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Original Article

Evaluating the effects of the ohmic process on the physicochemical properties of sour orange juice using principal component analysis

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ABSTRACT

In this study, the effects of the ohmic heating process at various voltage gradients (5, 7.5, and 10 V cm^{-1}) were investigated on the physicochemical and color properties of sour orange juice, considering various weight loss levels (10%, 20%, and 30%). Principal component analysis (PCA) was used to analyze the data and differentiate quality characteristics among the samples. Variables, including flavonoids, total phenols, color indices (L*, a*, and b*), pH, soluble solids, browning index, and total color change, were measured as key quality indicators. The results showed that a 10% weight loss under a 5 V cm^{-1} voltage gradient led to better preservation of bioactive compounds and the natural color of the product. In contrast, higher weight loss and the application of higher voltage gradients (especially 10 V cm^{-1}) caused degradation of bioactive compounds, increased soluble sugars, and intensified browning. The 7.5 V cm^{-1} voltage gradient showed a more balanced performance compared to the other two. These findings indicate that the optimal combination of a low voltage gradient with limited weight loss yields the best results in maintaining the nutritional and visual quality of sour orange juice. This method can be used as an efficient approach in the industrial processing of natural extracts to preserve nutritional value and visual appeal.

1. Introduction

Growing consumer awareness regarding healthy nutrition and the increasing demand for natural products free from chemical additives have drawn significant attention to the production and processing of natural beverages and fruit extracts (Qavanloo et al., 2023b). Among these, sour orange juice has gained a special place in the dietary habits and traditional medicine of Iran and parts of Asia, due to its high nutritional and medicinal value (Hasan et al., 2024; Mesías et al., 2021). Sour orange juice is rich in bioactive compounds such as flavonoids, total phenols, antioxidants, and vitamin C, and is noted for its anti-inflammatory, antibacterial, and anti-hypertensive properties. However, processing and preserving this product without compromising its chemical, nutritional, and sensory qualities remains a significant challenge in the food industry (Azadbakht et al., 2020b; Torshizi et al., 2020). Traditional thermal methods, such as pasteurization and concentration, while effective in extending shelf life, often result in the degradation of heat-sensitive compounds, loss of natural color, and decline in nutritional quality (Azadbakht et al., 2020c; Vahedi Torshizi et al., 2025, 2021). Consequently, extensive efforts have recently been made to develop novel technologies with minimal thermal damage, such as ultrasound, plasma, pulsed electric fields, and ohmic heating (Torshizi et al., 2019). Among these, ohmic heating has garnered special interest due to its features like uniform heat transfer, short processing time, reduction of localized hot spots, and efficient extraction of bioactive compounds (Vahedi Torshizi et al., 2024; Vahedi Torshizi et al., 2020).

Ohmic heating involves passing an alternating electric current through a food material with specific electrical conductivity, generating internal and uniform heat (Qavanloo et al., 2022; Vahedi Torshizi et al., 2019). This mechanism minimizes the destruction of bioactive compounds while effectively inactivating harmful microorganisms, unlike conventional thermal methods (Astráin-Redín et al., 2024). Additionally, since voltage and processing time can be precisely controlled, optimal conditions for quality preservation can be achieved. Nevertheless, selecting the appropriate voltage level and determining the optimal electrical contact time are critical for the effective use of this technology (Silva et al., 2022). Numerous studies have examined the effects of ohmic processing on various products such as pomegranate juice (Sharifi et al., 2022), grapes (Tunç et al., 2022), and oranges (Dhenge et al., 2022), showing that under optimal conditions, ohmic heating can preserve color, antioxidants, phenolic compounds, and sensory attributes. For instance, Azadbakht et al. (2021) reported that using low voltage in ohmic heating led to better preservation of flavonoids and minimized color loss in sour orange juice (Vahedi Torshizi and Kashaninejad, 2022). On the other hand, inappropriate use of high voltages or prolonged durations can cause caramelization, browning, and cell structure degradation, ultimately reducing product quality.

The current study aims to comprehensively investigate the effect of ohmic heating at three voltage levels (5, 7.5, and 10 V cm^{-1}), as well as three levels of weight loss (10, 20, and 30%), on the physicochemical properties and color characteristics of sour orange juice. Principal component analysis (PCA) was employed to analyze the data, distinguish between processed groups, and

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assess correlations among variables. This research is an effort to identify the optimal combination of voltage and weight reduction for the effective preservation of bioactive compounds and desirable color attributes of sour orange juice, thus providing a scientific basis for designing efficient and sustainable industrial processes. The findings from this study could help optimize ohmic heating technology in the natural beverage industry, supporting the production of healthy, nutritious, and shelf-stable products.

2. Materials and Methods

2.1. Experimental design

Figure 1 shows a schematic diagram of the heating process and system components. The experiments were carried out in a residential heating system comprised of a compact and transparent thermoset plastic cell (6 cm length, 6 cm width, 3 cm height, and 0.3 cm cell wall thickness), stainless steel electrodes (thickness 0.1 cm) with a distance of 6 cm, a variable transformer responsible for generating electric potential (3 kW, 0–300 V, 50 Hz, MST-3, Toyo, Japan), a power analyzer (Lutron DW-6090) responsible for monitoring and controlling the energy of the system via a thermocouple, and a computer used to store data.

The sour orange juice samples were poured between two electrodes located in the cell. All samples with a weight of 90 g were selected. Next, their initial temperature was recorded after stability. The voltage was applied to the set, and the samples were heated. Three heating voltage gradients of 5, 7.5, and 10 V cm^{-1} were selected for the heating process. Considering 10% (from 90 g to 81 g), 20% (from 90 g to 72 g), and 30% (from 90 g to 63 g) weight reductions, the percentage of the total weight of the sour orange juice samples poured into the cell during the warm-up process was determined. A scale of 0.01 g was used to measure the cell weight and its contents during the subcellular process (Azadbakht et al., 2020a; Vahedi Torshizi and Kashaninejad, 2022).

2.2. Color analysis

The L*, a*, and b* color values were measured due to their device-independent nature and their broader color representation range compared to RGB and CMYK models. ImageJ software, equipped with built-in plug-ins, was employed to process the images and extract color values. As part of the pre-processing step, the images were enhanced, and any irrelevant components were removed (Azadbakht et al., 2016). The primary objective during image processing was to identify features relevant to the intended analysis. To extract color data, the images were first converted from the RGB color space to XYZ, and subsequently to the L*a*b* color space in a two-step process. The transformation from RGB to XYZ was performed using Eq. (1). Eqs. (2) to (4) were then used to convert the XYZ values into the corresponding L*, a*, and b* values for further analysis (Cheng et al., 2001)

