Colegio de Postgraduados

Effect of hydrocooling with calcium chloride and silicon dioxide on post-harvest quality of Saladette tomatoes ‘Macizo’'and ‘Moctezuma’

Ruiz-Cisneros, María F.[1*]; Maya-Meraz, Irma O.[1]; Alonso-Villegas, Rodrigo[1]; Rios-Velasco, Claudio[2]; Ornelas-Paz, José, J.[2]; Berlanga-Reyes, David I.[2]; Cambero-Campos, Octavio J.[3]; Pérez-Corral, Daniel A.[4*]

1 Facultad de Ciencias Agrotecnológicas, Universidad Autónoma de Chihuahua, Av. Universidad S/N, Ciudad Universitaria, Chihuahua C.P. 31110, México.
2 Centro de Investigación en Alimentación y Desarrollo A.C., Av. Río Conchos S/N, Parque Industrial, Cd. Cuauhtémoc C.P. 31570, México.
3 Unidad Académica de Agricultura, Universidad Autónoma de Nayarit. Km 9 Carretera Tepic - Compostela, Xalisco C.P. 63780, México.
4 Facultad de Ingeniería y Negocios San Quintín, Universidad Autónoma de Baja California, Carretera Transpeninsular Km. 180.2 C. P. 22930, San Quintín, Baja California, México.
* Correspondence: mfruiz@uach.mx; daniel.perez.corral@uabc.edu.mx

Citation: Ruiz-Cisneros, M. F., Maya-Meraz, I. O., Alonso-Villegas, R., Rios-Velasco, C., Ornelas-Paz, J. J., Berlanga-Reyes, D. I., Cambero-Campos, O. J., & Pérez-Corral, D. A. (2026). Effect of hydrocooling with calcium chloride and silicon dioxide on post-harvest quality of Saladette tomatoes ‘Macizo’ and ‘Moctezuma’. *Agro Productividad*. https://doi.org/10.32854/3wyt5m69

Academic Editor: Jorge Cadena Iñiguez
Associate Editor: Dra. Lucero del Mar Ruiz Posadas
Guest Editor: Juan Francisco Aguirre Medina

Received: December 13, 2025.
Accepted: March 11, 2026.
Published on-line: April XX, 2026.

Agro Productividad, 19(3). March. 2026. pp: 199-214.

ABSTRACT

Objective: Saladette tomato (*Solanum lycopersicum* L.) is valued for its nutritional properties; however, the effects of postharvest applications of Ca^{2+}, Si, and hydrocooling remain insufficiently characterized.

Design/methodology/approach: This study evaluated calcium chloride ($CaCl_2$; 1% w/v), silicon dioxide (SiO_2; 1% w/v), and their combination. Treatments were applied at 0 °C (hydrocooling) for 5 min to ‘Macizo’ and ‘Moctezuma’ cultivars. Fruits were stored at 23±1 °C (ambient temperature) and 24±1% relative humidity for 21 days. Quality attributes were measured during storage. Measurements included weight loss, firmness, color, soluble solids content, and titratable acidity.

Results: Both cultivars lost weight and firmness. Hydrocooling, alone or with with calcium chloride, delayed this loss. Ripening was characterized by an increase in a*, a decrease in b*, and an initial decline followed by partial recovery in L*. Titratable acidity decreased, with the most pronounced decline observed in the presence of silicon dioxide. Soluble solids content fluctuated. The maturity index increased, indicating advanced ripening.

Findings/conclusions: These findings highlight the potential of hydrocooling alone or combined with calcium chloride as an effective postharvest strategy to preserve Saladette tomato quality during storage.

Keywords: Firmness, quality, *Solanum lycopersicum*, ripening, climacteric fruit.

INTRODUCTION

Tomato (*Solanum lycopersicum* L.; Solanales: Solanaceae) is a globally important commercial crop (Flores-López *et al.*, 2024). Mexico is its major exporter (Montaño-Méndez *et al.*, 2021). In 2024, 50,086.64 hectares were allocated to its cultivation,

resulting in the production of over 3.7 million tons (AEPA, 2025). Despite this progress, Mexico faces considerable post-harvest losses at the retail level, threatening its commercial competitiveness. Reducing these losses is crucial for maintaining Mexico's market share in the global tomato industry. The value of tomatoes extends beyond economic output and export volume, including their fresh and processed uses, as well as the nutritional benefits of carotenoids and phenols (Wu *et al.*, 2022; Bertin *et al.*, 2025). Maintaining the quality of tomato fruits, such as firmness, size, color, flavor, and nutritional value, until they reach consumers is difficult due to factors like pests, diseases, or handling during marketing (Bapary *et al.*, 2024; Flores-López *et al.*, 2024; Wang *et al.*, 2025). Cultivar, maturity and production methods influence tomato quality, but post-harvest processes, handling, storage, and transportation most substantially affect the final fruit characteristics (Ayuso-Yuste *et al.*, 2022; Bapary *et al.*, 2024). Importantly, because tomatoes are climacteric fruits, their natural ripening increases respiration and ethylene production, thereby accelerating quality loss and shortening shelf life (Salas-Méndez *et al.*, 2019). Elevated ethylene, in turn, influences phenolic content and fruit texture, which reduces consumer acceptance (Khalil *et al.*, 2020; Al-Dairi *et al.*, 2021; Baninaiem & Dastjerdi, 2023). Notably, in Latin America, consumers associate firmness with freshness, therefore any decrease in firmness caused by postharvest changes directly reduces retail prices.

Reducing postharvest quality loss depends on effective storage. Cold storage, high humidity, and controlled atmospheres help preserve tomato quality and extend shelf life (Flores-López *et al.*, 2024), but they can also cause chilling injury (Park *et al.*, 2018). Retail environments often lack these ideal conditions and typically experience higher temperatures and lower humidity (Sumonsiri *et al.*, 2022). These conditions increase respiration and moisture loss, causing faster deterioration in quality and economic losses (Baninaiem & Dastjerdi, 2023; Tigist *et al.*, 2013; Nkolisa *et al.*, 2018). Addressing these storage challenges is essential to minimizing postharvest decay.

Since most retail environments lack temperature and humidity control, we need to implement additional postharvest strategies. Physical methods such as hydrocooling and exogenous Ca^{2+} or silicon (Si) treatments delay firmness loss and extend shelf life in tomatoes and other fruits, especially at safe doses (Wang *et al.*, 2014; Shehata *et al.*, 2021; Wu *et al.*, 2025). Wang *et al.* (2014) found that dipping cherries for 5 min in cold water (0 °C) with $CaCl_2$ significantly increased the calcium content in fruit tissue. The increase in Ca and its effects on fruit and pedicel quality was dose-dependent: dipping in 0.2-0.5% $CaCl_2$ for 5 min increased tissue Ca and preserved both fruit and pedicel quality, whereas higher concentrations (1.0-2.0%) further increased tissue Ca but caused pedicel damage. $CaCl_2$ increases firmness by acting on cell wall pectin (Ornelas-Paz *et al.*, 2018), while sodium silicate $(Na_2OSiO_2)_3$ creates a protective surface, enhancing resistance and reducing water loss (Rombolà *et al.*, 2023). Applying treatments ($CaCl_2$) and (SiO_2) during hydrocooling shows potential for maintaining tomato quality during storage and retail (Maya-Meraz *et al.*, 2024). Previous reports indicate that Ca^{2+} and Si improve fruit quality. We hypothesize that postharvest hydrocooling and treatments with Ca^{2+}, Si, or both will extend tomato shelf life by strengthening cell walls, reducing postharvest stress, slowing ripening, and preserving overall quality during storage.

