvandi, A., Feng, H., & Shao, C. (2025). Uncertainty-aware constrained optimization for air convective drying of thin apple slices using machine-learning-based response surface methodology. *Journal of Food Engineering*, 394, 112503. <https://doi.org/10.1016/j.jfoodeng.2025.112503>
21. Lü, Y., Chen, Q., Li, X., Hu, J., & Bi, J. (2023). Recent progress in research on the effect of drying on the color of processed fruits and vegetables. *Food Science*, 44(13), 368–377. <https://doi.org/10.7506/spkx1002-6630-20220802-022>
22. Martynenko, A., Bashkir, I., & Kudra, T. (2021). The energy efficiency of electrohydrodynamic (EHD) drying of foods. *Trends in Food Science & Technology*, 118, 744–764. <https://doi.org/10.1016/j.tifs.2021.09.002>
23. Meng, Z., Cui, X., Liu, Y., Du, C., Hu, R., Wang, S., & Wang, F. (2022). Effect of electrohydrodynamics on hot air drying characteristics of fruits and vegetables. *Sustainable Energy Technologies and Assessments*, 53, 102716. <https://doi.org/10.1016/j.seta.2022.102716>
24. Moradi, M., Fallahi, M. A., & Mousavi Khaneghah, A. (2020). Kinetics and mathematical modeling of thin layer drying of mint leaves by a hot water recirculating solar dryer. *Journal of Food Process Engineering*, 43(1), e13181. <https://doi.org/10.1111/jfpe.13181>
25. Moradi, M., Raeesi, R., Rashidi, S., & Keramat-Jahromi, M. (2026). Predictive modeling of apple slice drying: Integrating temperature, thickness, and shrinkage dynamics. *PLOS ONE*, 21(3),

- e0341428. <https://doi.org/10.1371/journal.pone.0341428>
26. Namjoo, M., Moradi, M., Nematollahi, M. A., & Golbakhshi, H. (2025). Artificial neural network (ANN) modeling of plasma and ultrasound-assisted air drying of cumin seeds. *Journal of Agricultural Machinery*, 15(1), 1–22. <https://doi.org/10.22067/jam.2024.85744.1209>
 27. Nowacka, M., Matys, A., & Witrowa-Rajchert, D. (2024). Innovative technologies for improving the sustainability of the food drying industry. *Current Food Science and Technology Reports*, 2(2), 231–239. <https://doi.org/10.1007/s43555-024-00026-8>
 28. Nowicka, P., Lech, K., & Wojdyło, A. (2025). The influence of different drying techniques on polyphenols profile (LC–MS-PDA-Q/TOF) of peach fruit and their pro-health properties by in vitro. *Scientific Reports*, 15(1), 2623. <https://doi.org/10.1038/s41598-025-87003-w>
 29. Onwude, D. I., Iranshahi, K., Martynenko, A., & Defraeye, T. (2021). Electrohydrodynamic drying: Can we scale-up the technology to make dried fruits and vegetables more nutritious and appealing. *Comprehensive Reviews in Food Science and Food Safety*, 20(5), 5283–5313. <https://doi.org/10.1111/1541-4337.12799>
 30. Polat, A. (2024a). Analysis of drying characteristics and quality attributes in peach slices dried via electrohydrodynamic, hot air and electrohydrodynamic-hot air methods. *Journal of Thermal Analysis and Calorimetry*, 149(14), 7551–7563. <https://doi.org/10.1007/s10973-024-13292-4>
 31. Polat, A. (2024b). Drying strawberry slices: A comparative study of electrohydrodynamic, hot air, and electrohydrodynamic-hot air techniques. *Food Science & Nutrition*, 12(11), 9621–9631. <https://doi.org/10.1002/fsn3.4541>
 32. Prakasha, R., Vinay, G. M., Pandey, H., & Bhoi, P. M. (2025). Electrohydrodynamic drying: A comprehensive review of design considerations and quality effects on dried fruits and vegetables. *Journal of Food Process Engineering*, 48(1), e70029. <https://doi.org/10.1111/jfpe.70029>
 33. Rodríguez-Ortíz, D., García-Moreira, D. P., Vidaña, E. C. L., Alanis, A. Y., & Moreno, I. (2026). Predicting color change in solar-dried fruits using neural networks: A multilayer perception approach. *Journal of Stored Products Research*, 115, 102803. <https://doi.org/10.1016/j.jspr.2025.102803>
 34. Sharifi, S., Hafezi, N., & Aghkhani, M. H. (2025). Investigation, optimization of energy consumption and yield modeling of two paddy cultivars with genetic-artificial bee colony algorithm. *Journal of Agricultural Machinery*, 15(2), 145–164. [in Persian]. <https://doi.org/10.22067/jam.2022.77064.1108>
 35. Sun, T., Wang, N., Wang, C., & Ren, J. (2024). Effect of hot air temperature and slice thickness on the drying kinetics and quality of Hami melon (Cantaloupe) slices. *Scientific Reports*, 14(1), 29855. <https://doi.org/10.1038/s41598-024-81053-2>
 36. Teymori-Omran, M., Askari Asli-Ardeh, E., Motevali, A., & Taghinezhad, E. (2026). Evaluation of Energy Parameters and Pollutant Gases for Apple Drying in Refractance Window Solar Dryer Equipped with a PTC Solar Collector. *Journal of Agricultural Machinery*, 16(1), 119–135. <https://doi.org/10.22067/jam.2024.90300.1298>
 37. Tuly, S. S., Mahiuddin, M., & Karim, A. (2023). Mathematical modeling of nutritional, color, texture, and microbial activity changes in fruit and vegetables during drying: A critical review. *Critical Reviews in Food Science and Nutrition*, 63(13), 1877–1900. <https://doi.org/10.1080/10408398.2021.1969533>
 38. Yousefi, A. R., Niakosari, M., & Moradi, M. (2013). Microwave assisted hot air drying of papaya (*Carica papaya* L.) pretreated in osmotic solution. *African Journal of Agricultural Research*, 8(25), 3229–3235. <https://doi.org/10.5897/AJAR12.180>
 39. Yu, S., Zheng, H., Wilson, D. I., Yu, W., & Young, B. R. (2024). Integrating image analysis and machine learning for moisture prediction and appearance quality evaluation: A case study of kiwifruit drying pretreatment. *Foods*, 13(12), 1789. <https://doi.org/10.3390/foods13121789>

