



Preservation Challenges in Cherry Tomatoes: Evaluating Freezing Methods for Improved Color and Structural Integrity

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Abstract

Cherry tomato (*Solanum lycopersicum* L. var. *cerasiforme*) is a high-value horticultural product widely consumed due to its desirable sensory qualities and health-promoting properties. However, preserving its quality during freezing remains challenging, particularly because of freezing-induced skin cracking and color degradation. This study evaluated the effects of four freezing methods, multistage freezing (MF), individual quick freezing (IQF), static freezing (SF), and vacuum-assisted IQF (V+IQF), on the quality of cherry tomatoes during six months of storage at -20°C . Enzymatic activities of pectin methylesterase (PME), polygalacturonase (PG), and lipoxygenase (LOX), along with physicochemical properties including pH value, titratable acidity, soluble and total solids, lycopene content, color, and skin cracking, were determined. IQF resulted in the highest level of skin cracking, whereas V+IQF significantly reduced cracking; MF and SF showed intermediate effects. Residual PME, PG, and LOX activities were positively correlated with color and lycopene content, while skin cracking was negatively correlated with these attributes. Among the evaluated methods, V+IQF most effectively preserved structural integrity and color stability by reducing skin cracking and improving lycopene retention during long-term storage, demonstrating the potential of vacuum-assisted rapid freezing as an industry-relevant strategy for mitigating freezing-induced quality deterioration in cherry tomatoes.

Keywords Cherry tomato · Freezing methods · Post-freezing quality · Color retention · Enzyme activity · Storage

Introduction

The freezing process is widely recognized as an effective preservation method that can minimize nutrient losses compared to other processing techniques, while maintaining the sensory and nutritional quality of food products [1, 2]. In addition to the reduction in nutrient loss, the convenience of preparation, standardized availability, and time-saving

benefits for working people have made ready-made and frozen food products highly desirable [3]. The freezing process induces significant structural and biochemical changes in food materials, resulting in products with enhanced shelf life, year-round availability, uniform quality, and ease of preparation. Frozen food production has experienced remarkable growth in terms of both quantity and variety since the 1930s, concomitant with the evolving lifestyle patterns of consumers and the associated benefits of frozen food products [4].

In plant tissues, freezing often leads to cellular damage, as ice formation begins in the extracellular regions during the freezing process [5]. The extent of freezing damage is closely associated with the freezing rate, with slow freezing promoting the formation of large ice crystals that disrupt cellular integrity and result in cell volume expansion, elevated solute cryoconcentration, loss of cellular compartmentalization, and enhanced oxidative processes [6, 7]. Even when intracellular ice formation occurs at high freezing rates, both freezing conditions may lead to structural damage unless freezing parameters are properly

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controlled and optimized. Tissue weakening may cause differential contraction and internal stress, thereby promoting skin cracking. Pre-treatment strategies have been developed based on the biochemical changes that occur in plant tissues during freezing. Structural stabilization of the cell wall and membrane through targeted pre-treatments helps preserve membrane integrity and cellular compartmentalization, thereby limiting freezing-induced biochemical reactions and subsequent quality deterioration. Various pretreatment strategies including osmotic dehydration, vacuum impregnation [3, 8], sugar soaking, exogenously applied pectin methylesterase (PME), and the synergistic application of PME and CaCl_2 combined with heat pre-treatment [9] have been employed to mitigate freezing-induced biochemical reactions by stabilizing cellular structure, reducing enzyme activity, and limiting enzyme–substrate interactions that accelerate quality deterioration during freezing and subsequent storage.

Tomatoes (*Solanum lycopersicum*) are among the most widely produced and consumed horticultural crops worldwide, representing substantial agricultural and economic value [10]. Despite their global importance, tomatoes are highly susceptible to post-harvest deterioration, particularly under low-temperature conditions that may induce chilling injury and structural damage [11].

Despite being primarily processed, fresh tomatoes are still in demand, as consumers prefer healthy, nutritious foods with a fresh appearance [12]. Nevertheless, harvested tomatoes are highly susceptible to low temperatures and are prone to chilling injuries when exposed to freezing or prolonged cold storage. Chilling injuries refer to physiological alterations in fruits and vegetables that arise when they are stored at temperatures lower than their tolerance limits. The symptoms of chilling injuries include skin cracking, color changes, and textural losses, which can reduce the quality and shelf life of the fruits [13–15]. It is stated that pre-cooling, optimization of freezing speed, vacuum pre-treatment, and multistage freezing are effective in preventing shell cracking [16, 17]. However, a review of the literature reveals that studies on this topic remain limited, and the challenges involved have not yet been fully resolved. Paradoxically, despite limited success in conventional tomato freezing and ongoing research on novel freezing techniques, studies addressing currently applied freezing methods and industry-feasible pretreatments are still lacking. Although emerging freezing technologies such as magnetic field-assisted freezing [18], isochoric freezing [19], and ultrasonic pre-packaging freezing [20] methods have shown promising potential for improving frozen tomato quality, their industrial scalability and practical applicability remain limited. Moreover, currently applied commercial freezing systems and feasible pretreatment strategies have not been