Especially in the 'Moctezuma F1' and 'Macizo' cultivars, which are currently being cultivated under greenhouse conditions in Cuauhtémoc, Chihuahua. 'Moctezuma' is a hybrid tomato; it is a vigorous, early-maturing plant with excellent firmness, long shelf life, extra-large fruit, and high yield potential. 'Macizo', on the other hand, is an improved genotype emphasizing quality and resilience. Both cultivars share key attributes such as firmness, shelf life, and stress tolerance. We aim to demonstrate that hydrocooling with calcium chloride, silicon dioxide, or both can extend shelf life and maintain freshness in 'Macizo' and 'Moctezuma' tomatoes during storage.

MATERIALS AND METHODS

Reagents and plant material

Food-grade $CaCl_2$ and SiO_2 were purchased from Food Technologies Trading S.A. de C.V., Mexico. Saladette tomatoes from the 'Macizo' and 'Moctezuma' cultivars were selected for uniform size, color, and the absence of lesions or infections. Tomatoes were harvested manually at the red stage of physiological and commercial maturity from a commercial greenhouse in Cuauhtémoc, Chihuahua, Mexico. A total of 224 fruits (112 per cultivar) were immediately disinfected by immersion in a 1% (v/v) chlorine bleach solution for 3 min. Fruits were then washed twice with sterile distilled water and dried at room temperature in commercial plastic bags. Twenty-eight tomatoes were used per treatment. Post-harvest evaluations were performed on days 0, 7, 14, and 21 after treatment.

Post-harvest treatments of tomatoes

Four hydrocooling solutions were prepared and maintained at 0 °C using distilled water and ice: T1 (hydrocooling control; distilled water), T2 (1% $CaCl_2$), T3 (1% SiO_2), and T4 (0.5% $CaCl_2$+0.5% SiO_2) (Wang *et al.*, 2014). Tomatoes were immersed in one of the four solutions for 5 min, drained, dried on brown paper at room temperature, and placed on plastic racks. The fruits were stored in a controlled chamber at 23 °C and 24% relative humidity for 0, 7, 14, or 21 days (Nkolisa *et al.*, 2018; Vigneault *et al.*, 2000). At each storage interval, fruits were evaluated for weight, firmness, color, soluble solids content (SSC; °Brix), and titratable acidity (TA).

Measurement of physicochemical attributes in tomatoes

Physicochemical changes were evaluated by measuring weight, firmness, color, SSC, and TA at 0, 7, 14, and 21 days after treatment. For each measurement, 28 fruits per treatment were randomly divided into four groups. Seven biological replicates were destructively analyzed at each time point, ensuring that independent fruits were assessed. Fruit weight (g) was determined using a VelabTM electronic balance (Model VE-5000, Texas, USA).

Tomatoes' firmness was measured using puncture tests using a Universal Texture Analyzer Ta-XT2i (Texture Technologies Corp., USA). A 6 mm diameter metal probe was used to measure the maximum force (N) at a penetration speed of 5 mm s^{-1} and a depth of 15 mm (Ruiz-Cisneros *et al.*, 2018).

Skin color was measured at two opposite anatomical locations using a CR-300 colorimeter (Minolta Co. Ltd., Osaka, Japan) on the CIE-L*a*b* scale, as described by Ruiz-Cisneros *et al.* (2018). In this scale, L* indicates lightness (0=black, 100=white), a* represents the green-red axis, and b* the blue-yellow axis. The colorimeter was calibrated using a white standard prior to each measurement.

Soluble solids content (SSC, °Brix) and titratable acidity (TA, expressed as % malic acid according to NMX-F-102-S-1978) were measured in fruit juice. SSC was measured using a digital refractometer (PAL-1 pocket, Atago Co. Ltd., Tokyo, Japan). TA was determined by potentiometric titration of 50 mL of tomato juice, diluted 25-fold using 0.1 N NaOH as the titrant (Nkolisa *et al.*, 2018), and 0.5% phenolphthalein as the indicator (Ruiz-Cisneros *et al.*, 2018). Each sample was analyzed in quadruplicate. The maturity index was calculated as the SSC/TA ratio.

Experimental design and statistical analysis

Data were analyzed using a completely randomized 4×4×2 factorial design, with treatment (4 levels), storage time (4 levels), and cultivar (2 levels) as factors. Each experimental unit consisted of seven replicates (fruits) and was assigned a unique combination of factor levels to ensure independence.

The assumptions of normality, homogeneity of variances, and error independence were evaluated using the Shapiro-Wilk test ($W=0.988$; $p=0.070$), Levene's test ($F=1.2978$; $p=0.148$), and the Durbin-Watson statistic ($DW=1.8952$; autocorrelation=0.04546), respectively. Since these assumptions were satisfied, an analysis of variance (ANOVA) was performed to identify significant differences, followed by Tukey's test ($p\leq0.05$) for mean comparisons. All analyses were conducted using SAS software version 9.0 (SAS Institute Inc., Cary, NC, USA, 2002).

RESULTS AND DISCUSSION

The main finding was that hydrocooling and $CaCl_2$ or SiO_2 treatments, whether applied alone or together, influenced the physicochemical properties of tomatoes depending on the cultivar ('Macizo' and 'Moctezuma') and the storage time (0, 7, 14, and 21 days). As expected for climacteric fruits, both treated and untreated tomatoes exhibited physicochemical changes related to senescence, with a typical shelf life of 2-3 weeks (Thole *et al.*, 2021). Previous studies have indicated that the effects of postharvest treatments, such as Ca^{2+} application, harvest timing, and storage temperature, differ by cultivar and influence fruit quality and shelf life (Correia *et al.*, 2019; Al-Dairi *et al.*, 2021). During storage, physiological processes such as oxidation, transpiration, ethylene production, and enzymatic activity occur. Cooler temperatures (around 12 °C) are typically used to slow these processes and extend tomato shelf life (Park *et al.*, 2018; Sumonsiri *et al.*, 2022). In the present study, rapid changes in tomatoes may be attributed to storage under higher temperature (23 °C ± 1 °C) and lower humidity (24%), supporting the notion that elevated temperatures negatively affect tomato quality (Thole *et al.*, 2021).

Effect of calcium chloride and silicon dioxide on tomatoes' weight

Weight loss is a key factor influencing the quality and shelf life of horticultural crops, such as tomatoes. In this study, weight loss increased progressively in most treatments over time (Figure 1), consistent with previous findings (Chandra-Dhami *et al.*, 2023). Conversely, tomatoes of the 'Macizo' cultivar in the hydrocooling control group gained weight by the end of storage, possibly due to moisture absorption during hydrocooling. Weight loss during storage results from metabolic, transpiration, and respiration processes (Al-Dairi *et al.*, 2021), which release water, as well as from vapor pressure differences that drive moisture transfer. Godana *et al.* (2015) observed greater weight loss in tomatoes stored at room temperature, probably because of higher vapor pressure deficit and water loss. Kenghe *et al.* (2015) noted that 80%-90% relative humidity (RH) is ideal, as higher RH reduces water loss. However, low RH (~24%) and high temperature (23±1°C) likely accelerated evaporation, so hydrocooling or $CaCl_2$ treatment did not sufficiently reduce weight loss (Figure 1). Low RH during storage has been attributed to water loss in tomatoes, resulting in weight reduction (Peralta-Ruiz *et al.*, 2020), highlighting the importance of environmental conditions. Hydrocooling and $CaCl_2$-based treatments delayed weight loss during storage in both tomato cultivars (Figure 1), with the effect being most pronounced in 'Macizo' compared to the other cultivar. Hydrocooling treatments retain a large amount of water in tissues, resulting in slow weight loss (Vigneault *et al.*, 2000; Zainal *et al.*, 2019).