پایش رنگ و مدل سازی پیش بینی کننده برش های خرمای شاهانی طی خشک کردن به روش الکترو هیدرودینامیک

سید سعید محتسبی^۱، مهدی مرادی^{۲*}، مهدی کرامت جهرمی^۳

تاریخ دریافت: ۱۴۰۵/۰۶/۱۸

تاریخ پذیرش: ۱۴۰۵/۰۷/۱۹

چکیده

این پژوهش با هدف بررسی اثر دمای خشک کردن، سرعت هوا و زمان خشک کردن بر تکامل رنگ برش های خرمای شاهانی طی خشک کردن به روش الکترو هیدرودینامیک (EHD) همراه با جابه جایی اجباری انجام شد. آزمایش های خشک کردن در دماهای ۲۵، ۳۵ و ۶۰ درجه سلسیوس و سرعت های هوای ۰/۵، ۱/۰ و ۱/۵ متر بر ثانیه تا رسیدن رطوبت محصول به حدود ۱۲ درصد (بر پایه تر) انجام شدند. یک سامانه بینایی ماشین برخط، مختصات رنگ CIELAB شامل روشنایی (L^*)، قرمزی (a^*) و زردی (b^*)، اختلاف کلی رنگ (ΔE)، کروما، زاویه فام و شاخص قهوه ای شدن (BI) را در طول خشک کردن پایش کرد. به منظور تسهیل مقایسه تغییرات رنگ نسبت به حالت اولیه، از مقادیر نسبی روشنایی (L^*/L_0)، قرمزی (a^*/a_0)، زردی (b^*/b_0) و شاخص قهوه ای شدن (BI/BI₀) استفاده شد. اثرات اصلی و متقابل متغیرهای خشک کردن با استفاده از مدل های خطی آمیخته و مدل های رگرسیون چند جمله ای برای پیش بینی توسعه یافتند. با افزایش دما و سرعت هوا، زمان خشک کردن به طور محسوسی کاهش یافت و کوتاه ترین زمان در دمای ۶۰ درجه سلسیوس و سرعت هوای ۱/۵ متر بر ثانیه به دست آمد. تکامل رنگ وابسته به زمان و اختصاصی هر پارامتر بود؛ به طوری که مقادیر L^*/L_0 و b^*/b_0 عموماً کاهش یافتند، در حالی که قرمزی نسبی، ΔE و BI/BI₀ افزایش یافتند. اثرات متقابل معنی دار نشان دادند که اثر شرایط خشک کردن بر پاسخ های رنگی با مرحله خشک کردن تغییر می کند. مدل های پیش بینی کننده مبتنی بر نسبت رطوبت (MR)، دما و سرعت هوا، در مجموعه اعتبارسنجی مقادیر R^2 بین ۰/۸۷۱۷ تا ۰/۹۴۹۰ را به دست آوردند و مقادیر متناظر RMSE و MAE به ترتیب در محدوده ۰/۰۲۹۲-۰/۰۶۳۷۵ و ۰/۰۲۲۶-۰/۰۵۱۴۸ بودند. این نتایج نشان دهنده ظرفیت ترکیب پایش برخط رنگ با مدل های قلیل تفسیر برای پایش غیرمخرب فرایند و بهینه سازی آتی خشک کردن به روش الکترو هیدرودینامیک است.

واژه های کلیدی: بینایی ماشین، تکامل رنگ، رگرسیون چند جمله ای، نسبت رطوبت

۱- گروه مهندسی ماشین های کشاورزی، دانشکده مهندسی و فناوری کشاورزی، دانشگاه تهران، کرج، ایران

۲- گروه مهندسی بیوسیستم، دانشکده کشاورزی، دانشگاه فردوسی مشهد، مشهد، ایران

۳- بخش مهندسی بیوسیستم، دانشکده کشاورزی، دانشگاه شیراز، شیراز، ایران

(*)-نویسنده مسئول: Email: moradih@um.ac.ir, mahdikaramat@shirazu.ac.ir