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Evaluation of color quality and stability in celeriac slices dried by hot-air and vacuum using multivariate analysis

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Abstract: Physicochemical changes occurring during drying, especially affecting color attributes, structural integrity, and nutrient stability, remain critical factors influencing the final food quality. Although many drying studies focus on various vegetables, limited information exists regarding color alterations in celery, a plant with aromatic, medicinal, and functional food properties, under different drying conditions. This study was conducted to comparatively evaluate the effects of hot-air drying at 65 °C and vacuum drying (hot-air at 65 °C combined at 100 mm Hg) on the color parameters and visual quality of celeriac samples. Additionally, Principal Component Analysis (PCA) and Soft Independent Modeling of Class Analogy (SIMCA) analyses were conducted using color models. The results demonstrated that significant differences in L*, a*, b*, C*, and h values between fresh and dried samples depending on the drying method ($p < 0.05$). Hot-air drying led to a pronounced decrease in L*and b* values and noticeable darkening of the food due to oxidation reactions. In contrast, vacuum drying effectively minimized oxygen exposure and thermal damage, thereby preserving color quality at levels close to that of the fresh sample. The negative a* values observed in both fresh and vacuum-dried samples reflected the naturally light tones of celeriac, while the positive shift in a* values after hot-air drying indicated pigment degradation. Vacuum drying provided better preservation of color pigments. PCA, applied using the L*a*b*, L*Ch, and L*a*b*Ch color models, successfully distinguished the samples according to drying methods. PCA explained more than 95% of the variance, demonstrating its effectiveness in differentiating the effects of drying on color parameters. Furthermore, the SIMCA analysis revealed that celeriac slices obtained through different drying methods could be classified based on their color data with 100% accuracy. Present study highlights the superiority of vacuum drying in preserving the color quality of celeriac and offers valuable insights for the food industry in maintaining sensory and functional quality during drying processes.

Keywords: Celeriac chips, Celeriac root snacks, Color models, Dehydration, Functional foods, Multivariate data analysis, Vacuum drying

Sıcak hava ve vakumla kurutulan kereviz dilimlerinde renk kalitesi ve stabilitesinin çok değişkenli analizle değerlendirilmesi

Öz: Kurutma sırasında meydana gelen fizikokimyasal değişiklikler, özellikle renk özellikleri, yapısal bütünlük ve besin öğelerinin stabilitesi üzerinde etkili olup, nihai ürün kalitesini belirleyen kritik faktörler olarak öne çıkmaktadır. Çeşitli sebzeler üzerinde çok sayıda kurutma çalışması yapılmasına rağmen, aromatik, tıbbi ve fonksiyonel gıda özelliklerine sahip kereviz bitkisinde farklı kurutma koşullarının renk değişimleri üzerine sınırlı bilgi bulunmaktadır. Bu çalışmada, sıcak hava ile 65 °C'de kurutma ile vakum kurutma (65 °C sıcak hava ile desteklenmiş 100 mm Hg vakum kurutma) yöntemlerinin kereviz kökü örneklerinin renk parametreleri ve görsel kalitesi üzerindeki etkileri karşılaştırmalı olarak değerlendirilmiştir. Ayrıca renk modelleri kullanılarak Temel Bileşen Analizi (PCA) ve Sınıf Benzerliğinin Yumuşak Bağımsız Modellemesi (Soft Independent Modeling of Class Analogy / SIMCA) analizleri gerçekleştirilmiştir. Sonuçlar, kurutma yöntemine bağlı olarak taze ve kurutulmuş örnekler arasında L*, a*, b*, C* ve h değerlerinde anlamlı farklılıklar olduğunu göstermiştir ($p < 0.05$). Sıcak hava kurutması L* ve b* değerlerinde düşüşe ve ürün renginde koyulaşmaya neden olmuş, bu da oksidatif tepkimelere bağlanmıştır. Vakumlu kurutma ise oksijen maruziyetini ve ısıl zararı azaltarak renk kalitesini taze örneğe daha yakın seviyelerde korumuştur. Taze ve vakumla kurutulmuş örneklerde negatif a* değerleri kerevizin açık tonlarını

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yansıtırken, sıcak hava ile kurutmada gözlenen pozitif kayma pigment bozulmasına işaret etmiştir. PCA analizleri örnekleri kurutma yöntemlerine göre başarıyla ayırt etmiş ve toplam varyansın yüzde 95'inden fazlasını açıklamıştır. SIMCA analizi ise örneklerin renk verilerine dayanarak yüzde 100 doğrulukla sınıflandırılabildiğini göstermiştir. Elde edilen bulgular, kerevizde renk kalitesini korumada vakumlu kurutmanın üstünlüğünü ortaya koymakta ve gıda endüstrisine yönelik önemli çıkarımlar sunmaktadır.