Previous research indicates that $CaCl_2$ treatment delays weight loss, depending on the cultivar and Ca^{2+} concentration (Shehata *et al.*, 2021; Chandra-Dhami *et al.*, 2023; Correia *et al.*, 2019). In this study, the hydrocooling alone group and $CaCl_2$ in both cultivars showed the most significant delay in weight loss (Figure 1) and maintained firmness (Figure 2). Continuous exposure to $CaCl_2$ or hydrocooling is known to increase tissue Ca levels (Vigneault *et al.*, 2000). This could be caused by increased Ca^{2+} absorption or easier Ca^{2+} penetration through the exocarp/cuticle and stem scar/pedicel. Fruits with larger cell size may also accumulate Ca differently (Wu *et al.*, 2025). Increased Ca^{2+} in fruit tissue likely inhibits ripening and softening enzymes, delaying weight loss and preserving firmness during storage (Chandra-Dhami *et al.*, 2023). $CaCl_2$ may also help prevent rapid water loss and slow metabolic changes, thereby extending shelf life (Breda *et al.*, 2017; Shehata *et al.*, 2021). It may form a semipermeable film on the fruit surface, reducing transpiration (Moradinezhad *et al.*, 2019), or act as a calcium pectate hydrogel, retaining water and delaying dehydration (Turmanidze *et al.*, 2017). Additionally, it has been suggested that Ca^{2+} may block stomata and reduce respiration, further slowing weight loss.

SiO_2 and $CaCl_2 + SiO_2$ treatments increased weight loss in both cultivars. This effect was most evident in 'Macizo' tomatoes at the end of storage (Figure 1). SiO_2 forms a thin layer on the fruit surface, helping retain water (Rombolà *et al.*, 2023). We anticipated that combining $CaCl_2$ and SiO_2 would slow weight loss and keep tomatoes firmer than either treatment alone. However, the results did not support this: the combined treatment was no more effective than the individual treatments in reducing weight loss or enhancing firmness. Therefore, no synergy between $CaCl_2$ and SiO_2 was observed under the tested conditions.

In ‘Moctezuma’ tomatoes, those treated with $CaCl_2$ + SiO_2 and SiO_2 lost weight and firmness more quickly than those treated with hydrocooling control and $CaCl_2$ by day 21 (Figures 1, 2).

Effect of calcium chloride and silicon dioxide on tomato firmness

Firmness is an important quality attribute in tomatoes. It depends on structural components, including parenchymal cells, fibers, water content, pectin, and hemicellulose, which together influence texture and help maintain fruit integrity (Wang & Seymour, 2022). During storage, firmness drastically decreased in both cultivars, from approximately 75.42-88.75 to 29.35-37.86 N in ‘Macizo’ and from 69.22-79.66 to 13.25-34.69 N in

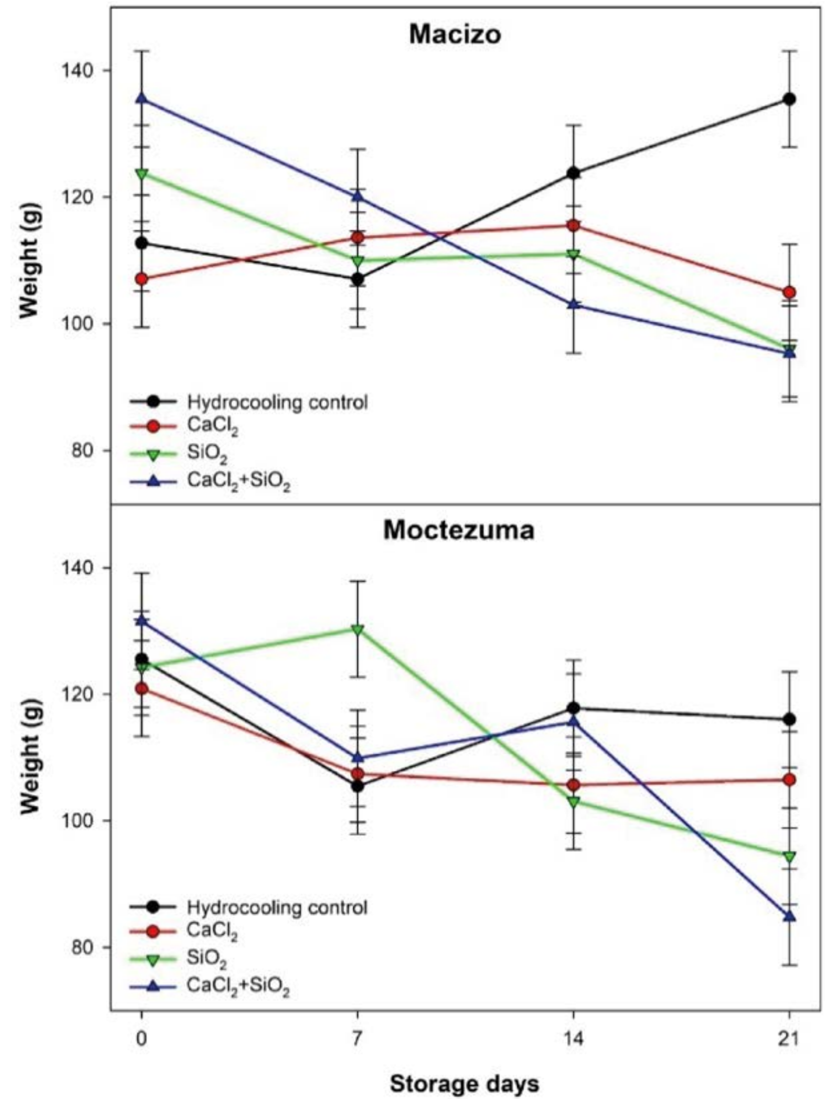

Figure 1. Effect of hydrocooling, $CaCl_2$, and SiO_2 (alone or combined in hydrocooling) on the weight of Saladette-type tomato cultivars ‘Macizo’ (upper) and ‘Moctezuma’ (lower) during storage. Values represent means ± standard error (n=7). Significant effects were observed for storage time ($F_{3,192}$=7.96, p<0.001) and the treatment × time interaction ($F_{9,192}$=3.96, p<0.001).