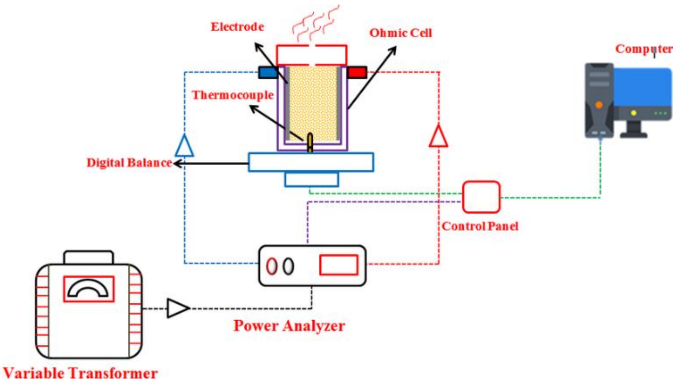

Figure 1. Schematics of the equipment for the ohmic heating process

$$\begin{bmatrix}\hat{X}\\ \hat{Y}\\ \hat{Z}\end{bmatrix}=\begin{pmatrix}0412456 & 0.257580 & 0.180423\\ 0212671 & 0.715160 & 0.072169\\ 0.019334 & 0.119194 & 0.950227\end{pmatrix}\begin{bmatrix}\hat{R}\\ \hat{G}\\ \hat{B}\end{bmatrix} \tag{1}$$

$$\hat{L}=\begin{bmatrix}116\times\left(\frac{\hat{Y}}{Y'}\right)^{\frac{1}{3}}-16\\ 903.3\times\left(\frac{\hat{Y}}{Y'}\right)ELSE\end{bmatrix} \tag{2}$$

$$\hat{a}=500\times\left[\left(\frac{\hat{X}}{X'}\right)^{\frac{1}{3}}-\left(\frac{\hat{Y}}{Y'}\right)^{\frac{1}{3}}\right] \tag{3}$$

$$\hat{b}=200\times\left[\left(\frac{\hat{Z}}{Z'}\right)^{\frac{1}{3}}-\left(\frac{\hat{Y}}{Y'}\right)^{\frac{1}{3}}\right] \tag{4}$$

where X ', Y', and Z ' are XYZ values in the D65 standard (Eq. 5) (Qavanloo et al., 2023a).

$$\begin{bmatrix}\hat{X}\\ \hat{Y}\\ \hat{Z}\end{bmatrix}=\begin{pmatrix}95.047\\ 100\\ 108.883\end{pmatrix} \tag{5}$$

The browning index (BI) was obtained based on the color components using Eqs. (6) and (7) (Azadbakht et al., 2024b):

$$x=\frac{a*+1.75\times\times L*}{5.645L*+a*-3.012b*} \tag{6}$$

$$BI=\frac{(100(x-0.33))}{0.17} \tag{7}$$

Eqs. (8) and (9) show the measurement of chroma indices and total color differences to describe color variations during heating of sour orange juice (Jafarzadeh et al., 2022).

$$C=\sqrt{a^{*2}+b^{*2}} \tag{8}$$

$$TCD=\sqrt{(L_0^*-L^*)^2+(a_0^*-a^*)^2+}(b_0^*-b^*)^2 \tag{9}$$

The zero indexes of the values read from the sample are not associated with fresh sour orange juice.

2.3. Physicochemical properties

2.3.1. Free radical scavenging activity

A DPPH solution with a concentration of 0.1 mmol L^{-1} was prepared by dissolving 0.4 mg of DPPH in 100 mL of methanol. From this solution, 2 mL was transferred into a test tube, followed by the addition of 2 mL of the prepared methanolic extract. The test tubes were kept in the dark for 15 min to allow the reaction to occur. After incubation, absorbance was measured at 517 nm using a UV/VIS spectrophotometer (Model 2800). The control sample consisted of 2 mL of DPPH solution mixed with 2 mL of methanol. Methanol was used to calibrate the spectrophotometer. The obtained absorbance values were then converted to percentage inhibition of free radicals using Eq. (10) (Azadbakht and Vahedi Torshizi, 2020a)

$$\text{DPPH}=\frac{(Ac-As)}{AC}\times 100 \tag{10}$$

where AC and AS are the control absorbance and sample absorbance, respectively.

2.3.2. Total phenolic content

To measure the total phenolic content, the Folin–Ciocalteu method was used. For this purpose, 2 µL of methanolic extract (containing 0.5 g in 5 mL of 80% methanol) was mixed with 100 µL of Folin–Ciocalteu reagent and 1.16 mL of distilled water. After resting for 5 to 8 min, 300 µL of 1 M sodium carbonate (containing 10.6 g in 100 mL of distilled water) were added to the mixture. The solution was then placed in darkness in a water bath at 40 °C for 30 min. Finally, the samples were read at a wavelength of 765 nm using a spectrophotometer. By substituting the absorbance value of the sample in place of *y* in the linear equation (Eq. 11), the total phenolic content (*x*) was obtained in terms of milligrams of gallic acid per gram (Azadbakht et al., 2021).

$$y = 0.0034\,x - 0.0114 \qquad (11)$$

2.3.3. Total flavonoid content

To measure total flavonoid content, the methanolic extract was mixed with methanol, 10% aluminum chloride solution (prepared by dissolving 10 g of $AlCl_3$ in 100 mL of distilled water), 1 M potassium acetate solution (prepared by dissolving 2.41 g in 10 mL of distilled water), and distilled water. For the blank sample, pure methanol was used instead of the methanolic extract. The prepared mixtures were incubated in the dark for 30 min. After incubation, the absorbance was recorded at 415 nm using a UV/VIS spectrophotometer. The obtained absorbance values were converted to actual flavonoid concentrations by referring to a standard calibration curve. This standard curve was generated using Eq. (12), based on a range of known concentrations of quercetin. Following the absorbance measurements of each standard, the total flavonoid content in the test samples was calculated (Azadbakht and Vahedi Torshizi, 2020b).

$$y = 0.0121\,x - 0.0722 \qquad (12)$$

2.3.4. pH

The pH of all samples was measured at 20 °C using a digital pH meter (PHS-3BW, Italy), according to the Iranian National Standard No. 2685. (Azadbakht et al., 2024a).

2.3.5. Total soluble solids

Since the majority of soluble solids in fruit juice are related to the concentration of dissolved sugars, the Brix value is used to estimate the sweetness level of the juice. The measurement was performed using a benchtop refractometer (MT-032ATC, Taiwan). The concentration of the solution was recorded as the percentage of total soluble solids (expressed in °Brix) at a temperature of 20 °C (Azadbakht et al., 2025).

2.4. Principal component analysis

The data were analyzed using The Unscrambler X 10.4 (64-bit) chemometric software. The main advantage of Unscrambler X lies in its robust tools for analyzing all types of multivariate data. This software calibrates datasets and is commonly used for model prediction and analysis. Initially developed by Harald Martens and later enhanced by CAMO Software, Unscrambler X supports various multivariate techniques such as PCA, partial least squares (PLS) regression, and multivariate curve resolution.
In this study, PCA was employed to examine the correlation between voltage gradients and weight loss percentages (scores), as well as their relationship with physical and physicochemical properties (loadings). PCA reduces the dimensionality of a dataset by transforming a large number of potentially correlated variables into a smaller set of uncorrelated variables called principal components, effectively minimizing noise. This technique serves as a data compression method, where interrelated variables are converted into new, uncorrelated components. It is considered an *unsupervised* method, meaning it does not require the specification of a dependent variable (Kamboj et al., 2020).