systematically evaluated in combination, particularly with respect to freezing-induced skin cracking and color deterioration in cherry tomatoes. Therefore, investigating scalable freezing methods combined with practical pretreatments is essential to bridge the gap between experimental innovation and industrial application.

Therefore, this study aimed to evaluate the efficacy of freezing methods systematically, multistage freezing (MF), static freezing (SF), individual quick freezing (IQF), and vacuum-assisted IQF (V+IQF), in mitigating freezing-induced skin cracking and color deterioration in cherry tomatoes (*Solanum lycopersicum* L. var. cerasiforme cv. ‘A. Albeni’). The combined effects of freezing strategy and vacuum pretreatment were assessed through changes in enzyme activities, pectin methylesterase (PME), polygalacturonase (PG), and lipoxygenase (LOX), and key physicochemical properties during six months of frozen storage.

Materials and Methods

The Materials and Methods section is presented as supplementary material.

Results and Discussion

Total and Water-Soluble Dry Matter, pH Value and Total Titratable Acidity

The total solids, water-soluble solids, pH value, and titratable acidity of fresh and frozen cherry tomatoes are given in Table 1. Fresh tomatoes had a total solids content of 6.78%, which slightly decreased to 6.47–6.73% after six months of frozen storage, with no significant differences observed among freezing methods or between the first and sixth months apart from the SF samples. Water-soluble solids decreased from 4.26 ± 0.35 in fresh tomatoes to 4.10–4.13 at the end of storage, showing a similar trend across all treatments. The initial pH value of fresh tomatoes was 4.16, and both pH value and titratable acidity remained largely unchanged during frozen storage, consistent with previous studies [16, 21].

Among the freezing methods, static freezing (SF) preserved total solids, while pH value, °Brix, and titratable acidity remained stable for all treatments. Vacuum-assisted IQF (V+IQF) maintained pH value stability comparable to IQF alone and resulted in similar dry matter content over time. Multistage freezing (MF) showed intermediate performance across all parameters. Overall, vacuum pretreatment maintained the effectiveness of the IQF method.

Table 1 Total and Water-Soluble Solid Content, pH Value, and Total Titratable Acidity of Fresh and Frozen Cherry Tomatoes

Analysis	Fresh Cherry Tomato	Method	1st Month	6th Month
Total solid content(%)	6.78±0.85 ^c	MF	6.60±0.08 ^{ab}	6.50±0.04 ^a
		IQF	6.56±0.15 ^{ab}	6.47±0.27 ^a
		SF	6.76±0.16 ^c	6.73±0.07 ^{bc}
		V+IQF	6.57±0.12 ^{ab}	6.50±0.01 ^a
Water soluble solid (°Brix)	4.26±0.35 ^a	MF	4.15±0.06 ^a	4.13±0.22 ^a
		IQF	4.15±0.06 ^a	4.10±0.14 ^a
		SF	4.15±0.13 ^a	4.13±0.14 ^a
		V+IQF	4.13±0.05 ^a	4.13±0.17 ^a
pH Value	4.16±0.17 ^a	MF	4.15±0.06 ^a	4.18±0.06 ^a
		IQF	4.16±0.04 ^a	4.17±0.07 ^a
		SF	4.15±0.04 ^a	4.17±0.04 ^a
		V+IQF	4.14±0.09 ^a	4.15±0.04 ^a
Titratable acidity (citric acid equivalent) (g/100 g)	0.37±0.05 ^a	MF	0.38±0.01 ^a	0.39±0.08 ^a
		IQF	0.38±0.02 ^a	0.38±0.03 ^a
		SF	0.38±0.01 ^a	0.41±0.04 ^a
		V+IQF	0.38±0.01 ^a	0.38±0.09 ^a

Different letters regarding each analysis represent statistically significant differences ($p < 0.05$)