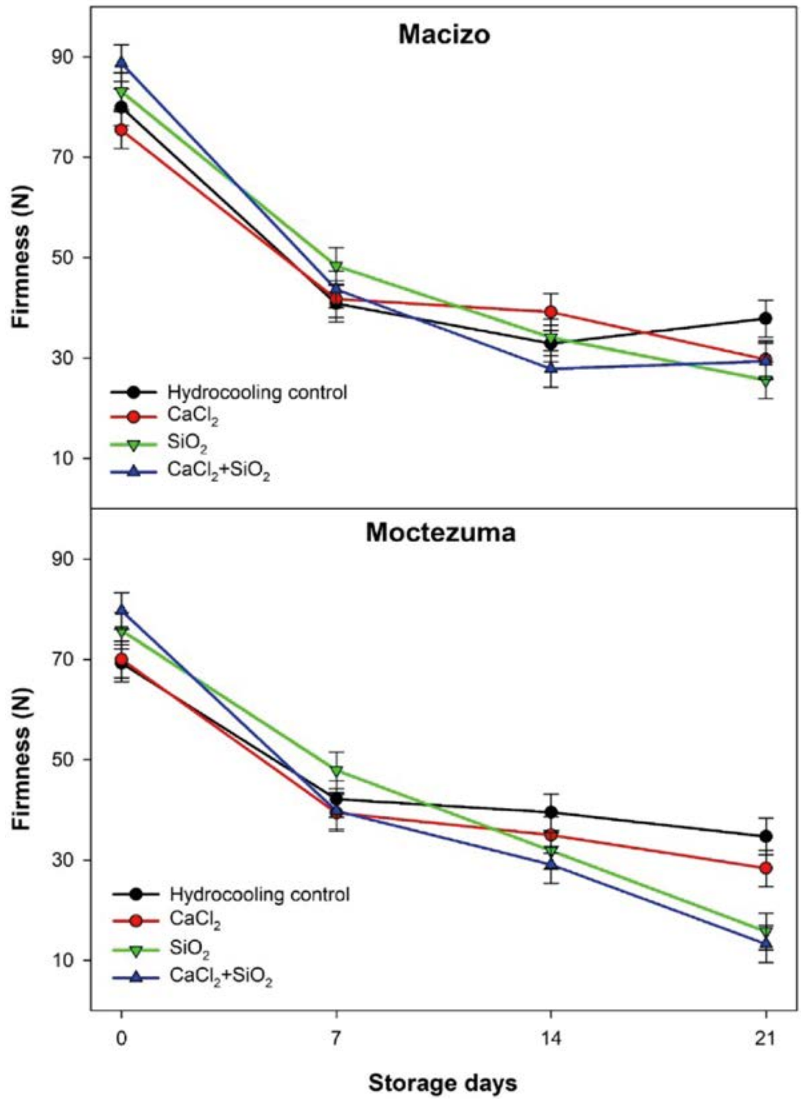

Figure 2. Effect of hydrocooling, $CaCl_2$ and SiO_2 (alone or combined in hydrocooling) on tomato firmness in Saladette-type cultivars 'Macizo' (upper) and 'Moctezuma' (lower) during ambient storage. Values represent means ± standard error (n=7). Significant effects were observed for storage time ($F_{3,192}$=306.58, p<0.001), cultivar ($F_{1,192}$=10.59, p=0.001), treatment × time interaction ($F_{9,192}$=5.03, p<0.001), and time × cultivar interaction ($F_{3,192}$=2.80, p=0.042).

'Moctezuma' (Figure 2). By day 7, firmness had decreased approximately 49.22% to 58.17% in 'Macizo' and about 49.91% to 63.21% in 'Moctezuma'. Notably, on day zero, initial firmness was higher in both 'Macizo' (>75 N) and 'Moctezuma' (>70 N) compared to values reported for 'Merlice' tomatoes (20.9 to 51.6 N; Ruiz-Cisneros *et al.*, 2018). At the end of storage, 'Moctezuma' tomatoes showed greater firmness than 'Macizo', especially in the hydrocooling control and $CaCl_2$ treatments, indicating cultivar-dependent differences in texture. This confirms previous findings that genotype significantly influences tomato firmness (Gong *et al.*, 2022; Nie *et al.*, 2024).

The lowest firmness (below 40 N) was observed on day 21 in both the treated and hydrocooling control groups, indicating that chemical and natural changes, such as cell damage or death, contributed to the fruits' softening during storage. Fruit softening occurs due to increased respiration, water loss, and pectin solubilization as the cell wall matrix progressively disassembles (Peng *et al.*, 2022). Cell wall-modifying enzymes degrade structural polysaccharides, including pectin, hemicellulose, and cellulose, thereby influencing the ripening process (Wang *et al.*, 2018). The loss of monosaccharides such as galacturonic acid, galactose, and arabinose from the cell wall further decreases firmness (Roohanitaziani *et al.*, 2022).

$CaCl_2$ treatment delayed firmness loss in 'Macizo' fruits, unlike the other treatments tested. This aligns with previous research, as delays caused by Ca^{2+} applications are well documented in fruits such as sweet cherries (***Prunus avium*** L.; Correia *et al.*, 2019; Rombolà *et al.*, 2023), jujube (***Ziziphus jujuba*** Mill; Moradinezhad *et al.*, 2019), blueberries (*Vaccinium corymbosum*; Angeletti *et al.*, 2010), Chilean strawberries (*Fragaria chiloensis*; Figueroa *et al.*, 2012), tomatoes (Shehata *et al.*, 2021), and others (Wang *et al.*, 2014).

$CaCl_2$ interacts with pectin in the cell wall (Ornelas-Paz *et al.*, 2018), thus delaying enzymatic degradation and lowering respiration and transpiration rates. By reducing water loss, $CaCl_2$ helps preserve cell wall structure and the middle lamella, which ultimately maintains tomato firmness (Shehata *et al.*, 2021). Consequently, increasing Ca^{2+} concentrations in the tested solutions and extending hydrocooling exposure times may further delay fruit softening. SiO_2 and $CaCl_2 + SiO_2$ treatments did not maintain fruit firmness after 21 days in either cultivar (Figure 2). In 'Moctezuma', firmness decreased by day 14 under SiO_2 treatment and by day 7 under $CaCl_2 + SiO_2$. This loss may be attributed to increased activity of cell wall-degrading enzymes, such as polygalacturonase and pectin methyl esterase, which degrade pectin in the cell wall and middle lamella, thereby causing tissue softening (Wang & Seymour, 2022). As fruit nears senescence, the production of essential compounds decreases, speeding up the degradation of proteins, chlorophyll, lipids, and nucleic acids (Gapper *et al.*, 2013). Ethylene also helps regulate phenolic metabolism and accelerates firmness loss (Khalil *et al.*, 2020).

Loss of firmness is often associated with changes in fruit color (Ayuso-Yuste *et al.*, 2022). For example, hydrocooling control 'Moctezuma' tomatoes exhibited greater softening and higher L* values, indicating chlorophyll degradation and lycopene accumulation (Choi & Park, 2023; Antala *et al.*, 2025).

Effect of calcium chloride and silicon dioxide on color in tomatoes

Color is a key visual quality attribute that strongly influences consumer preference for tomatoes (Baninaiem & Dastjerdi, 2023). During storage, peel color in both 'Macizo' and 'Moctezuma' cultivars changed as chlorophyll degraded and lycopene accumulated (Kapoor *et al.*, 2022; Zhu *et al.*, 2022). Starting on day 7, the L*, a*, and b* values changed in both cultivars. Specifically, a* increased by day 7 across all treatments, whereas b* decreased progressively until day 21, regardless of treatment.

L* initially decreased in all treatments and then increased from day 14 to 21, except in fruits treated with $CaCl_2 + SiO_2$, where a decline was observed only at the end of storage (Figure 3), consistent with previous reports (Breda *et al.*, 2017; Shehata *et al.*, 2021). This suggests that the $CaCl_2 + SiO_2$ treatment delayed the loss of lightness until day 21,