Anahtar kelimeler: Çok değişkenli veri analizi, Fonksiyonel gıdalar, Kereviz cipsi, Kereviz kökü atıştırmalıkları, Kurutma, Renk modelleri, Vakum kurutma

1. Introduction

Celery (*Apium graveolens* L.), belonging to the Apiaceae family, serves as a versatile vegetable with edible roots, stems, and leaves. This species finds extensive applications in both culinary practices and traditional medicine. Native to the Mediterranean region, celeriac is now widely cultivated across Asia, Europe, and the Americas. The vegetable gains prominence in dietetics due to its low energy content and high water percentage. Moreover, celeriac contains essential micronutrients such as ascorbic acid (vitamin C), vitamin K, potassium, calcium, and folic acid, alongside dietary fibers like cellulose and pectin (Khalil et al., 2015; Tan et al., 2023). In addition, celeriac includes various bioactive compounds, including flavonoids (e.g., apigenin, luteolin), phthalides (sedanolide, 3-n-butylphthalide), and phenolic acids (caffeic acid, ferulic acid). These constituents support its classification as a functional food (El-Beltagi & Dhawi, 2020; Khairullah et al., 2021). The anti-inflammatory, antihypertensive, antioxidant, and antimicrobial properties attributed to these compounds have attracted considerable attention within modern pharmacological research.

Drying fresh vegetables offers advantages such as enabling year-round consumption, extending shelf life, and reducing transportation costs. However, the technical parameters applied during this process play a decisive role in determining food quality. Various factors, including the type of drying system employed (Sabarez, 2016), applied temperature or power levels, drying time (Mujumder et al., 2021), cultivars or genotypes (Aygun et al., 2022; Aygun & Mert, 2022), growing conditions (Arslan et al., 2023a), maturity stages (Soysal et al., 2018), and freshness can influence the final quality. Temperature level, duration, and atmospheric conditions during drying significantly influence the plant's tissue structure, volatile compounds, nutrients, and, most importantly, color parameters (Soysal, 2004; Soysal et al., 2006; Liu et al., 2020; Arslan et al., 2023b; Milić et al., 2024). Although traditional hot air drying methods remain widespread, exposure to high temperatures can cause degradation of chlorophyll and phenolic compounds. Conversely, low-pressure hybrid drying systems conducted under vacuum conditions minimize thermal degradation while preserving bioactive components at higher rates (Ahmed et al., 2022). Therefore, optimization of drying technologies holds critical importance, especially concerning consumer-focused quality criteria such as color, aroma, and nutritional value. Vacuum drying technology was developed to dry foods quickly at low temperatures while preserving their structure and heat-sensitive components. Vacuum dryers operate in a low-temperature vacuum environment, effectively preventing aroma alterations and other forms of damage that can result from high temperatures (Zia & Alibas, 2021). Compared to traditional drying techniques, convective or hot air drying offers advantages in energy efficiency, control, and time efficiency, resulting in more uniform drying. When adjusted to the optimal drying conditions specific to the food, convective drying can help preserve material quality by minimizing heat damage and degradation (Arslan & Alibas, 2024).

The type of drying method and its operational parameters serve as critical determinants of color stability. Conventional hot air drying tends to promote pigment degradation due to direct exposure to oxygen and elevated temperatures. In contrast, vacuum drying systems limit oxidative and thermal degradation by maintaining low oxygen pressure and controlled temperature conditions, thereby enabling more effective preservation of pigments (Ahmed et al., 2022). On the other hand, hot air drying offers notable advantages such as lower equipment costs, operational simplicity, suitability for high-capacity processing, and widespread industrial application. Moreover, for certain products, hot air drying may be more suitable for achieving desired crispness and textural properties. Therefore, the selection of an appropriate drying method should be based on product type, targeted quality attributes, and economic considerations. Tan et al. (2023) reported that vacuum drying better preserved the stability of flavonoids such as apigenin compared to hot air drying. Similarly, higher chlorophyll content and brightness values were observed under vacuum drying method. A low color difference (ΔE) value indicates that the processed food retains a closer resemblance to its original appearance, reflecting a higher perceived quality from the consumer's perspective (Soysal, 2004; Soysal et al., 2018; Arslan et al., 2023a).

Color changes during drying primarily occur through three major mechanisms: (1) enzymatic browning, (2) Maillard reactions, and (3) thermal degradation of pigments. Enzymatic browning arises from the oxidation of phenolic compounds to quinones, predominantly driven by polyphenol oxidase (PPO) activity. This reaction tends to occur prior to heating or under low-temperature drying conditions. In contrast, Maillard reactions—non-enzymatic interactions between carbonyl groups and amino acids—are promoted at elevated temperatures and may lead to darkening, particularly in vegetables with high protein content. Additionally, degradation of heat- and oxygen-sensitive pigments such as chlorophylls, carotenoids, and anthocyanins constitutes a major cause of color loss. The conversion of chlorophyll into degradation foods like pheophytin and pheophorbide results in undesirable yellowing and fading, especially in green vegetables (Liu et al., 2020).