Skin Cracking

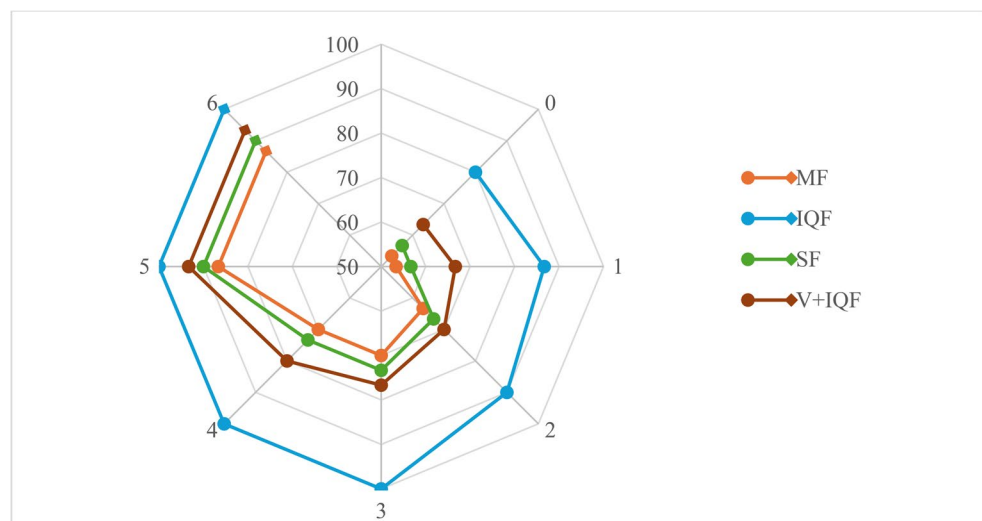
The cracking ratio of cherry tomatoes was assessed both immediately after freezing and at the end of each month during the frozen storage period. As shown in Fig. 1, cracking levels varied according to the freezing technique and were determined for six months at -20 °C. Right after freezing, the cracking percentages for MF, IQF, SF, and V+IQF methods were 53.33%, 80%, 56.67%, and 63.33%, respectively. No statistically significant differences were determined among the MF, SF, and V+IQF treatments ($p > 0.05$). The IQF method resulted in the highest cracking rate in cherry tomatoes. The IQF technique can cause skin cracking

in fruits, particularly in thin-skinned varieties. This occurs due to the mechanical stress induced by rapid freezing [22, 23]. The ultra-fast drop in temperature leads to uneven contraction between the skin and the pulp, resulting in microfractures. Furthermore, internal pressure from ice crystal formation can weaken the skin, especially in high-moisture fruits. Some researchers have also linked this issue to the pH value physical impacts between the fruits and the freezing equipment, which are caused by airflow [16].

Cracking increased in cherry tomatoes frozen by IQF, reaching 100% by the third month of storage. In contrast, V+IQF-treated samples exhibited a slower increase in cracking, reaching 93.3% by the end of the fifth month, indicating that vacuum pretreatment effectively reduced skin cracking. Samples frozen by MF and SF showed similar cracking values during storage, with final cracking rates of 86.6% and 90%, respectively. Skin cracking in cherry tomatoes is affected by fruit size and textural properties and is primarily caused by internal stresses due to contraction and expansion of the cells during freezing, which are strongly affected by the freezing rate. Additionally, the temperature gradient between the fruit and the freezing medium plays a critical role and can be controlled to minimize cracking. Similar trends have been reported in carrots and cherry tomatoes, where cracking initiates during freezing and continues to develop throughout frozen storage [16, 24].

Color Values

Color parameters (L^* and a^*/b^*) were measured in fresh cherry tomatoes prior to freezing and monitored throughout six months of frozen storage at -20 °C (Figs. 2 and 3). Color is an important quality attribute influencing consumer acceptance and is commonly used as a technological indicator of product quality, although it can be significantly

