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Investigating the Impact of Chilling Injury on Physical and Chemical Changes in Pomegranate Fruit

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Abstract

Given the importance of extending pomegranate storage life and reducing postharvest losses, this study investigated the effects of chilling injury during cold storage. Chilling injury is a major factor limiting pomegranate quality, causing changes in texture and chemical composition. The objective was to evaluate its effects on the physicochemical properties of 'Wonderful' pomegranate fruits by comparing fresh fruits (control) with fruits stored at 0 ± 0.5°C for two months (chilling-injured). Measured parameters included firmness (kg/cm^2), weight (g), soluble solids content (SSC, °Brix), pH, and titratable acidity (TA, % citric acid). Firmness was determined using a texture analyzer, SSC with a digital refractometer, pH with a pH meter, and TA by titration. Data were analyzed using SAS, and principal component analysis (PCA) was applied to compare healthy and chilling-injured fruits. Results showed that healthy fruits had significantly higher firmness than injured fruits (88.76 vs. 60.89 kg/cm^2, $P < 0.05$), whereas weight did not differ significantly (143.38 vs. 140.43 g, $P > 0.05$). Injured fruits had higher SSC (20.34 vs. 17.18 °Brix, $P < 0.05$), lower pH (2.84 vs. 3.02, $P < 0.05$), and higher TA (1.01% vs. 0.821% citric acid, $P < 0.05$). Overall, chilling injury caused softer texture, increased SSC, and altered acidity, indicating reduced suitability for fresh consumption but potential value for juice processing, where higher SSC and TA may be advantageous.

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1. Introduction

Postharvest quality of fruits is a key factor in market competitiveness, waste reduction, and consumer satisfaction. This is because physical characteristics such as firmness, color, and texture uniformity, along with chemical indicators like TSS (Total Soluble Solids), TA (Titratable Acidity), and pH, directly influence sensory acceptance and commercial value (Azadbakht et al., 2019a, 2019b, 2022).

Pomegranate is an economically important fruit crop in many countries, with significant export value. However, postharvest losses due to improper temperature management during cold storage are estimated at 15%-30% annually, depending on storage conditions and duration. Chilling injury, which occurs when fruits are exposed to temperatures at or below 0°C, is a major contributor to these losses, leading to fruit softening, discoloration, and reduced marketability. Quantifying the physicochemical changes caused by chilling injury is essential for developing improved storage protocols and reducing economic waste.

A thorough examination of the impact of chilling injury on the physical and chemical properties of pomegranate fruit requires a scientific, systematic approach that encompasses all dimensions of this phenomenon. Initially, it is necessary to define the key parameters related to healthy pomegranate fruit as a baseline. These criteria include physical specifications such as weight, dimensions, volume, external appearance, skin and aril color, tissue consistency and firmness, and even the extent of enzymatic activities under natural conditions. Furthermore, the chemical profile of healthy pomegranate fruit, including the concentration of sugars (such as fructose, glucose, and sucrose), organic acids (like citric acid), and pH, must be comprehensively identified. Although other compounds, such as vitamin C, phenolic compounds, and antioxidants, are important for pomegranate quality, they were not measured in the present study. This initial understanding provides the basis and foundation against which the changes induced by chilling injury will be measured and compared. Without precise and comprehensive data from healthy fruit, assessing the extent of damage and changes caused by chilling injury will lack sufficient accuracy and validity (Darvishi et al., 2013; M. Abbas & Al Bamarny, 2023; Mirdehghan et al., 2007).

The effect of chilling injury on the physical structure of pomegranate fruit is a tangible, observable aspect of this phenomenon. When the fruit's temperature drops below freezing point, water molecules within the cells and intercellular spaces begin to form ice crystals. This process, known as "internal freezing," increases volume and exerts pressure on cell membranes. Higher degrees of chilling injury lead to the rupture and destruction of cellular structures. Consequently, the fruit's firmness and consistency are significantly reduced, and its texture becomes soft and spongy (Icier et al., 2017; Nikbakht et al., 2014). The fruit peel may also become wrinkled, darkened, and more brittle. Pigments present in the skin and arils may also be affected, leading to color changes. Additionally, the fruit's size and external appearance may change, potentially making it appear bruised or misshapen. These physical changes not only affect the fruit's appearance but also influence subsequent processes such as cutting, peeling, and processing (Opara et al., 2015b; Tarighi et al., 2011).