3. Results and Discussion

3.1. Voltage gradient differences

The effects of a voltage gradient equal to 5 V cm^{-1} on the physicochemical and color properties of sour orange juice were analyzed, the results of which are illustrated in Figure 2. According to Figure 2(a), the first principal component (PC1) accounted for 95% of the variance in the data. In comparison, the second principal component (PC2) explained 4%, indicating that most of the sample differentiation occurred along PC1. Samples processed at different weight reduction levels (10, 20, and 30%) were distinctly separated.

The samples under 5 V cm^{-1} and 10% weight loss (identified as V5W10) showed the most significant separation from other groups, signaling a notable difference in quality attributes. According to Figure 2(b), these samples were most closely associated with positive quality indicators such as redness (a*), flavonoid content, total phenolics, and lightness (L*), all located in the positive region of PC1. This suggests that a 10% weight reduction under a 5 V cm^{-1} voltage gradient leads to better preservation of bioactive compounds and color quality. Conversely, the V5W30 group, standing for 30% weight loss, gradually shifted toward the center and then to the left side of the score plot, where they were associated with variables such as total soluble solids, total color difference, BI, and yellowness (b*)—all positioned on the negative PC1 axis. This pattern implies that greater weight loss, even under low voltage, tends to result in undesirable changes, such as increased sugar concentration and enhanced browning.

The V5W20 samples, indicating 20% weight loss, were positioned intermediately between the two extremes, reflecting a gradual transition in quality traits. These findings indicate that, while low voltage gradients cause less degradation compared to higher voltages, longer processing durations (caused by higher weight reductions) can still lead to gradual deterioration of product quality. Therefore, to maximize the retention of bioactive compounds and desirable color attributes, the application of a low voltage gradient (e.g., 5 V cm^{-1}) in combination with a minimal weight reduction (e.g., 10%) is recommended for sour orange juice processing.

Low voltage in ohmic heating, particularly in the fruit juice concentration process, plays a positive role in preserving product quality. Hwang et al. (2021), in the context of ohmic vacuum concentration of orange juice, observed that at lower voltage gradients (15–30 V cm^{-1}), the concentration time was reduced, and thermal damage to compounds such as pectin and vitamin C was minimized. This method not only shortens the process time but also preserves the final product quality (Hwang et al., 2022). Alkanan et al. (2021), in a comprehensive review on the application of ohmic heating, noted that this technique better preserves phenolic compounds compared to conventional thermal methods. It is also suitable for concentration and extraction processes, and at lower voltages and milder electric fields, the detrimental thermal effects are reduced (Alkanan et al., 2021). Jafarpour et al. (2022), in a study on the concentration of various fruit juices, reported that low voltage reduces processing time while maintaining pH and phenolic content. They found that high voltage under certain conditions may increase bitterness or trigger Maillard reactions, whereas at low voltage, these changes are negligible(Jafarpour and Hashemi, 2022).

In Figure 3, the effects of a 7.5 V cm^{-1} voltage gradient on the physicochemical properties of sour orange juice are examined. Based on Figure 3(a), PC1 explained 96%, while PC2 explained 3% of the total variance, together accounting for 99% of the data variation, indicating the adequacy of the model for sample discrimination. In terms of sample distribution, three distinct groups—V7.5W10 (10% weight loss), V7.5W20 (20%), and V7.5W30 (30%)—were separated. The V7.5W10 samples were clustered in the positive PC1 region and located close to one another, indicating uniformity and stability in their quality attributes. These samples showed strong associations with bioactive compounds (flavonoids, total phenolics) and a* and L*, all situated on the right side of the loading plot (Figure 3b). This positive correlation suggests that the combination of low weight loss and a voltage gradient of 7.5 V cm^{-1} promotes high product quality, likely due to shorter processing duration and reduced degradation.

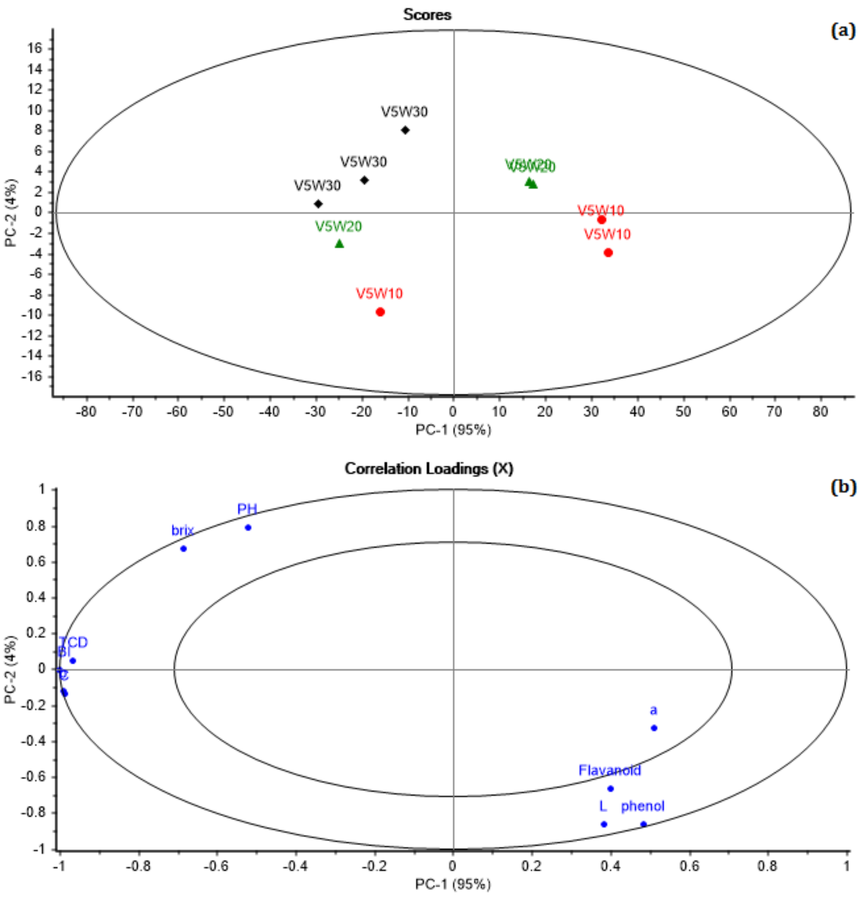

Figure 2. Score and loading plots from PCA at a voltage gradient of 5 V cm^{-1} across various weight reduction levels