Color is a key indicator of both consumer perception and food quality, serving as a critical physical attribute that directly reflects freshness, degree of processing, and the preservation of nutritional components (Arslan & Alibas, 2024). In products of fruit and vegetable origin, color is closely associated with the stability of phenolic compounds, chlorophyll, carotenoids, and flavonoids. Structural degradation of these pigments affects not only the visual appeal of the food but also its functional value (Kooti & Daraei, 2017; Godlewska et al., 2020).

These compounds exhibit high sensitivity to heat and oxidative conditions; therefore, temperature and atmospheric parameters applied during drying play a critical role in pigment stability (Kooti & Daraei, 2017).

In this context, color analysis holds critical importance in the production of functional foods, serving both quality control and formulation design purposes. Maintaining stable color parameters is essential not only for preserving consumer acceptance but also for ensuring the sustainability of antioxidant activity (Khalil et al., 2015; Tan et al., 2023).

Although existing literature presented numerous drying studies focused primarily on vegetables, research examining the color-related behavior of celeriac, a crop with both aromatic and medicinal properties, under different drying conditions remains limited. The findings are expected to strengthen quality control strategies in the development of functional foods and to offer a scientific framework for optimizing advanced drying technologies in plant-based matrices.

This study aims to comparatively evaluate the effects of two different drying methods—conventional hot-air drying at 65 °C and vacuum drying under vacuum conditions (hot-air at 65 °C combined at 100 mm Hg)—on the color parameters and visual quality of celeriac samples.

2. Materials and Methods

2.1. Celeriacs samples

Celeriacs (*Apium graveolens* L. var. *secalinum* Alef), selected from healthy and homogeneous plants, were obtained from commercial markets in Kayseri in 2023 for the drying experiments. The samples were stored at 4 ± 0.5°C until the drying process. Five different samples, each with a mass of 20 grams, were dried in an oven at 105 °C for 24 hours. The initial moisture content of the celeriacs was then determined as 87.64 ± 0.23% (w.b.). Celeriacs were precisely sliced into chip-like thin sections using a specialized slicing blade, achieving a uniform thickness of approximately 1 ± 0.11 mm.

2.2. Drying methods

The vacuum drying process was carried out in a vacuum dryer (Miprolab Mve30, Turkey) at a vacuum pressure of 100 mmHg and a temperature of 65 °C (n=15). The dryer temperature was maintained at 65 °C. The oven includes perforated polyamide platforms and trays that hold the samples. The drying process continued until the samples reached a final moisture content of approximately 0.10 kg [H2O] kg−1 [DM] on a dry basis. Under these conditions, drying celeriacs required approximately 460 ± 1.02 minutes to reach a final moisture content of 0.10 kg [H2O] kg−1 [DM].

Hot air convection drying at 65 °C was conducted using a convection oven (Arçelik KMF 833 I, Turkey) (n=15). The drying process was performed at an air velocity of 0.5 m s-1 and a constant temperature of 65 °C according to Rudy et al. (2024). Under these conditions, drying celeriacs required approximately 365 ± 0.12 minutes to reach a final moisture content of 0.10 kg [H2O] kg−1 [DM]. Fresh, vacuum (100 mmHg vacuum assisted by hot-air at 65 °C), and hot-air dried (65 °C) celeriac slices are shown in Figure 1.

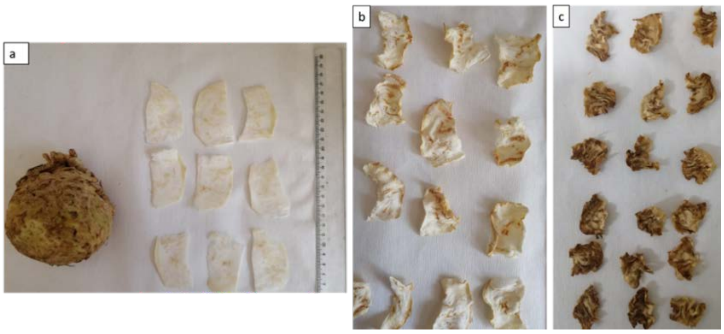

Figure 1. Fresh (a), vacuum (b) (hot-air at 65 °C combined at 100 mm Hg), and hot-air dried (65 °C) (c) celeriac slices

2.3. Color analysis

Fifteen drying experiments were conducted for each drying method. For color analysis, five color measurements were taken per sample, and average color values were calculated.