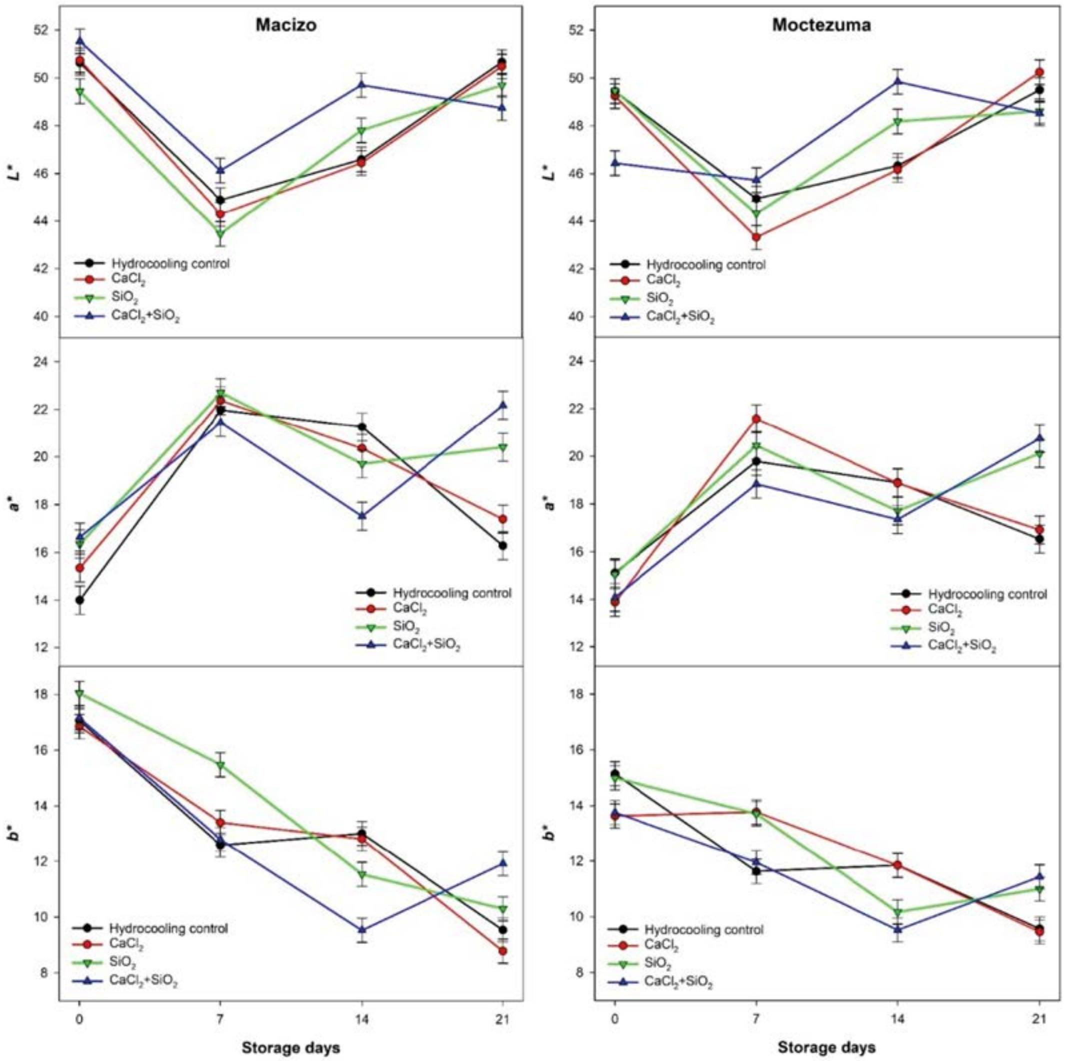

Figure 3. Effect of hydrocooling, $CaCl_2$, and SiO_2 (alone or combined in hydrocooling) on the color parameters L*, a*, and b* of Saladette-type tomato cultivars 'Macizo' and 'Moctezuma' during ambient storage. Values represent means ± standard error (n=7). Multivariate analysis indicated significant effects of treatment (Wilks' λ=0.75, $p<0.001$), storage time (Wilks' λ=0.015, $p<0.001$), cultivar (Wilks' λ=0.76, $p<0.001$), and the treatment × time × cultivar interaction (Wilks' λ=0.75, $p=0.001$). Univariate ANOVA showed significant treatment × time interactions for L*, a*, and b* ($p<0.001$).

possibly due to slower ripening or reduced dehydration (Lopez-Camelo & Gomez, 2004). By day 21, hydrocooling and $CaCl_2$ treatments maintained higher L* values than SiO_2 and $CaCl_2$ + SiO_2 treatments. Higher L* values have been associated with softer fruit, reflecting greater chlorophyll degradation and lycopene accumulation (Ayuso-Yuste *et al.*, 2022; Shehata *et al.*, 2021).

Consistent with this, loss of firmness influenced changes in tomato color, with effects varying among treatments. In hydrocooling controls, lightness (L*) initially increased and then decreased. In contrast, redness (a*) and yellowness (b*) gradually decreased in both cultivars, likely indicating pigment changes during ripening.

By day 21, SiO_2 and $CaCl_2$ + SiO_2 treatments showed higher a* values than hydrocooling controls, indicating a more intense red color (Figure 3). In contrast, the hydrocooling control and $CaCl_2$ treatments showed lower b* values on day 21. Fruits with b* values below 20 are generally considered suboptimal in red coloration, which might negatively affect perceived ripeness (Shehata *et al.*, 2021).

Effect of calcium chloride and silicon dioxide on TA and SSC in tomatoes

Titratable acidity (TA) indicates the organic acid content in fruits (Baninaiem & Dastjerdi, 2023). Similarly, soluble solids content (SSC) includes sugars, organic acids, and other soluble compounds that act as substrates for respiration (Shehata *et al.*, 2021; Wang *et al.*, 2023; Xu *et al.*, 2025). As expected, the TA and SSC values varied in tomatoes of both cultivars. TA decreased progressively with increasing storage time across all treatments (Figure 4). This trend is consistent with studies on tomatoes stored under ambient (25 °C; Hatami *et al.*, 2013) and cold conditions, where TA also decreased over time (Baninaiem & Dastjerdi, 2023; Chandra-Dhami *et al.*, 2023). In contrast, Shehata *et al.* (2021) reported an initial increase in TA up to 21 days of storage, followed by a subsequent decline. The gradual reduction in TA observed during storage is generally attributed to the use of organic acids as respiratory substrates and their depletion or oxidation during metabolic processes (Al-Dairi *et al.*, 2021; Wang & Seymour, 2022; Chandra-Dhami *et al.*, 2023; Zheng *et al.*, 2023).

Notably, SiO_2-treated 'Moctezuma' fruits showed higher TA values on day 21. This indicates that SiO_2 may have temporarily preserved acidity during mid- to late-stage storage. Although differences in fruit size have been associated with variations in acidity, this factor is unlikely to explain the observed behavior, since fruit size stayed consistent across treatments (Tigist *et al.*, 2013). Instead, the response may indicate different metabolic regulation or delayed acid use in SiO_2-treated 'Moctezuma'.

Regarding SSC, both cultivars showed temporal fluctuations consistent with typical ripening patterns (Figure 4). In 'Macizo', lower SSC values at day 7 under $CaCl_2$ and $CaCl_2$ + SiO_2 treatments, compared to the hydrocooling control, suggest a delay in sugar accumulation or a temporary suppression of carbohydrate metabolism.

Notably, these effects were temporary, as SSC levels in SiO_2 and hydrocooling control treatments were similar to those of the $CaCl_2$ and $CaCl_2$ + SiO_2 by days 14-21. By the end of storage, only SiO_2-treated fruits showed higher SSC values, indicating a late-stage enhancement in sugar accumulation specific to SiO_2.

In 'Moctezuma', SSC values were generally lower in $CaCl_2$ and hydrocooling-treated fruits compared to the SiO_2 and $CaCl_2$ + SiO_2 treatments at the end of storage. This reduction was most significant in hydrocooling control-treated tomatoes, which stayed at lower levels until day 21. These findings suggest that $CaCl_2$ + SiO_2, compared to the hydrocooling control, may reduce metabolic rate (Wang *et al.*, 2023; Kaygısız *et al.*, 2025) by limiting respiration and slowing the conversion of reserve carbohydrates into soluble sugars (Turmanidze *et al.*, 2017; Shehata *et al.*, 2021). Therefore, the lower SSC values observed with $CaCl_2$ treatment in both tomato cultivars probably indicate delayed ripening rather than a decrease in total sugar content (Shehata *et al.*, 2021; Chandra-Dhami *et al.*, 2023).