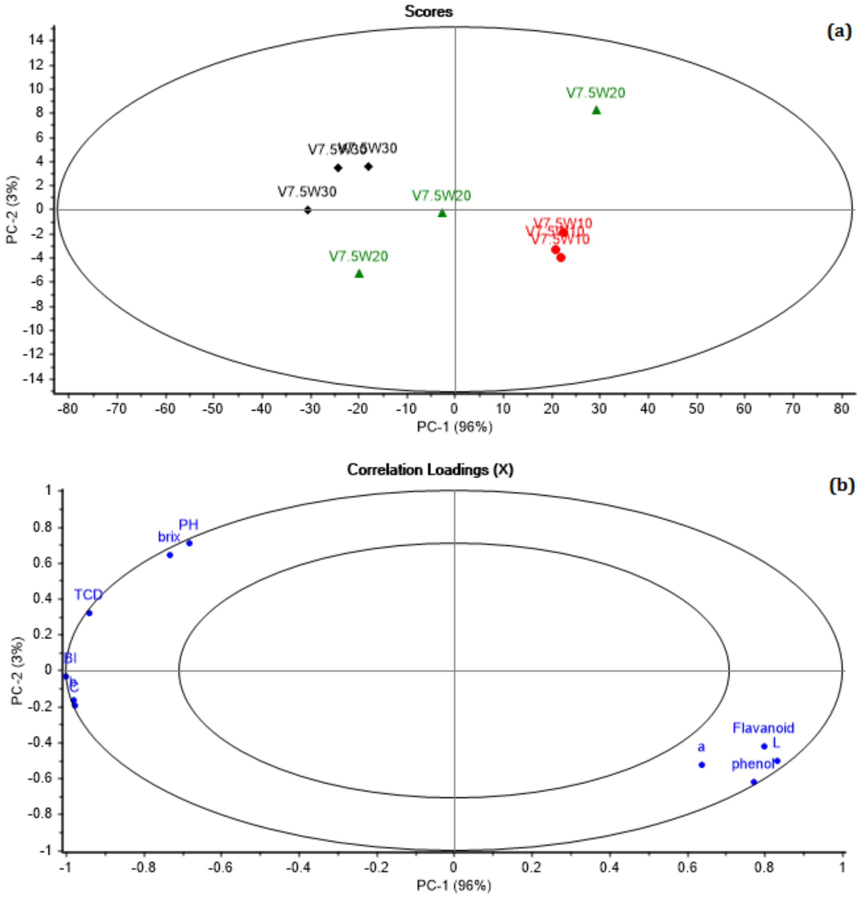

Figure 3. Score and loading plots from PCA at a voltage gradient of 7.5 V cm^{-1} across various weight reduction levels

In contrast, the V7.5W20 samples showed greater spread and variability, appearing in both positive and negative regions of the PC1 and PC2 axes. This suggests fluctuations in quality, where some samples retained desirable properties (e.g., flavonoids, L*, and a*), while others shifted toward the center, reflecting partial quality loss. These changes may be attributed to the extended processing time at higher weight reduction, which can compromise sensitive compounds.

The V7.5W30 samples tended to cluster on the left side of the score plot, aligning with variables such as total soluble solids, total color change, BI, and b*. These indicators are typically associated with increased sugar concentration, browning, and darker coloration, all of which reflect lower quality. In Figure 3(b), flavonoids, phenolics, and brightness were associated with the positive PC1 axis, while Brix, BI, and b* were on the opposing side. The clustering of pH and Brix in this region indicates a link between browning, acidity, and sweetness. Overall, applying a 7.5 V cm^{-1} voltage gradient with minimal weight reduction (≈10%) preserves bioactive compounds and color, whereas longer processing times (higher weight loss) lead to deterioration.

The effects of a 10 V cm^{-1} voltage gradient on the quality of sour orange juice were evaluated using PCA, as shown in Figure 4. In Figure 4(a), the first two principal components, PC1 and PC2, explain 99% and 1% of the data variance, respectively, indicating a dominant contribution of PC1 in describing the variation among the samples. The V10W10 samples (10% weight loss) clustered on the positive side of PC1, closely linked with phenolics, flavonoids, and favorable color attributes (a*, L*). This indicates that short exposure to a 10 V cm^{-1} voltage gradient helps preserve or even enhance bioactive compounds and visual quality.

In contrast, the V10W30 samples were separated on the negative PC1 axis, associated with soluble solids, pH, BI, and total color difference—signs of quality degradation due to extended processing. The V10W20 samples occupied an intermediate position, reflecting a gradual decline. The loading plot confirmed this separation, with beneficial attributes grouped on the positive axis and undesirable ones on the negative axis. The close association of soluble solids and pH also suggests they act together in browning and degradation. Overall, a 10 V cm^{-1} voltage gradient is advantageous only under short processing (≈10% weight loss), while more prolonged exposure leads to phenolic loss, sugar concentration, and browning. Thus, high voltage should be applied briefly and under controlled conditions to retain juice quality.

Cevik et al. (2021), in a study on the verjuice concentration process using ohmic heating, observed that increasing the voltage gradient improved process efficiency and reduced processing time; this reached the highest efficiency at a voltage of up to 19 V cm^{-1} (Cevik, 2021). Gavahian et al. (2022) demonstrated that increasing the voltage gradient also increases the evaporation rate, which is associated with higher ion concentration and a stronger electric field (Gavahian and Chu, 2022). Kumar et al. (2025) investigated the combined effect of voltage gradient and temperature in the ohmic process on kinnow juice. They found that increasing temperature while reducing voltage gradient led to higher juice recovery. Additionally, pH was directly influenced by the combined effect of voltage and temperature (Lalremmawii et al., 2025).

Gumustepe et al. (2023) reported on phenolic extraction from avocado leaves, indicating that the voltage gradient plays a significant role in increasing total phenolic content. However, excessive voltage combined with prolonged time may reduce extraction due to compound degradation (Gumustepe et al., 2023). Darvishi et al. (2019), in a study on grape juice, showed that increasing the voltage gradient helps better preserve antioxidant activity and results in minor pH changes—meaning that high voltage within a controlled range can be effective (Darvishi et al., 2020).