Color analysis was conducted on both fresh and dried celeriac samples using a colorimeter (CR-400 Konica Minolta, Tokyo, Japan). The CIELab color system was employed to determine L*, a*, and b* values. The color difference (ΔE) and chroma (C) values were calculated based on the equations provided Pathare et al. (2013).

Color attributes were analyzed using statistical software (SPSS, v.17, IBM, NY, USA). To identify significant differences among treatments, one-way analysis of variance (ANOVA) was conducted, and multiple comparisons of means were performed using Duncan's test at a 95% confidence level ($p<0.05$). Each experimental set included ten replicate measurements, and arithmetic means were computed to represent the colorimetric response for each parameter.

2.4. Principal component analysis (PCA)

Principal Component Analysis (PCA) enables pattern identification through dimensionality reduction in multivariate datasets without requiring predefined classifications. Observations sharing common statistical properties appear in close proximity within the principal component space (Esbensen, 2009). This method assists in revealing distributional tendencies among samples, and the resulting score plots offer a spatial overview of variation and grouping across the dataset.

The analysis was performed using Unscrambler X version 10.4 (Camo Software, Oslo, Norway). Color parameters were selected as input variables to investigate the influence of drying method and temperature. For hot-air drying at 65 °C, color measurements were performed in triplicate on fifteen samples (n = 15). For vacuum drying (65°C hot-air combined with 100 mm Hg vacuum), the same protocol was applied (n = 15). Fresh samples were measured in triplicate on three independent replicates (n = 15). The datasets were subjected to PCA to visualize the separation among treatments and to evaluate groupings based on color parameters.

2.5. Soft independent modeling of class analogy (SIMCA) analysis

SIMCA (Soft Independent Modeling of Class Analogy) is a qualitative data analysis method based on PCA used for the classification of samples (Davies & Fearn, 2008). The color data of dried celeriac slices were analyzed using the SIMCA technique to classify the samples into two groups (vacuum or hot air). The L*a*b* color model data of the celeriac samples were divided into training and validation sets. SIMCA classification was applied in two stages at a 5% significance level. In the first stage, two separate PCA models (vacuum and hot air) were created and saved using the training data. In the second stage, the data in the test set (Nval = 20) were classified according to the previously created PCA models. It was examined whether the samples could be classified based on the drying method. The classification results were evaluated based on the Coomans plot generated after the SIMCA analysis. This plot consists of four regions: vacuum, hot air, both vacuum and hot air (overlap), and unclassified. Classification ratios were calculated based on the Coomans plot and presented in tabular form.

3. Results and Discussion

3.1. Color parameters analysis results

Changes in drying temperature or energy input across product types may influence visual quality by modifying color attributes, which play a critical role in consumer decision-making. The measured L*, a*, b*, chroma, and hue angle values for both fresh and dried samples reported in Figure 2. Statistically significant differences in color metrics were observed depending on the drying technique applied ($p < 0.05$).

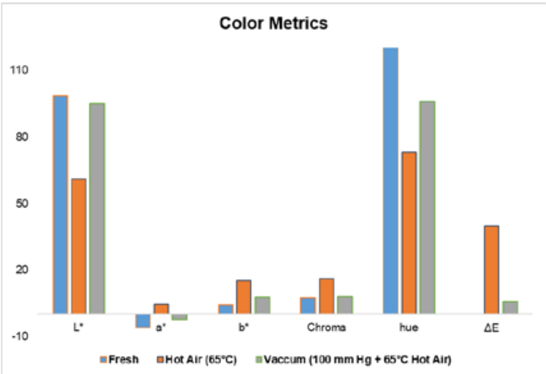

Figure 2. Average color parameters of celeriac obtained using hot-air and vacuum drying methods

The L* value of fresh celeriac was measured at 98.30, indicating a naturally bright white appearance. After drying at 65 °C using hot air, the L* value declined markedly to 61.46, reflecting a distinct darkening in the product. In contrast, samples dried by the vacuum drying method retained an L* value of 95.56, remaining very close to that of the fresh material. This discrepancy primarily results from the thermal exposure and oxygen availability during drying. Hot air drying involves elevated temperatures under atmospheric conditions, which can promote non-enzymatic browning reactions such as the Maillard reaction and caramelization, in addition to the oxidation of phenolic compounds. These reactions often lead to surface darkening, especially in root vegetables. Thermal degradation of heat-sensitive pigments further contributes to discoloration. The measured L*, a*, b*, chroma, and hue angle values for both fresh and dried samples are reported in Table 1.