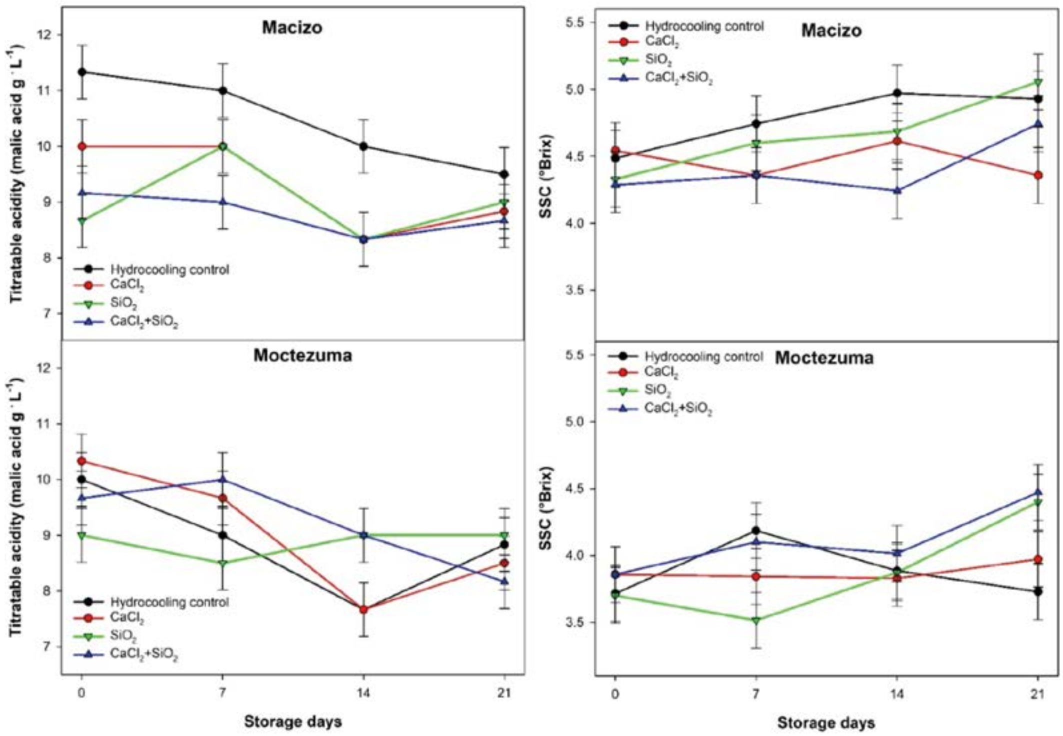

Figure 4. Effect of hydrocooling, $CaCl_2$, and SiO_2 (alone or combined in hydrocooling) on titratable acidity (TA; left) and soluble solids content (SSC; right) in Saladette-type tomato cultivars 'Macizo' and 'Moctezuma' during ambient storage. Values represent means ± standard error (n=7). For TA, significant effects were observed for treatment ($F_{3,64}$=3.77, p=0.015), storage time ($F_{3,64}$=12.75, p<0.001), cultivar ($F_{1,64}$=5.13, p=0.027), and the interaction between treatment and cultivar ($F_{3,64}$=6.23, p<0.001). For SSC, significant effects were found for storage time ($F_{3,192}$=4.15, p=0.007), cultivar ($F_{1,192}$=76.91, p<0.001), and the interaction between treatment and cultivar ($F_{3,192}$=3.27, p=0.022).

At the end of storage, higher SSC values were observed in 'Macizo' tomatoes treated with SiO_2 or hydrocooling control, and in 'Moctezuma' fruits under $CaCl_2$+SiO_2 or SiO_2, compared to other treatments for each cultivar. This increase is consistent with advanced ripening stages (Tigist *et al.*, 2013; Shehata *et al.*, 2021), during which the degradation of structural carbohydrates and polysaccharides results in the accumulation of soluble sugars (Baninaiem & Dastjerdi, 2023; Chandra-Dhami *et al.*, 2023). Additionally, water loss during storage can increase the concentration of soluble solids, which further increasing SSC (Tigist *et al.*, 2013; Al-Dairi *et al.*, 2021; Shehata *et al.*, 2021). Taken together, these factors indicate that although all treatments influenced SSC dynamics, their effects were largely mediated by cultivar-specific physiological responses and the ripening process during storage.

Effect of Calcium chloride and silicon dioxide on the maturity index in tomatoes

The SSC to TA ratio is a key indicator in tomatoes because both components significantly influence fruit maturity and postharvest quality (Flores-López *et al.*, 2024). The maturity index (SSC/TA) of both cultivars varied, sometimes even showing opposite trends. In 'Macizo', hydrocooling control treatments resulted in a higher maturity index from days 07 to 21 of storage (Figure 5), indicating that these treatments accelerated ripening in this cultivar. In contrast, in 'Moctezuma', SiO_2 treatments generally resulted in lower maturity indices from day 14 until the end of storage. The flavor of tomatoes depends on the composition and interaction of sugars and acids (Kaur *et al.*, 2023). An increase in the SSC/TA ratio occurs when SSC is high and TA is low (Al-Dairi *et al.*, 2021). Fruit maturation mainly influences SSC, TA, and the SSC/TA ratio, and changes in the tomato SSC/TA ratio are associated with respiratory activity during storage (Flores-López *et al.*, 2024).

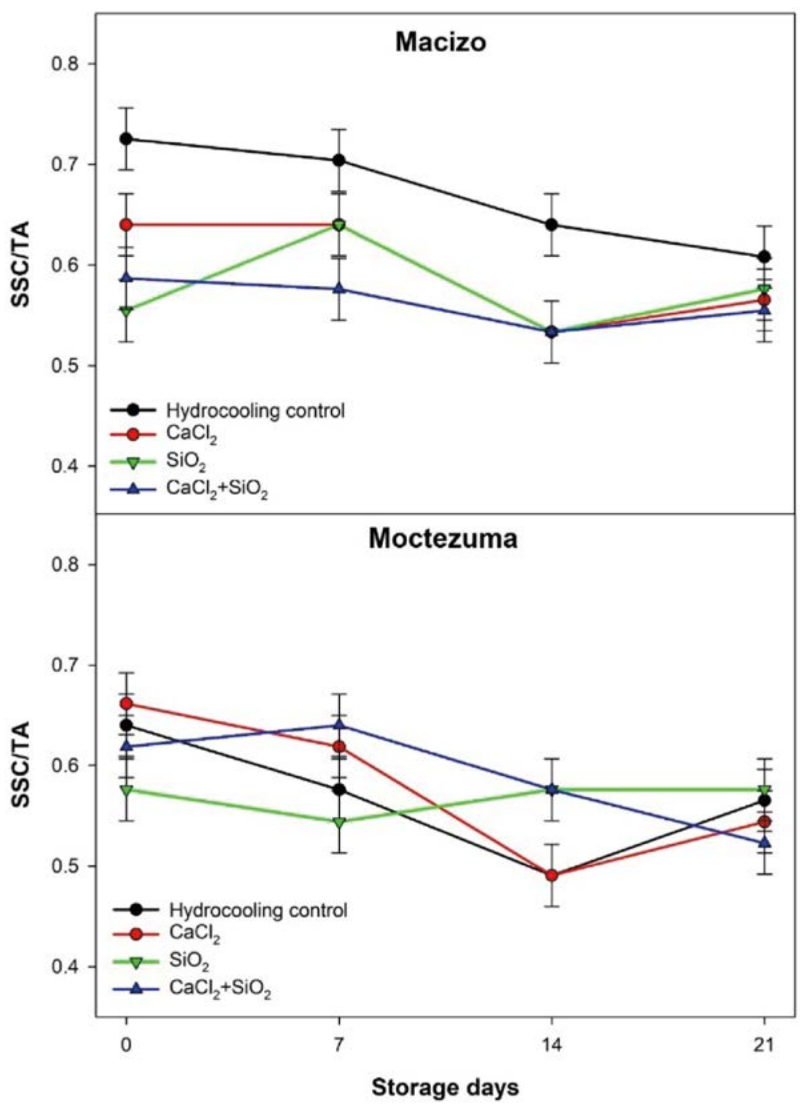

Figure 5. Effect of hydro-cooling, $CaCl_2$, and SiO_2 (alone or combined in hydro-cooling) on the maturity index (SSC/TA) of Saladette-type tomato cultivars 'Macizo' (upper) and 'Moctezuma' (lower) during storage at ambient conditions. Values represent means ± standard error (n=7). Significant effects were observed for treatment ($F_{3,64}$=3.77, p=0.015), storage time ($F_{3,64}$=12.75, p<0.001), cultivar ($F_{3,64}$=5.13, p=0.027), and treatment × cultivar interaction ($F_{3,64}$=6.23, p<0.001).