Fig. 1 Changes in skin cracking percentage during frozen storage

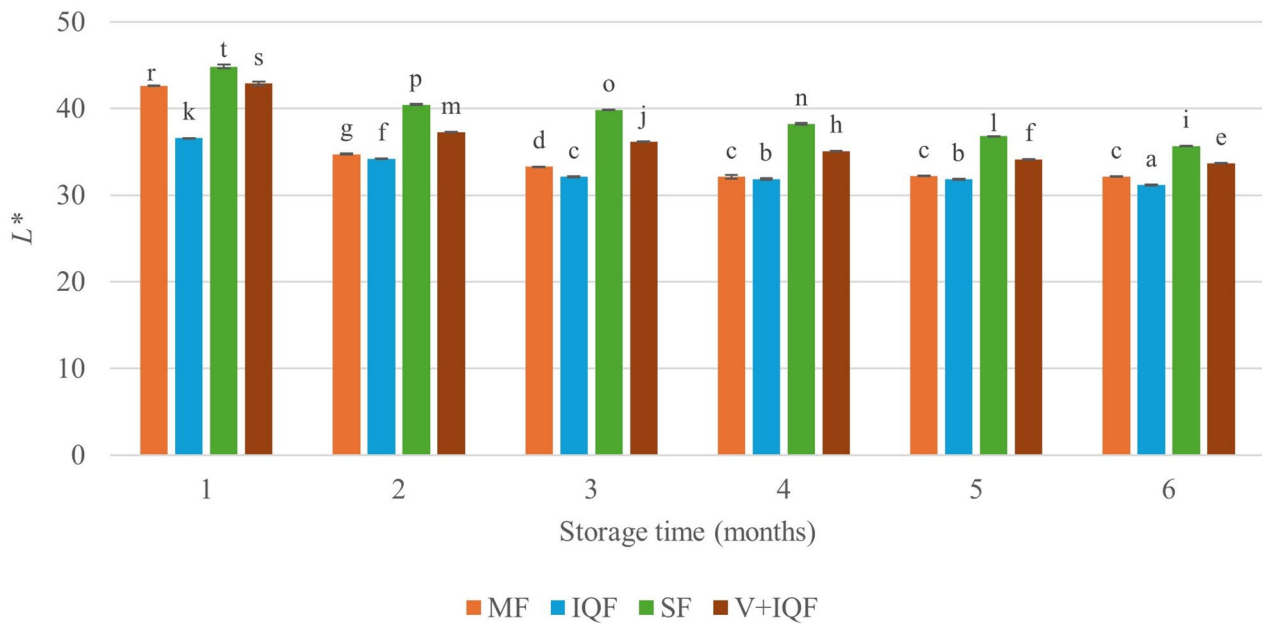
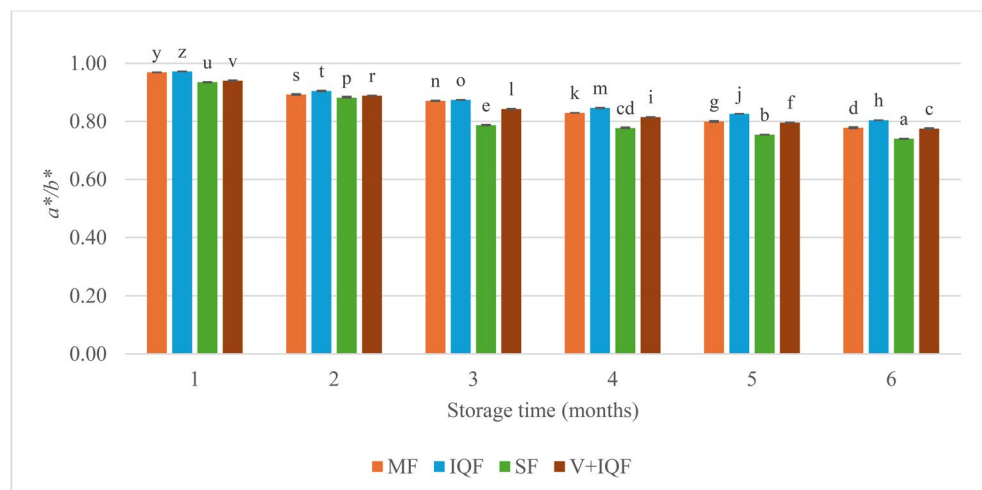


Fig. 2 L^* values of cherry tomatoes over frozen storage

Fig. 3 a^*/b^* values of cherry tomatoes over frozen storage



affected by postharvest processing [16, 25, 26]. The initial L^* value of fresh tomatoes was 46.41. After one month of storage, L^* values decreased by 8.08%, 21.16%, 3.34%, and 7.56% for MF, IQF, SF, and V+IQF, respectively, with SF showing the highest lightness retention. After six months, total reductions in L^* were 30.79% (MF), 32.86% (IQF), 23.16% (SF), and 27.45% (V+IQF).

Previous studies reported that vacuum pretreatment combined with IQF enhanced lycopene retention, although it did not yield the highest L^* values, while vacuum-assisted multistage freezing reduced early-stage skin cracking and minimized L^* losses [16]. Consistent with these findings, the present results indicate that vacuum pretreatment

significantly improves the color stability and overall quality of frozen cherry tomatoes; however, its effectiveness depends on the freezing method and storage duration.