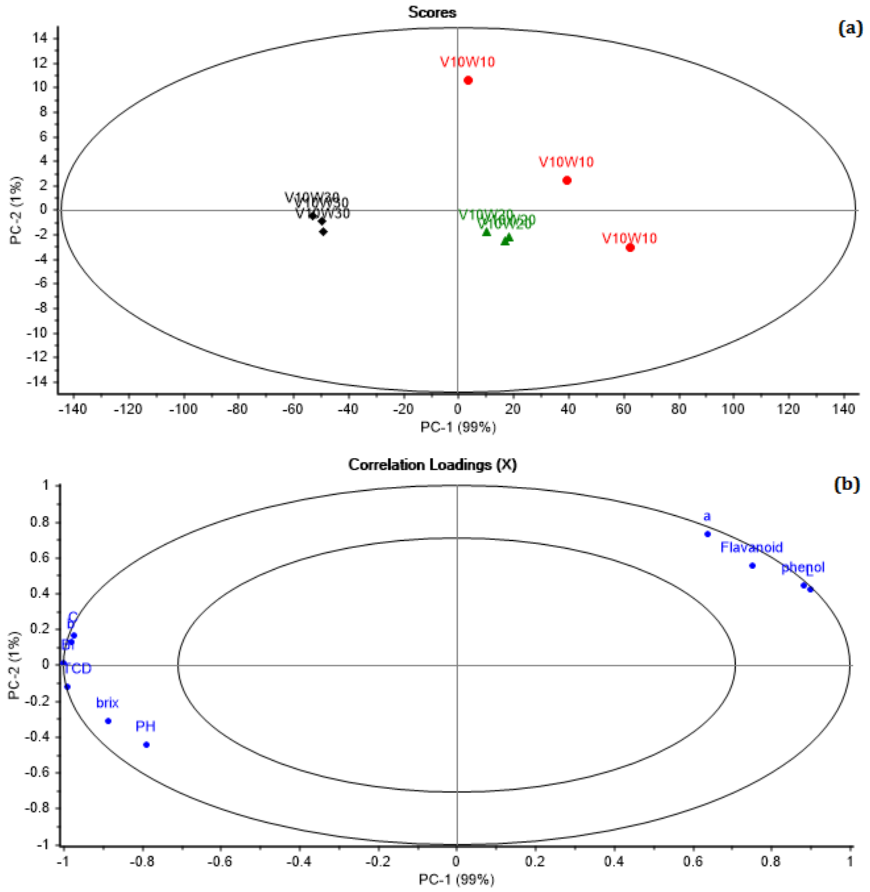

Figure 4. Score and loading plots from PCA at a voltage gradient of 10 V cm^{-1} across various weight reduction levels

3.2. Weight loss percentage

Figure 5 shows the effects of ohmic processing at 5, 7.5, and 10 V cm^{-1} on the physicochemical and color properties of sour orange juice. PCA results indicate that PC1 explains 96% of the variance and effectively separates the samples, while PC2 (2%) has little influence. In Figure 5(a), the V5W10 samples formed two clusters on the positive side of PC1, reflecting better retention of phenolics, flavonoids, and L*. The V10W10 samples were separated on the negative side, associated with higher soluble solids, BI, and total color change—signs of degradation likely linked to pigment loss, caramelization, and Maillard reactions. The V7.5W10 samples appeared near the center, showing more stable intermediate properties.

The loading plot confirmed these associations: beneficial attributes (phenols, flavonoids, pH, brightness) were correlated with low voltage gradients (e.g., V5W10), while undesirable traits (Brix, BI, TCD, a*, b*) were linked to high voltage gradients (e.g., V10W10). Overall, voltage was the dominant factor affecting juice quality, with lower levels preserving bioactive compounds and color, and higher levels accelerating quality loss. The results of this study are consistent with previous findings. Research has shown that low voltage in ohmic heating helps preserve bioactive compounds and color brightness (Norouzi et al., 2021; Hwang et al., 2021), whereas high voltage is associated with increased Brix, browning reactions, and decreased pH, accelerating product quality deterioration (Jafarpour et al., 2022).

Overall, it can be concluded that at a 10% weight loss level, the effect of voltage on the physicochemical and visual properties of sour orange juice is significantly observable. Low voltage gradients (e.g., 5 V cm^{-1}) help preserve the chemical and bioactive quality of the product, while high voltage gradients (e.g., 10 V cm^{-1}) mainly cause increased visual changes, Brix levels, and color shifts. The medium voltage gradients (e.g., 7.5 V cm^{-1}) occupy an intermediate position and may offer a more balanced approach to optimizing the final quality of the product. Therefore, depending on the processing objectives, e.g., preserving bioactive properties or enhancing visual traits, the appropriate voltage level can be selected to control the ohmic process. This information is essential for designing high-quality industrial processes in the production of natural extracts and beverages.

Figure 6 shows the effects of ohmic processing at three different voltage levels (5, 7.5, and 10 V cm^{-1}) on the physicochemical and color properties of sour orange juice under 20% weight loss conditions. PCA was used to analyze the data and visually and statistically assess the separation and correlation among the samples and their characteristics. Figure 6(a) showed that the samples treated at a voltage gradient of 5 V cm^{-1} (V5W20) were separated from the other two groups and positioned in the negative region of the PC1 axis, indicating a significant difference in their quality attributes. On the other hand, the samples treated at 10 V cm^{-1} (V10W20) were clustered in the positive region of the PC1 axis and showed high convergence with one another, suggesting greater stability of their characteristics under these conditions. The V7.5W20 group was positioned between the other two, representing an intermediate state, which may reflect a balanced effect of this voltage level in the ohmic process.

The loading plot (Figure 6b) illustrates the correlation of physicochemical and color variables with the PCA axes. Variables such as b*, BI, soluble solids content, and total color change were aligned with the positive direction of the PC1 axis, indicating a positive correlation with the high-voltage samples, particularly V10W20. This means that increasing voltage in the ohmic process intensifies these properties, possibly due to cell structure breakdown, greater release of color compounds, or caramelization of sugars. In contrast, variables such as flavonoids, pH, total phenols, and color components a* and L* were located in the negative PC1 region and were more closely associated with the low-voltage samples (V5W20). This indicates that using lower voltage helps better preserve bioactive compounds and the chemical quality of the product while reducing color degradation.

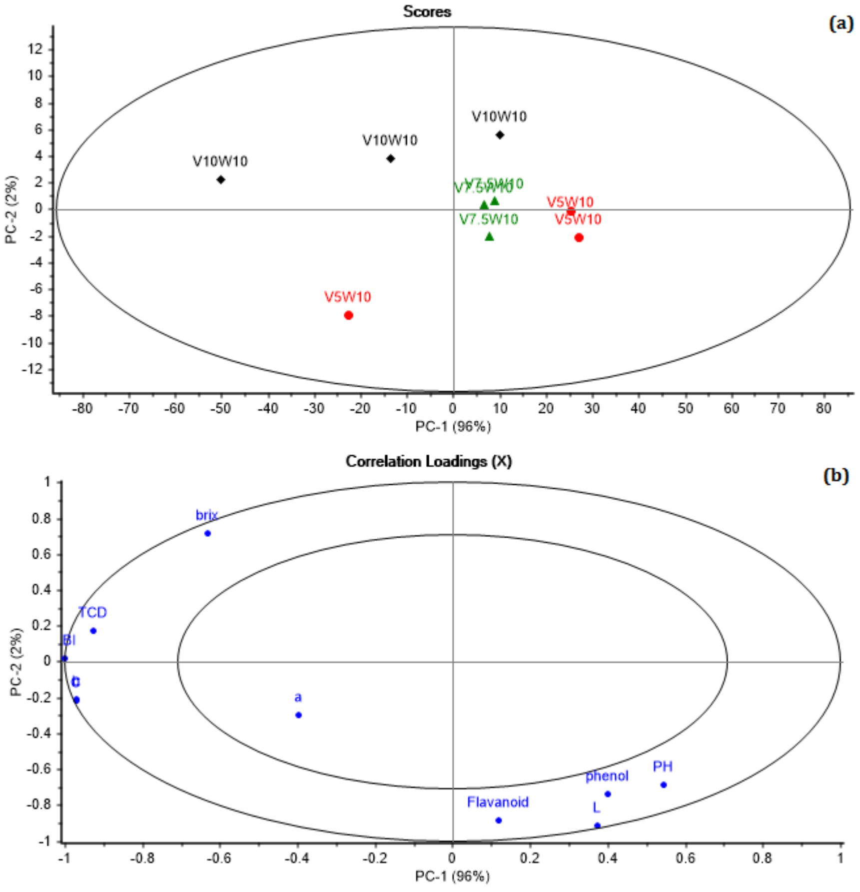

Figure 5. Score and loading plots from PCA at a weight loss of 10% across various voltage gradients