CONCLUSIONS

Regardless of cultivar, storage conditions strongly influence postharvest fruit quality. Among the treatments evaluated, hydrocooling alone or combined with $CaCl_2$ was effective in reducing weight and firmness loss, particularly in the 'Macizo' cultivar. Although lightness (L*) decreased by day 7 across treatments, it gradually recovered by days 14 and 21. Hydrocooling treatments also contributed to maintaining firmness until the end of storage. In contrast, SiO_2 treatment reduced titratable acidity in 'Moctezuma' and soluble solid content in 'Macizo'. Additionally, b* values decreased progressively during storage in both cultivars. These findings emphasize the potential of hydrocooling as an effective postharvest method to maintain tomato quality during storage.

ACKNOWLEDGMENTS

To the Laboratory of Postharvest Physiology, Plant Pathology, and Biological Control from the Research Center in Food and Development (CIAD, for its initials in Spanish), for providing its spaces and equipment to carry out this research.

REFERENCES

1. Flores-López, M.L., Vieira, J.M., Rocha, C.M.R., Lagarón, J.M., Cerqueira, M.A., Jasso de Rodríguez, D., & Vicente, A.A. (2024). Postharvest Quality Improvement of Tomato (*Solanum lycopersicum* L.) Fruit Using a Nanomultilayer Coating Containing Aloe vera. *Foods 2024*, 13, 83. https://doi.org/10.3390/foods13010083.
2. Montaño-Méndez, I.E., Valenzuela-Patrón, I.N. & Villavicencio-López, K.V. (2021). Competitividad del tomate rojo de México en el mercado internacional: análisis 2003-2017. *Rev. Mex. Cienc. Agric., 12*(7), 1185-1197. https://doi.org/10.29312/remexca.v12i7.2531
3. AEPA. Anuario Estadístico de Producción Agrícola. (2025). Available online. https://nube.agricultura.gob.mx/cierre_agricola/. Accessed November 2025.
4. Wu, X., Yu, L. & Pehrsson, P.R. (2022). Are Processed Tomato Products as Nutritious as Fresh Tomatoes? Scoping Review on the Effects of Industrial Processing on Nutrients and Bioactive Compounds in Tomatoes. *Adv. Nutr.,13*(1): 138-151. https://doi.org/10.1093/advances/nmab109.
5. Bertin, N., Constantinescu, D., Génard, M., Breniere, T., & Fanciullino, A.L. (2025). Integrative view of tomato fruit carotenoid and polyphenol accumulation for consumer health, *J. Exp. Bot*., 2025; eraf299, https://doi.org/10.1093/jxb/eraf299.
6. Bapary, M.S., Islam, M.N., Kumer, N., Tahery, M. H., Al Noman, M.A., & Mohi-Ud-Din, M. (2024). Postharvest physicochemical and nutritional properties of tomato fruit at different maturity stages affected by physical impact. *Appl. Food Res., 4*(2): 2024, 100636. https://doi.org/10.1016/j.afres.2024.100636.
7. Wang, Z., Wu, M., Liao, Q., Wang, Y., Sui, Y., & Gong, C. (2025). Current status and future trends of eco-friendly management of postharvest fungal decays in tomato fruit. npj Sci. *Food 9*, 104 (2025). https://doi.org/10.1038/s41538-025-00477-w.
8. Ayuso-Yuste, M.C., González-Cebrino, F., Lozano-Ruiz, M., Fernández-León, A.M., & Bernalte-García, M.J. (2022). Influence of Ripening Stage on Quality Parameters of Five Traditional Tomato Varieties Grown under Organic Conditions. *Horticulturae* 2022, 8, 313. https://doi.org/10.3390/horticulturae8040313.
9. Salas-Méndez, E.D.J., Vicente, A., Pinheiro, A.C., Ballesteros, L.F., Silva, P.; Rodríguez-García, R., Hernández-Castillo, F.D., Díaz-Jiménez, M.D.L.V., Flores-López, M.L., Villarreal-Quintanilla, J.Á., Peña-Ramos, F.M., Carrillo-Lomelí, D.A., & Jasso de Rodríguez, D. (2019). Application of edible nanolaminate coatings with antimicrobial extract of *Flourensia cernua* to extend the shelf-life of tomato (*Solanum lycopersicum* L.) fruit. *Postharvest Biol. Technol.* 2019, 150, 19–27.
10. Khalil, O.A.A., Mounir, A.M. & Hassanien, R.A. (2020). Effect of gamma irradiated Lactobacillus bacteria as an edible coating on enhancing the storage of tomato under cold storage conditions. *J. Radiat. Res. Appl. Sci., 13*(1), 317-329. https://doi.org/10.1080/16878507.2020.1723886