The a^*/b^* ratio was evaluated to further assess the chromatic quality of frozen cherry tomatoes. The mean a^*/b^* value of fresh tomatoes was 1.03. After one month of frozen storage, a^*/b^* values decreased by 5.83% for MF and IQF and by 8.74% for SF and V+IQF. Significant reductions in a^*/b^* ratio ($p < 0.05$) were observed between the first and sixth months of storage, amounting to 19.59%, 17.53%, 21.93%, and 17.02% for MF, IQF, SF, and V+IQF, respectively. Among the treatments, V+IQF showed the lowest decline in a^*/b^* values during storage. Differences in a^*/b^*

ratios among freezing methods were statistically significant throughout the storage period. Similar decreases in a^*/b^* values have been reported for whole and diced tomatoes frozen and stored at $-20\text{ }^{\circ}\text{C}$ [16, 27].

Lycopene Content

The lycopene content of cherry tomatoes used as raw material in the freezing process was found to be $110.84 \pm 0.99\text{ mg/kg}$ (FW). Figure 4 illustrates the change in lycopene contents of the frozen cherry tomatoes throughout the storage duration.

After one month of frozen storage, lycopene content decreased by 0.98%, 0.48%, 19.07%, and 18.30% in samples frozen by MF, IQF, SF, and V+IQF, respectively. Significant reductions in lycopene content ($p < 0.05$) were found between the first and sixth months of storage, reaching 58.10% (MF), 58.24% (IQF), 52.39% (SF), and 50.90% (V+IQF). Among the freezing methods, V+IQF most effectively limited lycopene degradation during storage. The higher initial lycopene retention in MF and IQF samples are primarily attributable to the application of freezing process without vacuum pretreatment, which limited pre-freezing mechanical and structural disturbances. In addition, the ultra-fast temperature reduction inherent to the IQF process limits the duration of enzymatic and oxidative activity during the initial stages resulting in minimal initial lycopene degradation. In contrast, the vacuum pretreatment applied in the V+IQF method, although potentially causing minor cellular alterations prior to freezing and slightly lower initial lycopene values, provided a protective advantage during frozen storage. By reducing the availability of reactive species within intercellular spaces and preserving cellular integrity, the V+IQF treatment effectively limited degradation pathways over time, leading to lower relative lycopene loss and superior retention during prolonged storage.

Changes in lycopene content were closely associated with color deterioration and residual enzyme activity and

were influenced by enzymatic, oxidative, and structural factors during frozen storage. Lycopene, a highly unsaturated compound, is particularly susceptible to enzymatic and oxidative degradation and is readily degraded or isomerized during processing and storage [19, 28]. The formation of large ice crystals during slower or prolonged freezing processes, such as MF and SF, can disrupt cellular structures and accelerate lycopene loss [29]. In IQF, increased oxygen exposure may further promote lycopene oxidation. In contrast, vacuum pretreatment in the V+IQF method likely reduced oxygen within cellular spaces, resulting in improved lycopene retention during frozen storage. Similar lycopene losses have been reported in frozen tomato products, including tomato cubes and whole cherry tomatoes stored at $-20\text{ }^{\circ}\text{C}$ for extended periods [16, 21, 27].

Enzyme Activities

Pectin degradation is mediated by a group of pectinolytic enzymes, including pectin methylesterase (PME), pectin acetyl esterase (PAE), pectin lyase (PL), and polygalacturonase (PG) [30]. Because PL and PG act preferentially on demethylated pectin, their activities depend largely on PME. PME (EC 3.1.1.11) catalyzes the demethylesterification of pectin, releasing methanol as a reaction product [31]. Therefore, PME activity can be quantified by measuring methanol formation and is considered the primary regulator of methanol production in tomato fruit [32]. In fresh cherry tomatoes, methanol formation due to PME activity was $4.26 \pm 0.20\text{ nmol/mg}$. Residual pectin methylesterase activity (RA_{PME}), expressed as methanol production, is presented in Fig. 5. Statistical analysis showed that the freezing method significantly affected methanol formation ($p < 0.05$).

Residual pectin methylesterase activity (RA_{PME}) in frozen cherry tomatoes declined sharply during the first two months of storage across all freezing methods. IQF samples retained the highest RA_{PME} after the first month, while SF samples showed the lowest. From the third month, PME