At the chemical level, freezing can lead to complex alterations in the biochemical composition of pomegranate fruit. As cell membranes are disrupted, intracellular enzymes and compounds are released and begin to interact. These interactions may result in the degradation of sugars, reductions in vitamin levels (particularly vitamin C, which is highly sensitive to cold and oxidation), and changes in the organic acid profile. However, phenolic compounds and other antioxidants are important for pomegranate quality (Aboutalebi et al., 2026; Azadbakht & Vahedi Torshizi, 2020). They were not analyzed in the present study, which focused on basic physicochemical parameters. Moreover, leakage of intracellular contents into the intercellular spaces, along with water loss through evaporation, may lead to the concentration of certain soluble compounds and, consequently, alterations in the fruit's flavor profile. Such chemical transformations can negatively impact the nutritional value and potential therapeutic properties of pomegranate (Aboutalebi et al., 2025; Opara et al., 2015a; Yildiz et al., 2009).

A comparative analysis between chilling-injured and fresh pomegranate fruit enables quantification of freeze-induced damage. Using standard physical and chemical analytical techniques, changes in multiple parameters can be assessed. For instance, texture analyzers can be employed to determine reductions in tissue firmness. Standard analytical techniques allow precise measurement of sugar, acid, and other compound concentrations in both fruit groups, although such detailed chemical profiling was beyond the scope of the present study. Additionally, imaging techniques and colorimetric analyses can be used to quantitatively assess changes in peel and aril color. Such detailed comparisons enable the determination of the tolerance threshold of pomegranate fruit to freezing and the quantification of damage at various freezing intensities (Barman et al., 2011; Meighani et al., 2014).

Understanding these changes is of great significance in agriculture and the food industry. In cases where pomegranate fruit is accidentally exposed to freezing conditions, this knowledge helps farmers estimate the extent of damage and make informed decisions regarding its sale or processing. For producers of pomegranate-based products (such as juice, paste, and extracts), awareness of the physical and chemical changes caused by freezing is essential to ensure product quality, optimize manufacturing processes, and preserve the final product's nutritional and sensory attributes. For example, if freezing leads to a substantial reduction in vitamin C, fortification of the final product may be necessary. Therefore, the specific objectives of this study were to: (1) compare selected physicochemical attributes (Firmness, weight, SSC, pH, and TA) between healthy and chilling-injured 'Wonderful' pomegranate fruits stored at 0°C for two months; (2) quantify the statistical significance of differences between the two groups; and (3) apply Principal Component Analysis (PCA) to identify correlations among the measured parameters.

While previous studies have investigated chilling injury in pomegranates at temperatures above freezing (2–5°C), the specific effects of chilling injury (storage at 0°C) on the physical and chemical properties of 'Wonderful' pomegranate have not been systematically quantified. Most existing research has focused on either aril quality or juice composition, with limited attention to whole-fruit physico-chemical changes after freezing. Furthermore, the combined assessment of Firmness, SSC, pH, and titratable acidity using multivariate analysis (PCA) in chilling-damaged pomegranates is lacking in the literature. Therefore, the novelty of this study lies in: (1) quantifying freezing-induced changes in whole 'Wonderful' pomegranate fruits stored at 0°C for two months; (2) providing a comparative statistical analysis between fresh and chilling-injured samples; and (3) applying Principal Component Analysis (PCA) to identify the most influential quality parameters affected by chilling injury. This research addresses the identified gap by offering systematic data on freeze-related quality deterioration in pomegranate.