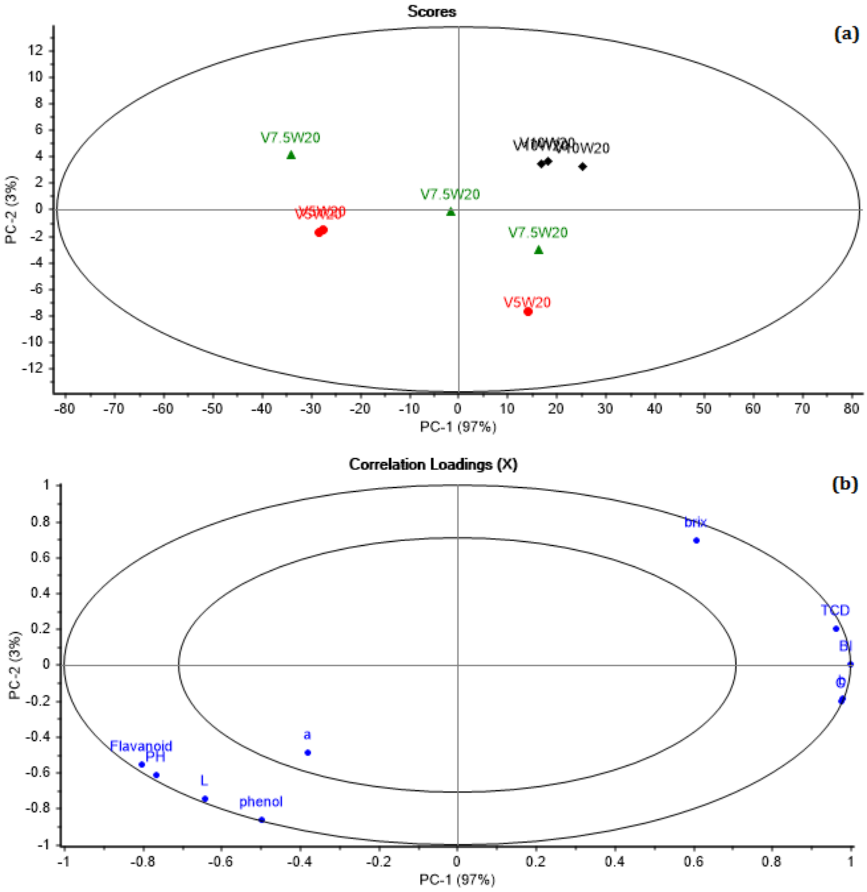

Figure 6. Score and loading plots from PCA at a weight loss of 20% across various voltage gradients

From a technical perspective, it can be concluded that the voltage level in the ohmic process plays a decisive role in the quality characteristics of sour orange juice. Low voltage (5 V cm^{-1}) preserves antioxidant properties, phenolic content, and the natural color of the product, though it may have a lower impact on microbial load reduction and concentration. Conversely, high voltage (10 V cm^{-1}) enhances color changes and increases variables such as soluble solids and BI, but also carries a higher risk of degrading beneficial compounds (like flavonoids). Medium voltage gradients (e.g., 7.5 V cm^{-1}), positioned between the two extremes, may provide a relative balance between preserving bioactive compounds and improving visual qualities. Therefore, the appropriate voltage level should be selected based on the processing goal: if the aim is to protect bioactive and antioxidant compounds, lower voltages are recommended; whereas for improving visual attributes and concentrating solids, higher voltages are more applicable. These findings can help optimize the ohmic process in the beverage and natural extract industries, especially to preserve or enhance the quality of the final product.

In Figure 7, the effects of the ohmic process on the physicochemical and color characteristics of sour orange juice under 30% weight loss are examined. The score plot in Figure 7(a) shows that PC1, with 99% variance, is the main factor distinguishing the samples. In comparison, PC2 explains only 1% of the variations. The V5W30 samples, processed under low voltage gradients (5 V cm^{-1}), are located on the right side of the plot, clearly separated from other groups. This distinct separation indicates the effect of low voltage in preserving the bioactive and color properties of the product. These samples are strongly associated with characteristics such as pH, total phenols, flavonoids, and the color components L* and a*, all of which are positioned in the positive direction of PC1 in the loading plot. In other words, low voltage gradients help retain more beneficial bioactive compounds and reduce unwanted color changes.

In contrast, the V10W30 samples, treated with high voltage, are clustered on the left side of the plot and show correlation with characteristics such as soluble solids content, BI, and color components b* and negative a*. This group is more associated with browning changes, increased soluble sugars, and color alterations resulting from the degradation of pigments and phenolic compounds due to high temperatures caused by higher voltage. The V7.5W30 samples are located near the center of the plot and show more overlap and proximity with the V5W30 group, suggesting a more balanced effect at this voltage level. They were not as degraded as V10W30, yet also not as rich in beneficial compounds as V5W30. The orientation of vectors in the loading plot confirms these findings: quality-enhancing features are located on the right, while negative attributes (such as color change and high Brix) appear on the left, directly correlating with the cluster distribution of the groups. Overall, this analysis indicates that under 30% weight loss, increasing voltage leads to a decline in the physicochemical and color quality of sour orange juice. In contrast, lower voltage gradients better preserve the product’s bioactivity and color. Therefore, depending on the final production goal, optimal selection of the voltage level in the ohmic process is of great importance.

4. Conclusion

In this study, the ohmic process was evaluated as a novel and mild method for processing sour orange juice. The findings showed that low voltage gradients (5 V cm^{-1}), especially under 10% weight loss, led to high retention of flavonoids, total phenols, and L*. This was observed in the PCA clustering, where the V5W10 samples were distinctly separated from other samples. Such characteristics are essential for natural products with significant bioactive and antioxidant value.