Fig. 4 Lycopene content (mg/kg FW) of cherry tomatoes over frozen storage

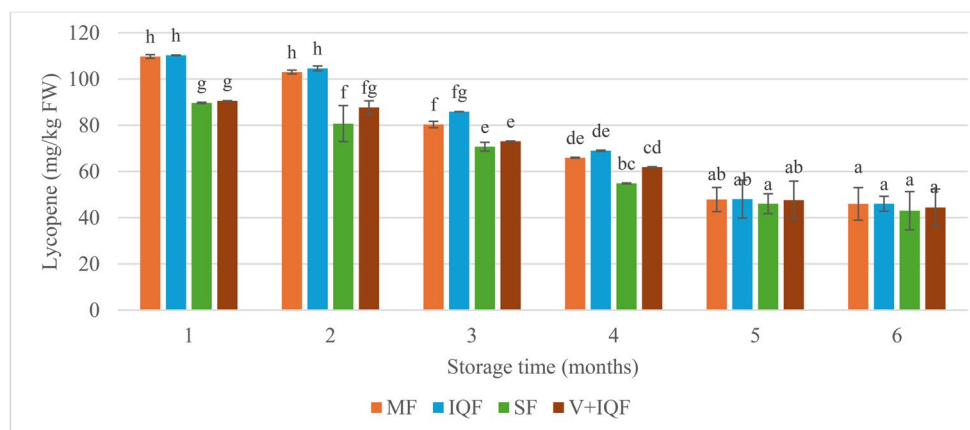
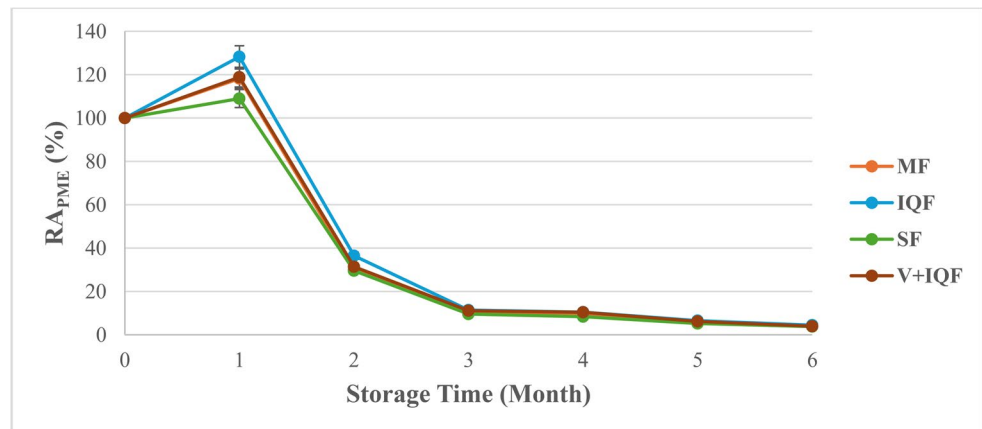


Fig. 5 Residual enzyme activity of PME over frozen storage

activity stabilized at low levels (~ 5 – 10% of initial activity) for all methods, indicating that most PME inactivation occurs early in frozen storage. V+IQF slightly enhanced enzyme retention compared to methods without vacuum pretreatment. Methanol production decreased significantly over time, with no significant differences was found between the 3rd, 4th, and 5th months for MF, IQF, and SF.

Previous studies similarly reported increased residual PME activity in the first month of frozen storage for MF, V+IQF, V+SF, and V+MF [16]. Enzyme activity is influenced by pH value, with lower pH value increased protein denaturation [33, 34]. Although freezing methods did not significantly affect pH value ($p > 0.05$), MF and SF samples had slightly lower pH value than IQF and V+IQF, potentially contributing to their lower PME activity. Mechanical damage also affects enzyme-substrate interactions, as PME and esterified pectin are normally compartmentalized in intact tissue; disruption allows contact and enhances activity [35]. Beyond PME, the study also evaluated residual polygalacturonase activity (RA_{PG}), with results presented in Fig. 6.

Polygalacturonase (PG) activity in fresh cherry tomatoes was 1.00 ± 0.02 nmol galacturonic acid/min. Significant

increases in PG activity were observed in samples frozen by IQF, SF, and V+IQF ($p < 0.05$), whereas MF did not cause a statistically significant change in PG activity after the first month. Similar trends were found in a previous study on the Atom F1 cultivar for MF and V+MF [13]. Across all freezing methods, residual PG activity (RA_{PG}) declined by approximately 30–40% during early storage. From the third month onward, RA_{PG} remained very low (2–5% of the initial activity) and stayed at this level until the end of the six-month storage period, showing that although PG activity was minimal, it continued at a low but detectable level in all treatments. These results are compatible with the known fact that enzymes retain activity during freezing and frozen storage.

In addition to cell wall-degrading enzymes, the study assessed lipoxygenase (LOX) due to its role in oxidative degradation of frozen products. Fresh cherry tomatoes exhibited LOX activity of 38.60 ± 1.83 $\mu\text{mol/g FW/min}$. Despite this initially high activity, a substantial decrease in residual LOX activity (RA_{LOX}) was determined after one month of frozen storage across all freezing methods (Fig. 7).