Vacuum drying minimizes oxygen exposure and enables water evaporation at lower temperatures due to reduced pressure. These milder thermal conditions suppress oxidative reactions and limit pigment degradation. As a result, vacuum drying effectively preserves the original brightness of the product and maintains color quality comparable to that of the fresh sample. Similarly, Karabacak et al. (2018) reported the preservation of high L* values during vacuum drying. Their findings emphasized that hot air drying disrupts the light-reflective structure of the food, resulting in surface darkening. Nurkhoeriyati et al. (2021) evaluated color parameters of celeriac slices after hot air drying at 60–80 °C. Results showed a significant decrease in L* value with increasing temperature, indicating reduced brightness. The a* value shifted from green toward red, reflecting chlorophyll degradation. The b* value increased, suggesting a dominance of yellow tones and pigment loss. Hot air drying caused deterioration in color parameters due to thermal degradation of chlorophyll and phenolic pigments. Hot air drying at 80 °C, the L* value dropped below 45 Nurkhoeriyati et al. (2021). These findings align with the results of the present study. Latinović et al. (2024) emphasized that hot air drying in celeriac samples led to a substantial decline not only in bioactive compounds but also in color parameters. The L* value decreased from approximately 90 to 65, while a* and b* values showed nearly 40% losses. Color degradation paralleled phenolic oxidation, resulting in both aesthetic and functional quality losses. Kręcisz et al. (2023) reported that convective hot air drying reduced L* values and significantly increased ΔE values. At 65 °C, ΔE exceeded 150, indicating color loss that could negatively affect consumer perception.

Table 1. Color parameters of fresh and dried celeriac snacks under different drying conditions

Drying Method	Color Parameters					
	L*	a*	b*	C	h	ΔE
Fresh	98.30±1.89[a]	-5.97±0.18[a]	4.42±0.41[a]	7.43±0.55[a]	143.44±1.42[a]	
65°C hot air	61.46±1.73[b]	4.53±0.69[b]	15.28±1.10[b]	15.94±1.05[c]	73.49±1.52[b]	39.81±1.43
Vacuum (65°C hot air + 100 mm Hg)	95.56±0.85[a]	-2.32±0.40[a]	7.72±0.23[b]	8.06±0.56[b]	106.34±2.22[a]	5.63±0.56

Different letters on the same columns for each parameter indicate that the difference between the means is significant (*p*<0.05).

The a* values of root celeriac samples demonstared negative values in both fresh samples and those dried using vacuum drying methods. These negative values align with the naturally light white tones of the celeriac root. In contrast, samples dried by hot air at 65°C exhibited positive a* values. This shift indicates pigment alterations and oxidative reactions occurring during hot air drying, leading to color changes toward yellowish-red hues in the root. Nurkhoeriyati et al. (2021) reported a similar observation in their study, where hot air drying (60–80°C) caused the a* value of celeriac slices to shift from green toward red due to chlorophyll degradation. Considering that chlorophyll content in celeriac is naturally low, the positive increase in the a* parameter in this study is most likely related to thermal degradation of phenolic pigments and other color compounds. In conclusion, hot air drying induces color changes in celeriac, while vacuum drying better preserves the natural color tones.

The b* value of fresh celeriac root indicates strong yellow tones. After hot air drying at 65°C, the b* value significantly decreased. This decline suggests that hot air drying causes thermal degradation of yellow pigments. Among these pigments, compounds such as flavonoids likely contribute to the yellow coloration; however, their sensitivity to thermal and oxidative stress can lead to color loss. The vacuum drying method (65°C + 100 mm Hg) maintained the b* value, demonstrating better pigment preservation compared to hot air drying. Literature reported that vacuum conditions slow oxidative degradation and reduce color loss. In conclusion, the reduction in b* value primarily results from the thermal and oxidative degradation of yellowish pigments.

The b* parameter represents the yellow-blue color axis, and a decrease in b* values during drying generally indicates the loss of yellow pigments that are sensitive to heat and oxidation. Numerous studies emphasize that thermal drying leads to the degradation of pigments such as carotenoids and flavonoids, resulting in a reduction of yellowness in fruits and vegetables (Zhang et al., 2020). For instance, Nurkhoeriyati et al. (2021) reported significant decreases in b* values of celeriac slices dried with hot air at 60–80°C, attributing this decline to the thermal degradation of phenolic compounds and flavonoids. Similarly, Alibas and Yilmaz (2022) observed marked reductions in b* values in samples dried by hot air, while vacuum drying better preserved these pigments by reducing oxygen exposure and thermal stress. Vacuum drying slows oxidative reactions of yellow pigments by lowering the partial pressure of oxygen (Kumar et al., 2017). This mechanism explains why vacuum drying maintains higher b* values compared to conventional hot air drying. Overall, the preservation of yellow color during drying largely depends on minimizing pigment oxidation and thermal degradation, which is more effectively achieved under vacuum or low-temperature drying conditions (Arslan & Alibas, 2024).