2. Materials and Methods

2.1. Sample Preparation

Eighty 'Wonderful' pomegranate fruits at commercial maturity were used. Fruits were divided into two groups of 40 each: fresh (control) and chilling-injured. The chilled group was stored in a cold-storage chamber at 0 ± 0.5°C for two months. The storage chamber was maintained at a relative humidity of 81 ± 5%. Fruits were placed in ventilated plastic crates without individual packaging to allow adequate air circulation. Continuous mechanical ventilation was provided to ensure uniform temperature and humidity distribution throughout the storage period. Temperature and relative humidity were monitored regularly using a digital data logger. Fruits were randomly selected from a single commercial orchard at harvest and randomly assigned to the two treatment groups (fresh and chilled).

After storage, both groups were removed and allowed to equilibrate to room temperature (25°C) for 2 hours before measurements. The following parameters were measured for each fruit: firmness (kg/cm²), weight (g), soluble solids content (SSC, °Brix), pH, and titratable acidity (TA, % citric acid).

2.2. Measurement of Physicochemical Properties

To determine the physical properties of the pomegranate before loading. The selected samples were weighed using a digital balance with an accuracy of 0.001 g.

2.2.2. Firmness

Fruit firmness was measured using a texture analyzer (Model TA.XTplus, Stable Micro Systems, UK) equipped with a 5-mm-diameter cylindrical probe. Each pomegranate fruit was placed on the platform, and the probe was driven into the fruit surface to a depth of 5 mm at a constant speed of 1 mm/s. The maximum force (N) recorded during penetration was converted to kg/cm². Measurements were performed in triplicate on three different points of each fruit, and the average value was reported (Vahedi Torshizi et al., 2020).

2.2.3. pH measurement

Pomegranate juice was extracted from each fruit using a manual juicer. The pH of the fresh juice was measured immediately after extraction using a digital pH meter (Model 8689, AZ Instrument orp., Taiwan) equipped with a glass electrode. The pH meter was calibrated using standard buffer solutions at pH 4.0 and 7.0 before each measurement session. The electrode was rinsed with distilled water between samples. All measurements were performed in triplicate for each fruit, and the average value was recorded (Azadbakht et al., 2026a; Jafarzadeh et al., 2022).

2.2.4. Measurement of dissolved solids

Fresh pomegranate juice was extracted from each fruit using a manual juicer. The juice was filtered through double-layered cheesecloth to remove pulp and seeds. A few drops of the filtered juice were placed on the prism of a digital refractometer (Model MT-032ATC, Taiwan), and the soluble solids content was recorded as °Brix. The refractometer was calibrated with distilled water before each measurement session. Measurements were performed in triplicate for each fruit (Azadbakht, Vahedi, et al., 2026b).

2.2.5. Titratable acidity measurement

Titratable acidity was determined by titration with 0.1 N sodium hydroxide (NaOH). Two mL of fresh pomegranate juice was diluted with 38 mL of distilled water in a 100 mL beaker. Three drops of phenolphthalein indicator (1% solution in 95% ethanol) were added to the diluted juice. The solution was then titrated with 0.1 N NaOH until a persistent pale pink color appeared (pH ≈ 8.2). The volume of NaOH used was recorded (Patel et al., 2019).

$$\mathrm{TA}(\%) = (V \times N \times 64.04) / (W \times 1000) \times 100 \quad (1)$$

where V = volume (mL) of NaOH used, N = normality of NaOH (0.1 N), 64.04 = equivalent weight of citric acid (g/mol), and W = sample volume (2 mL).

2.3. Statistical Analysis

The experiment was conducted as a completely randomized design (CRD) with two treatments (healthy and chilling-injured pomegranate fruits), each consisting of 40 fruits. Statistical analyses were performed using SAS software version 9.2. Analysis of variance (ANOVA) was used to evaluate the effect of pomegranate type on the measured physicochemical properties. When significant differences were detected at the 5% probability level ($P < 0.05$), mean comparisons were performed using the Least Significant Difference (LSD) test.

2.4. Principal Component Analysis (PCA)

Principal Component Analysis (PCA) was performed using The Unscrambler X 10.4 software (CAMO Analytics, Norway) to examine correlations between pomegranate type (fresh vs. chilled) and the measured physicochemical properties (Firmness, weight, SSC, pH, TA). PCA reduces data dimensionality by transforming correlated variables into uncorrelated principal components (Vahedi Torshizi et al., 2025).