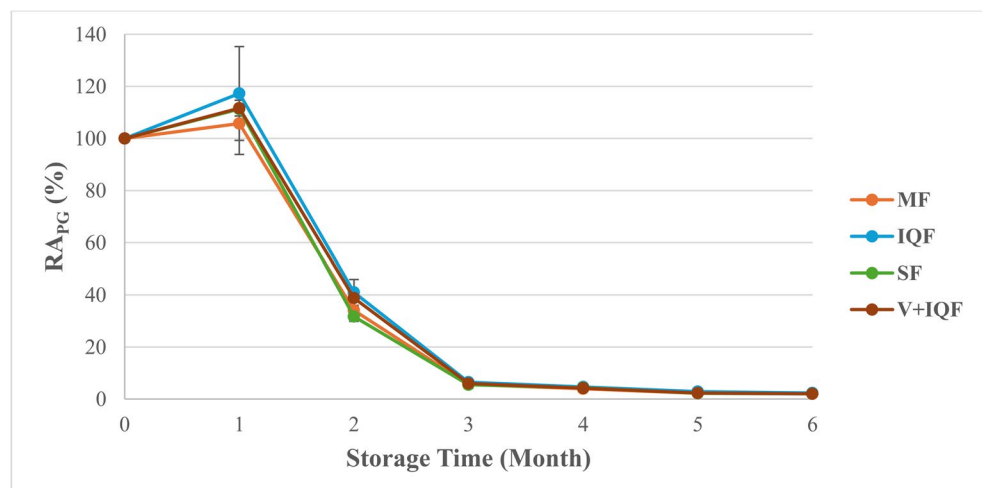
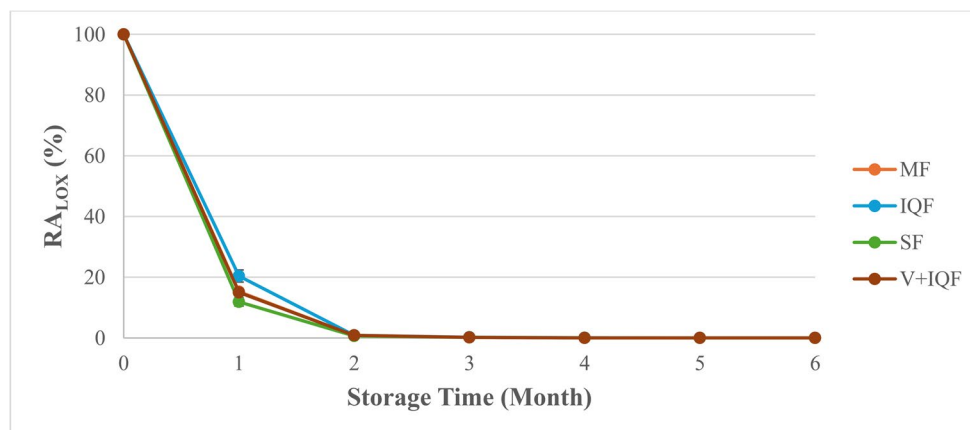
Fig. 6 Residual enzyme activity of PG over frozen storage

Fig. 7 Residual enzyme activity of LOX over frozen storage

LOX activity decreased significantly after one month of storage, with reductions of 79.67% (IQF), 88.2% (SF), 85% (V+IQF), and 84.8% (MF). A higher decline was found during the second month, after which LOX activity remained stable for the remainder of the six-month storage period, with no significant differences among freezing methods. This stabilization suggests that the rate of oxidative degradation slowed after an initial higher decline. The residual LOX activity (RA_{LOX}) may be attributed to differences in isoenzyme stability, as labile isoenzymes are inactivated early while more resistant isoenzymes remain partially active throughout prolonged frozen storage.

Correlation Analysis of Dependent Parameters in Frozen Cherry Tomatoes

Table 2 presents the Pearson correlation coefficients among the measured variables. Residual PME activity (RA_{PME}) was nearly perfectly correlated with RA_{PG} ($r=0.988$, $p<0.01$) and strongly correlated with RA_{LOX} ($r=0.968$, $p<0.01$), highlighting the coordinated behavior of these enzymes under different freezing treatments. These correlations underscore the role of pectic enzymes in pectin breakdown and LOX in lipid oxidation, collectively influencing the texture and quality of frozen cherry tomatoes.