Chroma (C*) values represent color saturation or intensity and are considered crucial indicators of color quality. In this study, high chroma values were observed in fresh celeriac samples, reflecting a vivid and intense color. Significant decreases in chroma values were recorded following hot air drying, which is attributed to the thermal degradation of pigments and bioactive compounds. In vacuum drying, chroma values remained close to those of fresh samples, indicating better preservation of pigments against oxidative degradation. Similar findings have been reported in the literature (Alibas & Yilmaz, 2022; Nurkhoeriyati et al., 2021). The reduction in chroma values signifies a decline in the visual appeal and functional quality of the food. Therefore, drying techniques involving low temperatures and vacuum drying conditions are recommended to maintain high chroma values.

Hue angle (h) serves as a critical parameter indicating color tone and direction of color change. High hue values observed in fresh celeriac root samples reflect the presence of light and natural color tones. A significant decrease in hue angle occurred after hot air drying, indicating a shift in color tone. In vacuum drying, hue values remained comparable to those of fresh samples. These color tone changes result from thermal and oxidative degradation of pigments. Similar adverse effects of hot air drying on color tone have been reported in the literature (Alibas & Yilmaz, 2022; Nurkhoeriyati et al., 2021). Preserving the hue angle plays an important role in maintaining the aesthetic quality of the food. Nakornpanom and Chaovanalikit (2024) reported that vacuum microwave drying preserved a* values at higher levels; however, an increase in variation was observed. Chen et al. (2020) indicated a reduction in yellowness (b* values) during hot-air drying due to chlorophyll degradation. Vacuum drying contributed to the mitigation of a* value loss. Godlewska et al. (2020) demonstrated that elevated Chroma values were associated with pigment stability, and the combination of low temperature and vacuum conditions enhanced this stability. Kowalska et al. (2024) emphasized that hue values remained closer to those of fresh samples during vacuum drying, representing an important indicator for color tone preservation. Consistent with the present study, Karabacak et al. (2018) and Tan et al. (2023) reported lower ΔE color difference values under vacuum drying conditions. Similarly, Alibaş (2012) reported that celeriac slices subjected to vacuum drying at 75 °C and 0.1 kPa exhibited color properties closely resembling those of the fresh product. In contrast, the most pronounced color degradation and darkening were observed under hot-air drying at 55 °C and vacuum drying at high pressure (17 kPa). These findings underscore the critical importance of combining low pressure with elevated temperature to preserve color stability during drying. Moreover, the results highlight the sensitivity of color parameters to variations in temperature and pressure, emphasizing that careful optimization of drying conditions plays a decisive role in maintaining the visual quality of the product.

3.2. Principal component analysis (PCA) results

Colorimetric methods based on chromameter measurements provide a practical alternative to conventional laboratory-based analytical protocols by enabling rapid data acquisition, minimal sample handling, and cost-efficient operations (Esbensen, 2009; Arslan et al., 2025a; Arslan et al., 2025b). In the context of data interpretation, multivariate statistical techniques support the exploration of structural relationships and variability patterns within sample populations. Techniques such as Principal Component Analysis (PCA) is extensively used for this purpose. PCA facilitates unsupervised dimensionality reduction by projecting data into orthogonal components, enabling visual differentiation of sample groupings according to spectral similarity, although it lacks predictive classification capability (Esbensen, 2009; Arslan, 2021). PCA was conducted using color parameters obtained from the L*a*b* color model. The PCA model demonstrated strong discrimination capability regarding color variation. The first principal component (PC1) accounted for 87% of the total variance, and the second principal component (PC2) accounted for 10%, resulting in a cumulative explained variance of 97% (Figure 3)

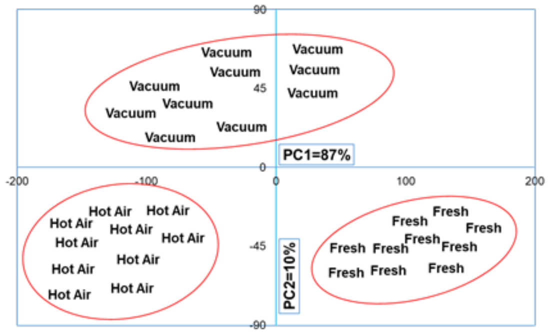

Figure 3. Principal Component Analysis results of celeriac slices obtained by hot-air and vacuum drying methods using the L*a*b* color model

This high percentage indicates that the selected color parameters effectively capture the variability within the dataset. Score plot analysis indicated clear separation between sample groups according to drying methods. Vacuum-dried and fresh samples predominantly appeared on the right side of the PC2 axis, suggesting better preservation of original color characteristics. Hot-air dried samples clustered on the left side of PC2 and below the PC1 axis, reflecting greater deviations in color attributes due to the drying process. These results highlight the significant impact of brightness (L*) and red-green (a*) parameters on the observed color stability.