3. Results and Discussion

The analysis of variance (ANOVA) clearly demonstrated that the freezing process had statistically significant effects on several pomegranate quality attributes, while others remained unaffected. Regarding fruit firmness, the P-value was less than 0.0001 (Pr>F = <.0001), indicating a substantial reduction in firmness in chilling-injured samples compared with fresh ones. Similarly, the soluble solids content (SSC) increased significantly ($P < .0001$), likely due to water loss and the resulting solute concentration during freezing and thawing. Changes in pH and titratable acidity were also statistically significant ($P = 0.0004$ for pH and $P < .0001$ for acidity). The observed decrease in pH and the increase in titratable acidity in chilling-injured pomegranates suggest enhanced release or formation of organic acids, which may influence the fruit's flavor profile.

In contrast, overall fruit weight exhibited no statistically significant difference ($P = 0.442$), implying that the water loss associated with freezing was either negligible at the whole-fruit level or offset by other factors.

The statistical evaluation of pomegranate firmness showed that fresh samples were significantly firmer than chilling-injured samples. The mean firmness score for the fresh pomegranates was 88.76, compared with 60.89 for the chilling-injured samples. Statistical analysis, which assigned the letter 'a' to the fresh group and 'b' to the chilling-injured group, confirmed the presence of a statistically significant difference ($P < 0.05$) between the two groups. This notable reduction in firmness of chilling-injured pomegranates can be attributed to the destructive effects of freezing on the cell wall structure and the pectin matrix. It is hypothesized that the formation of intracellular ice crystals causes rupture of cell membranes and may degrade cell wall components, including pectin and protein–carbohydrate networks, which are responsible for maintaining tissue strength and integrity. However, direct measurements of cell wall structure were not performed in this study.

Table 1. ANOVA results for chilling-injured and fresh pomegranate samples.

	df	Mean Square	F Value	Pr > F
			Firmness	
Pomegranate type	1	16671.558	47.32	<.0001
Error	78		352.332	
CV			24.91	
			SSC	
Pomegranate type	1	28.025	22.78	<.0001
Error	78		1.2301182	
CV			7.25	
			Acidity	
Pomegranate type	1	77421125.0	21.91	<.0001
Error	78		3533637.8	
CV			20.42	
			Weight	
Pomegranate type	1	174.050	0.60	0.442
Error			292.486	
CV			**12.05**	
			pH	
Pomegranate type	1	0.6319	13.55	0.0004
Error	78		0.0466	
CV			7.36	

The analysis of fruit weight after storage indicated no statistically significant difference between fresh and chilling-injured samples. The mean weight for fresh pomegranates was 143.38 g, while that of chilling-injured samples was 140.43 g. Both values were marked with the letter ‘a’ in the results table, indicating the absence of a significant statistical difference (P > 0.05) between the two groups. This finding suggests that the freezing process and low-temperature storage did not exert a substantial effect on overall fruit mass at a statistically detectable level. Although some water loss may occur during thawing, the amount was likely insufficient to produce a measurable difference in total fruit weight.

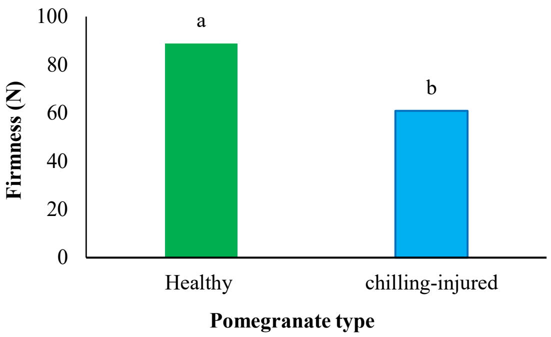

Figure 1. Comparison of the mean Firmness of chilling-injured and fresh pomegranate samples.