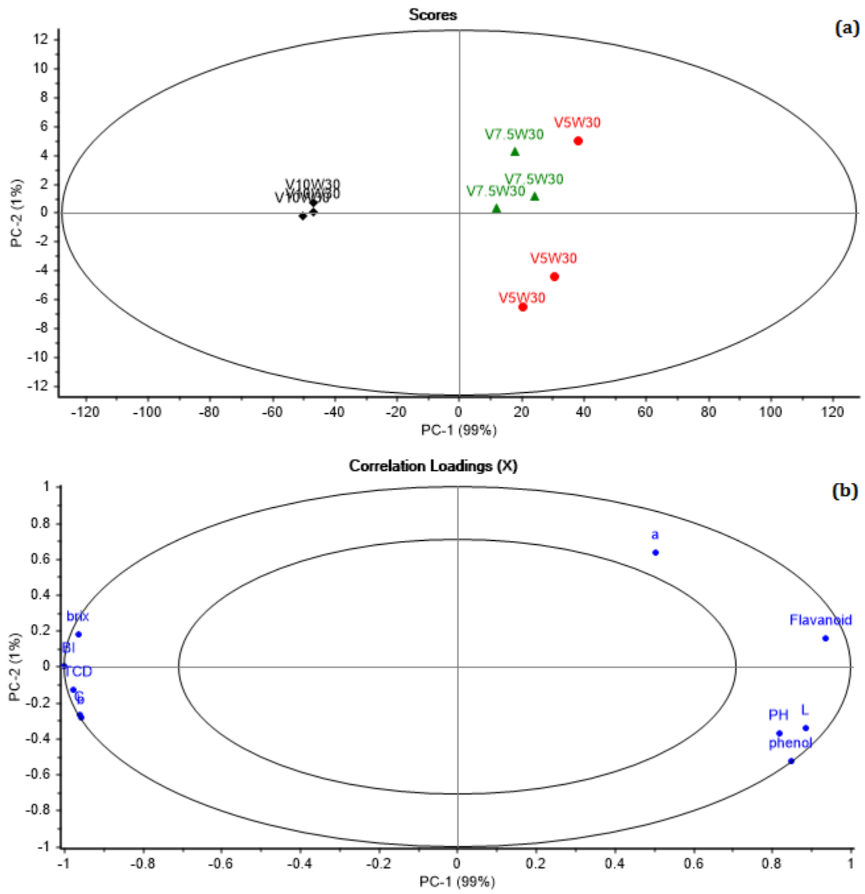

Figure 7. Score and loading plots from PCA at a weight loss of 30% across various voltage gradients

In contrast, using a high voltage gradient (10 V cm^{-1}), particularly at higher weight loss levels (20 and 30%), resulted in increased variables such as soluble sugar, BI, color change, and loss of bioactive compounds. This is likely due to the temperature increase caused by the electric current, which accelerates Maillard reactions and degrades sensitive compounds. Notably, in the V10W30 samples, a significant decline in bioactive compounds was observed, accompanied by increased undesirable color changes and pH shifts. Interestingly, the 7.5 V cm^{-1} voltage gradient played an intermediate role between the two other voltage gradients. Under 10% weight loss conditions, this voltage performed well in maintaining quality; however, at higher weight loss levels, adverse effects began to emerge. Thus, in industrial processes, this voltage level can be considered a balanced option. The comparison between groups showed that the combined impact of voltage and weight loss is highly significant, and neither factor alone can be regarded as solely responsible for the final product quality. Instead, it is the interaction between these two factors that leads to either quality optimization or degradation. Therefore, the ohmic process must be carefully designed to achieve a proper balance between microbial load reduction and quality preservation.

From an industrial standpoint, the results of this study are applicable in optimizing the processing of natural extracts. Especially in cases where the goal is to preserve nutritional and bioactive properties, low voltage and limited weight loss are recommended. In contrast, if the goal is to increase Brix or concentrate the product, higher voltages may be used with precise control over processing time.

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Competing interests

No competing financial interests or personal relationships are known to the authors that could have influenced this study.

Data availability statement

The data supporting the results of this study are available from the corresponding author upon reasonable request.

References

Alkanan, Z. T., Altemimi, A. B., Al-Hilphy, A. R. S., Watson, D. G., & Pratap-Singh, A. (2021). Ohmic heating in the food industry: Developments in concepts and applications during 2013–2020. *Applied Sciences, 11*(6), 2507. https://doi.org/10.3390/app11062507

Astráin-Redín, L., Ospina, S., Cebrián, G., & Álvarez-Lanzarote, I. (2024). Ohmic heating technology for food applications: From ohmic systems to moderate electric fields and pulsed electric fields. *Food Engineering Reviews, 16*(2), 225–251. https://doi.org/10.1007/s12393-024-09368-4

Azadbakht, M., Hashemi Shabankareh, S., Kiapey, A., Rezaeiasl, A., Mahmoodi, M. J., & Torshizi, M. V. (2024a). Assessing kiwifruit quality in storage through machine learning. *Journal of Food Process Engineering, 47*(1), e14681. https://doi.org/10.1111/jfpe.14681

Azadbakht, M., Rayeni Moghbeli, H., & Vahedi Torshizi, M. (2020a). Investigation of the effect of ohmic heat treatment on some mechanical properties of closed pistachio. *Journal of Innovative Food Technologies, 7*(2), 189–200. https://doi.org/10.22104/jift.2019.3383.1810

Azadbakht, M., Rezaeiasl, A., Mahmoodi, M. J., Vahedi Torshizi, M., & Hashemi Shabankareh, S. (2021). Evaluation of ambient light and moisture, and edible coatings in different storage periods on pressurized kiwifruit antioxidant properties. *Journal of Food*

Measurement and Characterization, 15(1), 697–706. https://doi.org/10.1007/s11694-020-00674-z

Azadbakht, M., Torshizi, M. V., & Kashaninejad, M. (2024b). Investigating the variations of sour orange juice color during the heating process. *Agricultural Engineering International: CIGR Journal, 26*(3), 1–12.

Azadbakht, M., Torshizi, M. V., & Kashaninejad, M. (2020b). Application of the response surface method in the analysis of ohmic heating process performance in sour orange juice processing. *Agricultural Engineering International: CIGR Journal, 22*(2), 250–261.

Azadbakht, M., Torshizi, M. V., Ziaratban, A., & Ghajarjazi, E. (2016). Application of artificial neural network (ANN) in predicting mechanical properties of canola stem under shear loading. *Agricultural Engineering International: CIGR Journal, 18*(4), 413–425.

Azadbakht, M., & Vahedi Torshizi, M. (2020b). The antioxidant activity components change of pears subject to static and dynamic loads. *International Journal of Fruit Science, 20*(1), 1255–1275. https://doi.org/10.1080/15538362.2020.1718053

Azadbakht, M., Vahedi Torshizi, M., & Jafari, H. (2020c). Investigation of drying process of different Iranian rice cultivars by ohmic pre-treatment in microwave dryer and modeling by response surface methodology and artificial neural network. *Journal of Innovative Food Technologies, 7*(4), 497–515. https://doi.org/10.22104/jift.2020.3902.1920

Azadbakht, M., Vahedi Torshizi, M., Nouri, N., Varasteh, F., & Kariman, M. (2025). Effects of spermidine, putrescine, and chitosan coatings on the postharvest storage life of pear fruits in different packaging. *Applied Fruit Science, 67*(3), 289. https://doi.org/10.1007/s10341-025-01480-x

Cevik, M. (2021). Electrical conductivity and performance evaluation of the verjuice concentration process using the ohmic heating method. *Journal of Food Process Engineering, 44*(7), e13672. https://doi.org/10.1111/jfpe.13672

Cheng, H. D., Jiang, X. H., Sun, Y., & Wang, J. L. (2001). Color image segmentation: Advances and prospects. *Pattern Recognition, 34*(12), 2259–2281. https://doi.org/10.1016/S0031-3203(00)00149-7