PCA applied to the L*Ch color models revealed a pronounced ability to differentiate sample groups based on drying treatments. The first principal component (PC1) explained 95% of the total variance, while the second principal component (PC2) accounted for the remaining 5%, summing to a cumulative variance explanation of 100% (Figure 4). The PCA score plot demonstrates that fresh and vacuum-dried samples are predominantly positioned in the upper region of the plot. This indicates that these samples exhibit higher values along the PC2 axis. Although PC2 accounts for a relatively small portion of the variance, it captures certain distinctions among the samples. The clustering of fresh and vacuum-dried was in the upper section of the plot along PC2 suggests that these samples share similar characteristics related to specific color parameters represented by PC2 within the L*Ch color models. Conversely, samples subjected to hot-air drying appear in the lower part of the plot, indicating differentiation along the PC2 axis. Accordingly, PCA based on the L*Ch color model indicates a pronounced similarity in the color profiles of fresh and vacuum-dried samples with relative to PC2, while hot-air dried samples diverge from this group. These findings underscore the utility of multivariate analyses in elucidating the impacts of different drying methods on color parameters represented in the L*Ch color models.

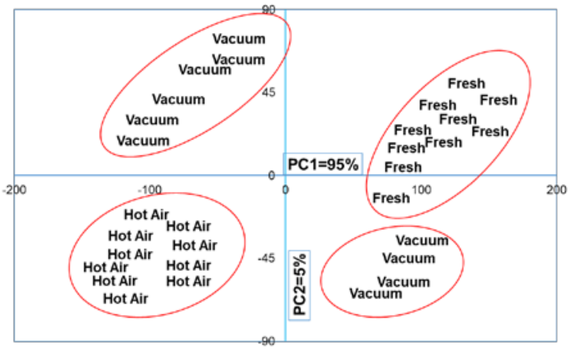

Figure 4. Principal Component Analysis results of celeriac slices obtained by hot-air and vacuum drying methods using the L*Ch color model

PCA based on the L*a*b*Ch color model, the first principal component (PC1) explained approximately 90% of the variance, while the second principal component (PC2) accounted for about 8%. (Figure 5) The clustering pattern was consistent with that observed in the L*Ch color model. Fresh and vacuum-dried samples mainly clustered in the upper section of the plot, whereas hot air-dried samples were located in the lower left quadrant relative to PC2. These results indicate that the PCA using the L*a*b*Ch model effectively distinguishes sample groups and captures color parameter variations similarly to the L*Ch color model. The L*Ch color model provides a perceptually relevant framework aligned with human vision by emphasizing lightness (L*), chroma (C*), and hue (h). This facilitates intuitive interpretation of color differences that correlate well with sensory perception and consumer preferences.

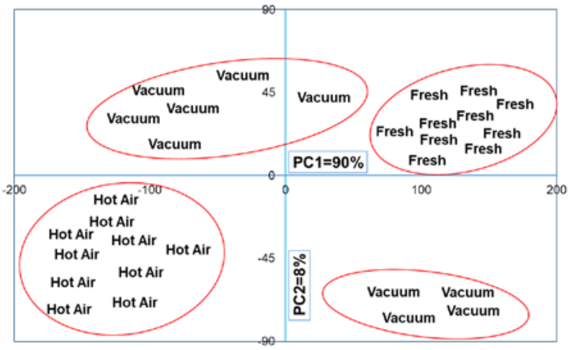

Figure 5. Principal Component Analysis results of celeriac slices obtained by hot-air and vacuum drying methods using the L*a*b*Ch color model