The soluble solids content (SSC), a key indicator of sugar concentration and sweetness, was significantly higher in chilling-injured pomegranates compared with fresh ones. The mean SSC value for the chilling-injured group was 20.34, while the fresh group showed a mean of 17.18. The assignment of the letter ‘a’ to the chilling-injured samples and ‘b’ to the fresh samples confirms a statistically significant difference (P < 0.05). This increase in soluble solids concentration in chilling-injured fruit is likely due to water loss via osmotic processes during freezing and thawing. As water molecules exit the cells, the concentration of sugars, organic acids, and other soluble compounds in the remaining intracellular spaces increases. This phenomenon may affect the flavor profile of chilling-injured pomegranate, making it appear sweeter, although freshness and flavor complexity may diminish.

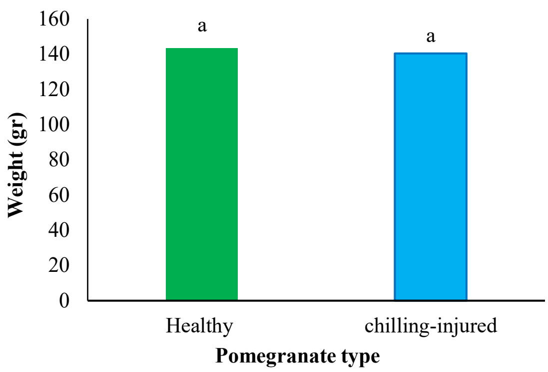

Figure 2. Comparison of the mean weight of chilling-injured and fresh pomegranate samples.

The pH value, which reflects overall acidity or alkalinity, was significantly higher in fresh pomegranates than in chilling-injured samples. The mean pH of the fresh group was 3.02, whereas the chilling-injured group showed a mean of 2.84. Statistical analysis, with ‘a’ assigned to the fresh samples and ‘b’ to the chilling-injured samples, confirmed a significant difference (P < 0.05). The reduction in pH in chilling-injured pomegranates indicates a general increase in acidity. This phenomenon may result from several factors: (1) the release of organic acids from cellular vacuoles due to freeze-induced cell damage; and (2) alterations in cellular buffering systems in response to cold stress. A lower pH typically corresponds to a more tart flavor and can also influence microbial activity. In pomegranates, citric acid is the predominant organic acid, followed by malic acid. The decrease in pH observed in chilled fruits corresponds to the increase in titratable acidity, as these two parameters are inversely related.

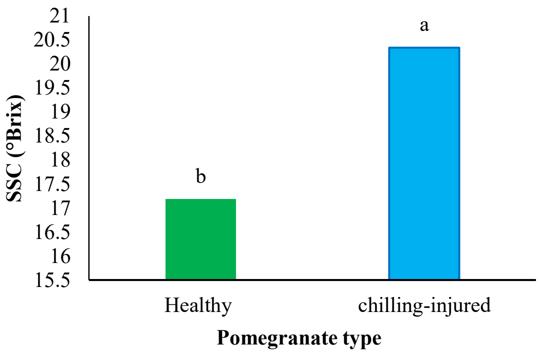

Figure 3. Comparison of the mean SSC of chilling-injured and fresh pomegranate samples.

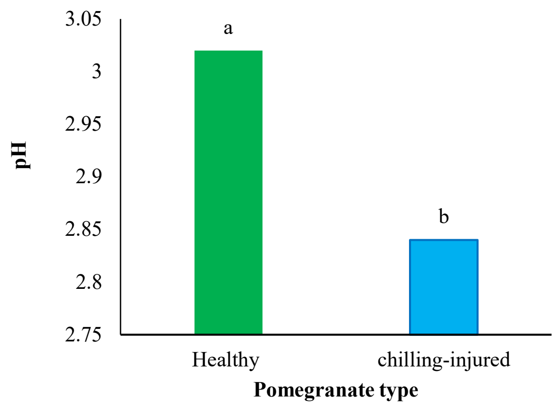

Figure 4. Comparison of the mean pH of chilling-injured and fresh pomegranate samples.