Darvishi, H., Koushesh Saba, M., Behroozi-Khazaei, N., & Nourbakhsh, H. (2020). Improving quality and quantity attributes of grape juice concentrate (molasses) using ohmic heating. *Journal of Food Science and Technology, 57*(4), 1362–1370. https://doi.org/10.1007/s13197-019-04170-1

Dhenge, R., Langialonga, P., Alinovi, M., Lolli, V., Aldini, A., & Rinaldi, M. (2022). Evaluation of quality parameters of orange juice stabilized by two thermal treatments (helical heat exchanger and ohmic heating) and non-thermal (high-pressure processing). *Food Control, 141,* 109150. https://doi.org/10.1016/j.foodcont.2022.109150

Hasan, M. M., Islam, M. R., Haque, A. R., Kabir, M. R., Khushe, K. J., & Hasan, S. M. K. (2024). Trends and challenges of fruit by-products utilization: Insights into safety, sensory, and benefits of the use for the development of innovative healthy food: A review. *Bioresources and Bioprocessing, 11*(1), 10. https://doi.org/10.1186/s40643-023-00722-8

Hwang, J. H., Jung, A. H., & Park, S. H. (2022). Efficacy of ohmic vacuum concentration for orange juice concentrates and their physicochemical properties under different voltage gradients. *LWT - Food Science and Technology, 154,* 112750. https://doi.org/10.1016/j.lwt.2021.112750

Jafarpour, D., & Hashemi, S. M. B. (2022). Ohmic heating application in food processing: Recent achievements and perspectives. *Foods and Raw Materials, 10*(2), 216–223. https://doi.org/10.21603/2308-4057-2022-2-531

Jafarzadeh, S., Azadbakht, M., Varasteh, F., & Vahedi Torshizi, M. (2022). Effects of various coatings and packing materials on persimmon fruit color indexes during quasi-static loading. *Iranian Food Science and Technology Research Journal, 18*(2), 1–12. https://doi.org/10.22067/ifstrj.2021.72937.1098

Kamboj, U., Kaushal, N., & Jabeen, S. (2020). Near infrared spectroscopy as an efficient tool for the qualitative and quantitative determination of sugar adulteration in milk. *Journal of Physics: Conference Series, 1531,* 012024. https://doi.org/10.1088/1742-6596/1531/1/012024

Lalremmawii, Kumar, S., & Kaur, M., & Samota, M. K. (2025). Ohmic heating enhanced the extraction and yield kinetics of kinnow juice. *Discover Food, 5,* 206. https://doi.org/10.1007/s44187-025-00499-z

Mesías, F. J., Martín, A., & Hernández, A. (2021). Consumers' growing appetite for natural foods: Perceptions towards the use of natural preservatives in fresh fruit. *Food Research International, 150,* 110749. https://doi.org/10.1016/j.foodres.2021.110749

Qavanloo, M., Azadbakht, M., Varasteh, F., & Vahedi Torshizi, M. (2023). The effects of ohmic cooking process on some physical and chemical characteristics of button mushrooms. *Journal of Innovative Food Technologies, 10*(3), 281–298. https://doi.org/10.22104/ift.2023.6244.2139

Qavanloo, M., Azadbakht, M., Varasteh, F., & Vahedi Torshizi, M. (2022). Investigation and evaluation of engineering characteristics of ohmic process system during the button mushroom cooking process. *Agricultural Mechanization Systems Research, 23*(1), 87–102. https://doi.org/10.22092/amsr.2023.361338.1440

Qavanloo, M., Varasteh, F., & Vahedi Torshizi, M. (2023). Analysis of energy and exergy in the ohmic process during cooking: A case study of button mushroom. *Food Engineering Research, 22*(3), 195–208. https://doi.org/10.22092/fooder.2023.360992.1355

Sharifi, A., Hamidi-Esfahani, Z., Ahmadi Gavlighi, H., & Saberian, H. (2022). Assisted ohmic heating extraction of pectin from pomegranate peel. *Chemical Engineering and Processing: Process Intensification, 172,* 108760. https://doi.org/10.1016/j.cep.2021.108760

Silva, R., Rocha, R. S., Ramos, G. L. P. A., Xavier-Santos, D., Pimentel, T. C., Lorenzo, J. M., Henrique Campelo, P., Cristina Silva, M., Esmerino, E. A., Freitas, M. Q., & Cruz, A. G. (2022). What are the challenges for ohmic heating in the food industry? Insights of a bibliometric analysis. *Food Research International, 157,* 111272. https://doi.org/10.1016/j.foodres.2022.111272

Tunç, M. T., Akdoğan, A., Baltacı, C., Kaya, Z., & Odabaş, H. İ. (2022). Production of grape pekmez by ohmic heating-assisted vacuum evaporation. *Food Science and Technology International, 28*(1), 72–84. https://doi.org/10.1177/1082013221991616

Vahedi Torshizi, M., Azadbakht, M., & Kashaninejad, M. (2024). Analyzing greenhouse gas emissions in the ohmic heating drying process of sour orange juice. *Agricultural Engineering International: CIGR Journal, 26*(2), 1–12.

Vahedi Torshizi, M., Azadbakht, M., & Kashaninejad, M. (2020). Application of response surface method to energy and exergy analyses of the ohmic heating dryer for sour orange juice. *Fuel, 278,* 118261. https://doi.org/10.1016/j.fuel.2020.118261

Vahedi Torshizi, M., Azadbakht, M., & Kashaninejad, M. (2019). Investigation of experiment data and sensitivity coefficient data with artificial neural network in the ohmic heating process for sour orange juice. *Carpathian Journal of Food Science and Technology, 11*, 15–27. https://doi.org/10.34302/crpjfst/2019.11.3.2

Vahedi Torshizi, M., Azadbakht, M., & Kashaninejad, M. (2021). Investigation of color changes in sour orange juice during the ohmic heating process by response surface method. *Agricultural Mechanization Systems Research, 22*(2), 81–96. https://doi.org/10.22092/AMSR.2021.354561.1384

Vahedi Torshizi, M., Azadbakht, M., & Kashaninejad, M. (2020). A study on the energy and exergy of ohmic heating (OH) process of sour orange juice using an artificial neural network (ANN) and response surface methodology (RSM). *Food Science and Nutrition, 8*(8), 4432–4445. https://doi.org/10.1002/fsn3.1741

Vahedi Torshizi, M., Azadbakht, M., & Kashaninejad, M. (2019). Investigating effect of physical factors on ohmic thermal process performance in sour orange juice processing. *Journal of Innovative Food Technologies, 7*(1), 1–15. https://doi.org/10.22104/jift.2019.3411.1818

Vahedi Torshizi, M., & Kashaninejad, M. (2022). Investigation of changes in the qualitative properties of sour orange juice during the ohmic heating process. *Food Engineering Research, 21*(1), 1–14. https://doi.org/10.22092/fooder.2022.353850.1297

Vahedi Torshizi, M., Rokhbin, A., & Mahmoodi, M. J. (2025). The effect of different pre-treatments on the rate of changes in the thermal properties of rosemary leaves. *Biosystems Engineering and Renewable Energies, 1*(1), 29–36. https://doi.org/10.22069/bere.2024.22957.1004