Meanwhile, the Lab*Ch model extends the CIELAB color space by explicitly integrating chroma and hue parameters, preserving the uniformity of the CIELAB system. This allows for more detailed and precise quantification of color variations and supports robust multivariate statistical analyses. Both models showed comparable clustering results and variance explanations in this study, demonstrating their equivalent capability in characterizing the color properties of celeriac samples subjected to different drying treatments. The L*Ch model's advantage lies in its straightforward applicability for sensory and practical evaluations, whereas the Lab*Ch model offers enhanced analytical precision beneficial for technical assessments. Therefore, the selection between these models should be based on research goals. L*Ch is recommended for sensory-focused and consumer-related studies, while Lab*Ch suits applications requiring rigorous colorimetric analysis. Using both models in a complementary manner can provide a more comprehensive understanding and strengthen the reliability of the results. Turkmen et al. (2022) investigated the fixed oil composition, seed yield, and quality of eight basil genotypes with different leaf colors (purple and green). According to the results of PCA, purple- and green-leafed basil genotypes exhibited distinct chemical profiles in terms of fixed oil composition. This divergence suggests that leaf color may have a determining influence on fixed oil profiles and potential functional properties. In particular, green-leafed genotypes were found to be superior in terms of fixed oil constituents. Similarly, Keskin et al. (2021) reported that PCA analysis based on color values of organic and conventional red pepper powders dried using intermittent microwave (IMW) provided clear separation according to both product type and drying power level. The first principal component (PC1) represented the product type, while the second component (PC2) reflected the applied power level, with a cumulative variance explanation of 98%. In a related study, Arslan et al. (2023b) demonstrated that PCA based on color data effectively discriminated between organic and conventional black carrot powders under hot-air (HA) drying conditions, where PC1 was associated with product type and PC2 with temperature, accounting for 92% of the total variance. Under IMW conditions, color-based PCA achieved 95% classification accuracy. Arslan et al. (2025b) also showed that PCA using color parameters (L*, a*, b*, C, h*) captured the variance induced by different drying methods in black carrot samples and successfully clustered the samples. Arslan et al. (2025a) found that PCA analysis of color data from linseed genotypes enabled clear differentiation among genotypes, and FT-NIRS data analysis indicated that PC1 and PC2 accounted for the majority of the variance. Arslan and Alibaş (2025) demonstrated that PCA of fresh and dried chili peppers based on color parameters effectively separated samples according to the drying method used.

3.3. SIMCA results

The Coomans plot obtained from the SIMCA analysis is presented in Figure 6. According to the SIMCA classification results, it was observed that color data could be effectively used to distinguish celeriac slices dried by different drying methods. All of the samples (100%) were correctly classified into their respective PCA model classes.

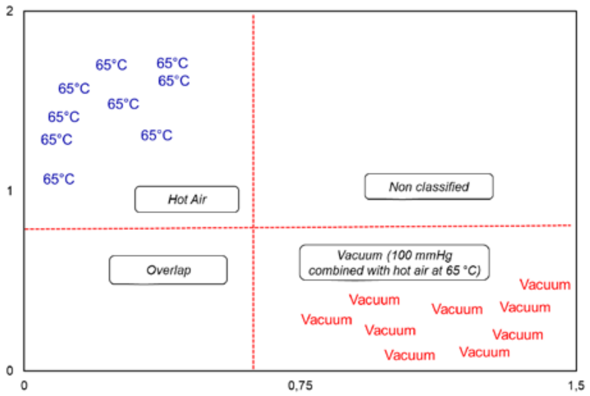

Figure 6. The Coomans graph of the color data of hot air-dried and vacuum-dried celeriac snacks

Different drying methods influence the levels of various compounds and properties in celeriac slices, such as phenolics, flavonoids, antioxidants, vitamins, minerals, and pigments (Keser et al., 2020; Arslan et al., 2020; Arslan et al., 2023a; Arslan & Alibas, 2025), and that these variations affect the color characteristics, thereby enabling successful classification. Keskin et al. (2022) evaluated the distinguishability of organic and conventional pepper samples using the SIMCA method and successfully classified the samples with an accuracy rate of 94%.

4. Conclusion

This study revealed that vacuum drying (hot-air at 65 °C assisted at 100 mm Hg) significantly outperformed conventional hot-air drying at 65 °C in preserving the color quality and visual appearance of celeriac slices. The vacuum drying method effectively reduced oxidative browning and pigment degradation and maintained higher L* (lightness) values. In contrast, hot-air drying caused notable darkening and pigment loss. Principal Component Analysis (PCA) explained over 95% of the variance and distinctly separated samples by drying method, confirming the sensitivity of color parameters as indicators of drying effects. Furthermore, the SIMCA analysis revealed that celeriac slices obtained through different drying methods could be classified based on their color data with 100% accuracy. Present study findings underscore the superiority of vacuum drying in maintaining sensory and functional qualities, providing valuable guidance for the food industry to optimize drying protocols for aromatic, medicinal, and functional vegetables like celeriac. The reduced drying time compared to traditional methods further highlights its industrial applicability, promoting production efficiency without compromising food quality.

The vacuum drying method effectively reduced oxidative browning and pigment degradation, thereby preserving higher L* (lightness) values compared to hot-air drying that caused significant darkening and pigment loss. Maintaining the natural color of celeriac is important not only for preserving its sensory and nutritional qualities but also because color strongly influences consumer purchasing decisions. Thus, celeriac chips produced via vacuum drying can be recommended as a healthy snack option with appealing visual quality.

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Conflict of interest

The authors declare no conflicts of interest.

Authorship contribution statement

A.A:. Conceptualization; Investigation; Methodology; Resources; Data Curation; Formal Analysis; Validation; Writing-original draft.

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