In contrast to the pH findings, the titratable acidity (TA)—which measures the total amount of organic acids in the fruit—was significantly higher in chilling-injured pomegranates compared with fresh ones. The mean TA value for the chilling-injured group was 1.01, while the fresh group averaged 0.821. The assignment of the letter 'a' to the chilling-injured samples and 'b' to the fresh samples confirms this statistical difference ($P < 0.05$). The increase in TA supports the pH results. The freezing–thawing process can break down complex compounds and release free organic acids, such as citric and malic acids. Alternatively, the increase in TA may not result from de novo synthesis (given the low metabolic activity at 0°C) but rather from the release of organic acids from cellular compartments (vacuoles) following membrane disruption during chilling injury. This heightened acidity can influence the flavor profile of chilling-injured pomegranate, making it noticeably more tart.

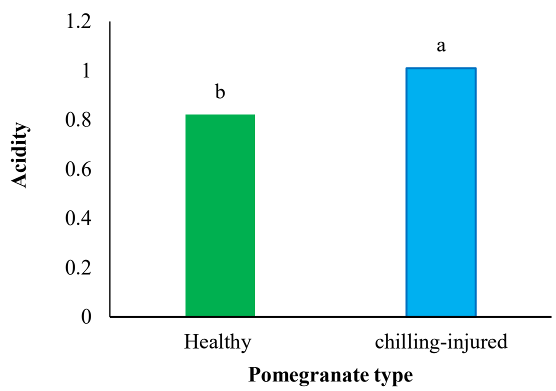

Figure 5. Comparison of the mean acidity of chilling-injured and fresh pomegranate samples.

Table 2 shows a moderately strong negative correlation between Firmness and acidity ($r = -0.33$). With a P-value of 0.0028, this relationship is statistically significant, indicating that within the range of the collected data, higher acidity is generally associated with lower firmness. In contrast, the correlations between firmness and weight ($r = 0.07986$), Firmness and SSC ($r = -0.0729$), and firmness and pH ($r = 0.19164$) exhibit substantially higher P-values (approximately 0.48 to 0.0886), providing no strong statistical evidence for meaningful linear associations among these variables. Similarly, weight does not display a reliable statistically significant correlation with the other traits. For instance, the correlation between weight and SSC ($r = 0.20352$, $P = 0.0702$) does not reach significance at commonly accepted thresholds such as $P < 0.05$, indicating that weight alone does not present a clear or consistent linear relationship with the remaining characteristics.

A notable pattern emerges in the relationship between pH and acidity. The correlation coefficient for these variables is $r = -0.3731$ with a P-value of 0.0007, confirming a statistically significant association. This finding implies that as pH increases—reflecting a reduction in effective acidity in most food systems—titratable acidity tends to decrease, consistent with established acid–base chemistry. The correlation between SSC and pH ($r = -0.2021$, $P = 0.0723$) does not meet the conventional significance threshold ($P < 0.05$), although it may suggest a weak or borderline trend. Finally, the correlation between SSC and acidity ($r = 0.14352$, $P = 0.2041$) offers no strong statistical support for a meaningful linear relationship.

Overall, Table 2 indicates that among the evaluated variables, only the relationships between firmness–acidity and pH–acidity are statistically consistent and significant. Weight and SSC, aside from minor tendencies, do not exhibit strong or meaningful linear correlations with the other quality parameters.

Table 2. Correlation of physical and chemical properties of pomegranate

	Firmness	Weight	SSD	pH	Acidity
Firmness	1	0.07986 0.4813	-0.0729 0.5207	0.19164 0.0886	-0.33 0.0028
Weight	0.07986 0.4813	1	0.20352 0.0702	0.06695 0.5551	-0.1337 0.2372
SSC	-0.0729 0.5207	0.20352 0.0702	1	-0.2021 0.0723	0.14352 0.2041
pH	0.19164 0.0886	0.06695 0.5551	-0.2021 0.0723	1	-0.3731 0.0007
Acidity	-0.33 0.0028	-0.1337 0.2372	0.14352 0.2041	-0.3731 0.0007	1

Figure 6 displays a score plot that effectively differentiates between fresh and chilling-injured pomegranate samples. The fresh fruit samples exhibit greater dispersion compared to the chilling-injured samples. The chilling-injured fruits are predominantly located on the negative axis (left side) of the plot, while the fresh fruits are situated on the positive axis (right side). Furthermore, the chilling-injured samples show a tighter concentration distribution, indicating less variability in their characteristics, whereas the fresh samples display a wider distribution. This suggests greater heterogeneity among the fresh fruit samples regarding the measured attributes, with the chilling-injured samples being more uniform.