Color parameters (L^* , a^*/b^*) and lycopene content also showed strong positive correlations with residual enzyme activities ($r=0.616$ – 0.714 , $p<0.01$). Although residual

enzyme activity is often considered detrimental to color and pigment stability, the positive correlations were found likely result from pectolytic enzyme-mediated cell wall disintegration, which facilitates lycopene release. This mechanism aligns with extraction studies reporting higher lycopene yields following enzymatic breakdown of cell-wall polysaccharides [36, 37]. Similar trends were reported in previous studies on vacuum-assisted and conventional freezing of cherry tomatoes, where residual enzyme activities positively correlated with color and lycopene content [16].

The positive correlation between residual LOX activity and color does not indicate a protective effect of LOX. As observed in unblanched tomato purees stored at -7 and -18 °C [38], the radical nature of enzymatic and chemical reactions can explain color changes even at very low LOX activity across different freezing methods. Although LOX activity is typically associated with pigment degradation and subsequent color loss, the positive correlation observed in this study, even at the minimal residual levels following frozen storage, points to a complex interplay of isoenzyme-specific effects. This trend may be attributed to the diversity of LOX isoenzymes, which range from those facilitating robust pigment oxidation to others with lower catalytic efficiency or involvement in alternative sub-reactions. These factors, alongside tissue heterogeneity and the modulating effects of endogenous antioxidant systems, likely explain the observed trend.

Table 2 Pearson correlation coefficients among parameters

Parameter	Cracking	L^*	Lycopene	RA_{PME}	RA_{PG}	RA_{LOX}	a^*/b^*
Cracking	1	−0.720**	−0.529**	−0.508**	−0.525**	−0.389**	−0.491**
L^*		1	0.461**	0.702**	0.714**	0.616**	0.474**
Lycopene			1	0.719**	0.735**	0.618**	0.912**
RA_{PME}				1	0.988**	0.968**	0.845**
RA_{PG}					1	0.944**	0.852**
RA_{LOX}						1	0.760**
a^*/b^*							1

Correlation is significant at the 0.01 level (2-tailed)

Skin cracking showed a strong negative correlation with L^* ($r=-0.720$) and moderate negative correlations with a^*/b^* ratio ($r=-0.491$) and lycopene content ($r=-0.529$). Unlike the Atom F1 cultivar in our previous study, where cracking was correlated only with lightness, skin cracking in Albeni cherry tomatoes is influenced not only by L^* but also by pigment stability, as reflected in a^*/b^* and lycopene values. This indicates that color-related quality parameters in Albeni are more closely correlated to skin structural integrity. Albeni tomatoes also exhibited higher skin cracking during freezing and subsequent storage compared to Atom F1. Such cultivar-specific differences may be due to thinner skin, weaker cuticular resistance, or reduced pigment stability, making Albeni more prone to cracking.

Conclusion

Freezing and frozen storage significantly affected the quality of cherry tomatoes yet did not fully inactivate key enzymes involved in postharvest deterioration. Residual activities of PME, PG, and LOX decreased in higher ratios during the early stages of storage and stabilized at low levels, highlighting that enzyme inactivation is influenced by both the freezing method and storage duration. Variations in residual enzyme activities were also affected by cultivar-specific properties and the presence of isoenzymes with differing stability.

The study demonstrated that structural characteristics of the fruit, such as skin thickness and cuticular resistance, interact with biochemical factors to determine susceptibility to skin cracking and color changes. In Albeni cherry tomatoes, skin integrity was closely correlated not only with lightness (L^*) but also with pigment stability (a^*/b^* ratio and lycopene content), emphasizing the role of cultivar-specific physiology in determining frozen product quality. Among the freezing methods, vacuum-assisted IQF (V+IQF) most effectively minimized enzyme activity losses, preserved lycopene, and reduced skin cracking, highlighting the benefits of combining vacuum pretreatment with rapid freezing for industrial applications.

Overall, the findings underline that optimizing frozen cherry tomato quality requires a holistic approach, considering both the intrinsic properties of the cultivar and the choice of freezing strategy. Monitoring key enzyme activities with color, lycopene content, and mechanical integrity provides a practical framework for enhancing the storage stability, visual appeal, and nutritional value of frozen cherry tomatoes, offering valuable guidance for industrial processing and postharvest management.

Supplementary Information The online version contains supplementary material available at <https://doi.org/10.1007/s11483-026-10122-y>.

Author contributions Atiye DEĞİRMENÇİ: Methodology, Software, Visualization, Formal Analysis, Investigation, Writing – Original Draft. İdil TEKİN: Investigation, Software, Formal Analysis, Writing – Original Draft. Seda ERSUS: Conceptualization, Supervision, Methodology, Writing – Review & Editing, Funding Acquisition, Resources, Validation.

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Data Availability No datasets were generated or analysed during the current study.

Declarations

Competing interests The authors declare no competing interests.

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