Based on the correlation loadings, weight, pH, and firmness show a positive direct relationship. Similarly, SSC and acidity exhibit a positive, direct relationship. These two groups of characteristics also display an inverse relationship. These findings are consistent with the statistical analyses, both in the significance of the relationships and in the nature of the associations (positive or negative).

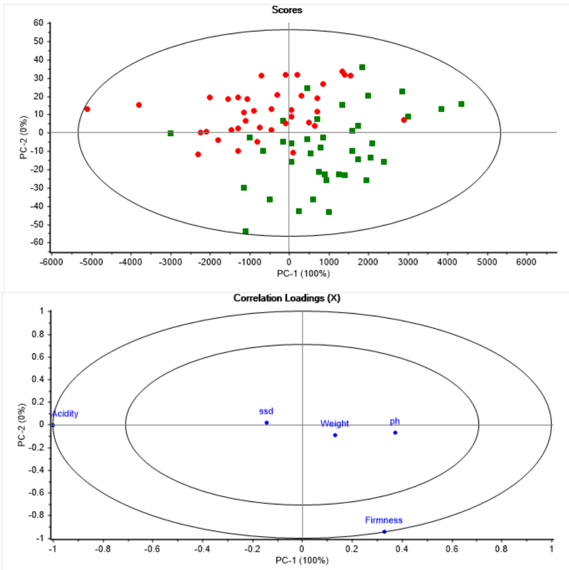

Figure 6. (Scores) plot from Principal Component Analysis (PCA) for Pomegranate fruit based on physical and chemical properties

Table 3 presents the factor loadings for each measured variable (Firmness, Weight, SSC, pH, Acidity) onto the Principal Components (PCs). These loadings are the correlation coefficients between the original variables and their corresponding principal components, indicating the extent to which each variable contributes to defining and orienting each component.

The first principal component (PC-1) exhibits the strongest negative loading on acidity (-1), indicating that PC-1 primarily represents a gradient of decreasing acidity. It also shows a substantial positive loading with pH (0.37305) and a weaker positive loading with firmness (0.33001). This component can be interpreted as an “overall quality index” or “freshness factor,” where higher PC-1 values (associated with lower acidity, higher pH, and greater firmness) correspond to more desirable quality attributes. Weight (0.13366) and SSC (-0.14352) have the least influence on this component, with small positive and negative loadings, respectively.

The second principal component (PC-2) is heavily dominated by firmness, with a very strong negative loading (-0.94275), indicating that this component primarily represents “lack of firmness” or softness. The other variables have negligible impact on PC-2: Weight (-0.08827), SSC (0.01551), pH (-

0.07325), and acidity (0.00004) all show loadings close to zero. Thus, PC-2 can be considered a component that predominantly explains variations in fruit firmness.

The third principal component (PC-3) is strongly influenced by weight, with a very strong negative loading (-0.98709). This component largely represents “low weight” or lightness in the samples. SSC also shows a significant negative loading (-0.22816), suggesting that samples with lower weight tend also to have lower SSC. Firmness (0.04806) and pH (-0.01058) have minimal effects on this component.

Table 3. PCA Correlation loading

	Firmness	Weight	ssc	ph	Acidity
PC-1	0.33001	0.13366	-0.14352	0.37305	-1
PC-2	-0.94275	-0.08827	0.01551	-0.07325	-0.00004
PC-3	0.04806	-0.98709	-0.22816	-0.01058	0.00001
PC-4	-0.00009	0.00119	-0.96285	0.16054	-0.00001

The fourth principal component (PC-4) is almost exclusively defined by SSC, with a very strong negative loading (-0.96285). This component effectively captures variations in soluble solid content. pH has a small positive loading (0.16054), but its influence is considerably less than that of SSC. The remaining variables (Firmness, Weight, Acidity) have loadings close to zero.

This Principal Component Analysis (PCA) indicates that the first three components (PC-1, PC-2, and PC-3) capture the majority of the total data variance: PC-1 relates to a combination of pH and acidity (and to some extent Firmness), PC-2 is associated with firmness, and PC-3 is linked to weight. PC-4 primarily accounts for the variance related to SSC. These derived components can serve as new, uncorrelated dimensions for subsequent analyses, such as modeling or clustering, as they effectively compress the original variables into a reduced set of dimensions while mitigating linear collinearity. Table 3 presents the factor loadings for each measured variable onto the principal components (PCs).

4. Conclusion

This study demonstrated that chilling injury (storage at 0°C for two months) significantly impacts the quality of 'Wonderful' pomegranate fruits. Key findings indicate that chilled pomegranates are markedly softer than fresh counterparts (88.76 vs. 60.89 kg/cm², $P < 0.05$). Additionally, chilled fruits exhibit higher concentrations of soluble solids (20.34 vs. 17.18 °Brix, $P < 0.05$) and titratable acidity (1.01% vs. 0.821% citric acid, $P < 0.05$), accompanied by a corresponding decrease in pH (2.84 vs. 3.02, $P < 0.05$). These physicochemical modifications are likely to affect fruit texture and flavor, although direct sensory evaluation was not performed in this study. In contrast, overall fruit weight did not differ significantly after chilling storage ($P > 0.05$). Correlation analyses revealed negative relationships between firmness and acidity ($r = -0.33$, $P = 0.0028$) and between pH and acidity ($r = -0.37$, $P = 0.0007$). PCA clearly distinguished fresh from chilled samples, confirming the multivariate impact of chilling injury on fruit quality.

Several limitations of this study should be acknowledged. First, only one pomegranate cultivar ('Wonderful') was examined, so the findings may not be generalizable to other cultivars. Second, the study focused on a limited set of physicochemical parameters; other quality attributes such as phenolic compounds, antioxidant activity, and vitamin C were not measured. Third, no direct sensory evaluation was conducted to link physicochemical changes to consumer perception. Fourth, microscopic examination of cell wall damage was not performed.

Based on these findings, the following recommendations are proposed for future research: (1) investigating the effects of chilling injury on other commercially important pomegranate cultivars; (2) examining the efficacy of postharvest treatments (e.g., edible coatings, polyamines) in mitigating chilling injury symptoms; (3) conducting sensory evaluation to correlate physicochemical changes with consumer acceptability; and (4) using microscopic imaging to visualize cell wall damage in chilled tissues directly.

For the food industry, these findings offer insights for assessing the quality of chilled pomegranates and optimizing storage procedures. Chilled pomegranates with increased SSC and TA may be suitable for juice processing, while softening limits their suitability for fresh consumption.

Author Contributions

M.Vahedi Torshizi: Conceptualization, Methodology, Investigation, Formal analysis, Data curation, Software, Validation, Visualization, Writing – original draft

M, Azadbakht and Sajad Sabzi: Conceptualization, Methodology, Resources, Supervision, Validation, Project administration, Writing – review & editing.

Raziyeh Pourdarbani: Conceptualization, Design, Methodology, Investigation, Formal analysis, Data curation, Supervision, Validation, Writing – review & editing.

M.J. Mahmoodi: Investigation, Formal analysis, Data curation, Software

Data Availability Statement

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

Ethical Considerations

This study was conducted in accordance with ethical research standards. No data fabrication, falsification, plagiarism, or other research misconduct occurred during the preparation of this manuscript. No human or animal subjects were involved; therefore, formal ethical approval was not required. Additionally, no generative artificial intelligence tools (such as ChatGPT, Claude, or Gemini) were used in producing this article.

Conflict of Interest

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