11. Al-Dairi, M., Pathare, P.B. & Al-Yahyai, R. (2021). Effect of postharvest transport and storage on color and firmness quality of tomato. *Horticulturae*, 7, 163. https://doi.org/10.3390/horticulturae7070163
12. Baninaiem, E. & Dastjerdi, A.M. (2023). Enhancement of storage life and maintenance of quality in tomato fruits by preharvest salicylic acid treatment. *Front. Sustain. Food Syst.*, 7, 1180243. https://doi.org/10.3389/fsufs.2023.1180243
13. Park, M.H., Sangwanangkul, P., & Choi, J.W. (2018). Reduced chilling injury and delayed fruit ripening in tomatoes with modified atmosphere and humidity packaging. *Sci. Hortic.* (Amst.) 2018, 231, 66-72.
14. Sumonsiri, N., Charoensantisuk, K., Paonoi, N. & Kittayangkul, P. (2022). Physical properties and sensory acceptability of gum arabic-coated cherry tomato fruit during storage. *Food Res., 6*(3): 42-48. https://doi.org/10.26656/fr.2017.6(3).395.
15. Tigist, M., Workneh, T.S. & Woldetsadik, K. (2013). Effects of variety on the quality of tomato stored under ambient conditions. *J. Food Sci. Technol.*, 50, 477- 486. https://doi.org/10.1007/s13197-011-0378-0
16. Nkolisa, N., Magwazaa, L.S., Worknehb, T.S. & Chimphangoc, A. (2018). Evaluating evaporative cooling system as an energy- free and cost- effective method for postharvest storage of tomatoes (*Solanum lycopersicum* L.) for smallholder farmers. *Sci. Hortic.*, 241, 131-143. https://doi.org/10.1016/j.scienta.2018.06.079
17. Wang, Y., Xie, X., & Long. L.E. (2014). The effect of postharvest calcium application in hydro-cooling water on tissue calcium content, biochemical changes, and quality attributes of sweet cherry fruit. *Food Chem.* 160, 22-30. https://doi.org/10.1016/j.foodchem.2014.03.073.
18. Shehata, S.A., Abdelrahman, S.Z., Megahed, M.M.A., Abdeldaym, E.A., El-Mogy, M.M. & Abdelgawad, K.F. (2021). Extending shelf life and maintaining quality of tomato fruit by calcium chloride, hydrogen peroxide, chitosan, and ozonated water. *Horticulturae, 7*(9), 309. https://doi.org/10.3390/horticulturae7090309
19. Wu, C., Xia, N., & Wang, W. (2025). Exogenous calcium on calcium accumulation, uptake and utilization in tomato. *Horticulturae*, 2025, 11, 986. https://doi.org/10.3390/horticulturae11080986.
20. Ornelas-Paz, J.J., Quintana-Gallegos, B.M., Escalante-Minakata, P., Reyes-Hernández, J., Pérez-Martínez, J.D., Rios-Velasco, C. & Ruiz-Cruz, S. (2018). Relationship between the firmness of Golden Delicious apples and the physicochemical characteristics of the fruits and their pectin during development and ripening. *J. Food Sci. Technol.*, 55, 33-41. https://doi.org/10.1007/s13197-017-2758-6
21. Rombolà, A.D., Quartieri, M., Rodríguez-Declet, A., Minnocci, A., Sebastiani, L. & Sorrenti, G. (2023). Canopy-applied silicon is an effective strategy for reducing sweet cherry cracking. *Hortic. Environ. Biotechnol.*, 64, 371-378. https://doi.org/10.1007/s13580-022-00486-8
22. Maya-Meraz, I. O., Díaz-Calzadillas, M. F., Ruiz-Cisneros, M. F., de Jesús Ornelas-Paz, J., Rios-Velasco, C., Berlanga-Reyes, D. I., Pérez-Corral, D.A., & Alonso-Villegas, R. (2024). Effects of postharvest treatments based on calcium and silicon in hydro-cooling on the basic quality attributes of 'Bing' sweet cherries (*Prunus avium* L.) during storage. *Rev. Fac. Cienc. Agrar. UNCuyo, 56*(2), 114-125.
23. Vigneault, C., Bartz, J. A., & Sargent, S. A. (2000). Postharvest decay risk associated with hydrocooling tomatoes. *Plant Dis.* 84:1314-1318. https://doi.org/10.1094/PDIS.2000.84.12.1314
24. Ruiz-Cisneros, M.F., Ornelas-Paz, J.J., Olivas-Orozco, G.I., Acosta-Muñiz, C.H., Sepúlveda-Ahumada, D.R., Pérez-Corral, D.A., Rios-Velasco, C., Salas-Marina, M.A., & Fernández-Pavía, S.P. (2018). Effect of *Trichoderma* spp. and phytopathogenic fungi on plant growth and tomato fruit quality. *Rev. Mex. Fitopatol., 36*(3), 444-456. https://doi.org/10.18781/r.mex.fit.1804-5
25. Thole, V., Vain, P., & Martin, C. (2021). Effect of elevated temperature on tomato post-harvest properties. *Plants, 10*(11), 2359. https://doi.org/10.3390/plants10112359.
26. Correia, S., Queirós, F., Ribeiro, C., Vilela, A., Aires, A., Barros, A.I., Schouten, R.; Silva, A.P. & Gonçalves, B. (2019). Effects of calcium and growth regulators on sweet cherry (*Prunus avium* L.) quality and sensory attributes at harvest. *Sci. Hortic.*, 248, 231-240. https://doi.org/10.1016/j.scienta.2019.01.024
27. Chandra-Dhami, J., Raj-Katuwal, D., Raj-Awasthi, K. & Singh-Dhami, K. (2023). Effect of different post-harvest treatments on quality and shelf life of tomato (*Lycopersicon esculentum* Mill.) fruits during storage. *Nepalese Hort.*, 17, 41-48. https://doi.org/10.3126/nh.v17i1.60631
28. Godana, E.A., Satheesh, N. & Hailu, A. (2015). Effect of storage methods and ripening stages on postharvest quality of tomato (*Lycopersicom esculentum* Mill.) Cv. Chali. *Annals. Food Sci. Technol.*, 16, 127-137. Available online at file:///C:/Users/fsds/Downloads/ourpublication.pdf
29. Kenghe, R., Fule, N., & Kenghe, K., (2015). Design, development and performance evaluation of an on-farm evaporative cooler. *Intl. J. Sci. Technol. Soc.*, 2, 1-5. https://doi.org/10.11648/j.ijsts.s.2015030202.11
30. Peralta-Ruiz, Y., Tovar, C.D.G., Sinning-Mangonez, A., Coronell, E.A., Marino, M.F., & Chaves-Lopez, C. (2020). Reduction of Postharvest Quality Loss and Microbiological Decay of Tomato 'Chonto'

(*Solanum lycopersicum* L.) Using Chitosan-E Essential Oil-Based Edible Coatings under Low-Temperature Storage. *Polymers*. 2020 Aug 13;12(8):1822. https://doi.org/10.3390/polym12081822.
31. Zainal, B., Ding, P., Ismail, I. S., & Saari, N. (2019). Physico-chemical and microstructural characteristics during postharvest storage of hydrocooled rockmelon (*Cucumis melo* L. reticulatus cv. Glamour). *Postharvest Biol. Technol.,* 152, 89-99. https:// doi.org/10.1016/j.postharvbio.2019.03.001
32. Breda, C.A., Morgado, D.L., de Assis, O.B.G., & Duarte, M.C.T. (2017). Effect of chitosan coating enriched with pequi (*Caryocar brasiliense* Camb.) peel extract on quality and safety of tomatoes (*Lycopersicon esculentum* Mill.) during storage. *J. Food Process. Preserv*., 41, e13268. https://doi.org/10.1111/jfpp.13268
33. Moradinezhad, F., Ghesmati, M., & Khayyat, M. (2019). Postharvest calcium salt treatment of fresh jujube fruit and its effects on biochemical characteristics and quality after cold storage. *J. Hort. Res., 27*(2), 39-46. https://doi.org/10.2478/johr-2019-0009
34. Turmanidze, T., Gulua, L., Jgenti, M., & Wicker, L. (2017). Potential antioxidant retention and quality maintenance in raspberries and strawberries treated with calcium chloride and stored under refrigeration. *Braz. J. Food Technol*., 20, e2016089. https://doi.org/10.1590/1981-6723.8916.
35. Wang, D., & Seymour, G.B. (2022). Molecular and biochemical basis of softening in tomato. *Mol. Hort. 2, 5*(2022). https://doi.org/10.1186/s43897-022-00026-z.
36. Gong, T., Brecht, J.K., Hutton, S.F., Koch, K.E., & Zhao, X. (2022). Tomato fruit quality is more strongly affected by scion type and planting season than by rootstock type. *Front. Plant Sci*. 13:948556. doi: 10.3389/fpls.2022.948556.
37. Nie, H., Yang, X., Zheng, S., & Hou, L. (2024). Gene-based developments in improving quality of tomato: Focus on firmness, shelf life, and pre- and post-harvest stress adaptations. *Horticulturae*, 2024, 10, 641. https://doi.org/10.3390/horticulturae10060641.
38. Peng, Z., Liu, G., Li, H., Wang, Y., Gao, H., Jemrić, T., & Fu, D. (2022). Molecular and genetic events determining the softening of fleshy fruits: A comprehensive review. *Int. J. Mol. Sci*. 2022, 23, 12482. https://doi.org/10.3390/ijms232012482.
39. Wang, D., Trevor, H., Yeats, T.H., Uluisik, S., Jocelyn, K.C., Rose, J., & Seymour, G.B. (2018). Fruit softening: Revisiting the role of pectin. *Trends Plant Sci., 23*(4), 302-310. https://doi.org/10.1016/j.tplants.2018.01.006.
40. Roohanitaziani, R., Lammers, M., Molthoff, J., Tikunov, Y., Meijer-Dekens, F., Visser, R. G., van Arkel, J., Finkers, R., de Maagd, R.A., & Bovy, A. G. (2022). Phenotyping of a diverse tomato collection for postharvest shelf-life. *Postharvest Biol. Technol*., 188, 111908. https://doi.org/10.1016/j.postharvbio.2022.111908
41. Angeletti, P., Castagnasso, H., Miceli, E., Terminiello, L., Concellon, A., Chaves, A., & Vicente, A.R. (2010). Effect of preharvest calcium applications on postharvest quality, softening, and cell wall degradation of two blueberry (*Vaccinium corymbosum*) varieties. *Postharvest Biol. Technol., 58*(2), 98-103. https://doi.org/10.1016/j.postharvbio.2010.05.015
42. Figueroa, C., Opazo, M.C., Vera, P., Arraigada, O., Díaz, M., & Moya-León, M. (2012). Effect of postharvest treatment of calcium and auxin on cell wall composition and expression of cell wall-modifying genes in the Chilean strawberry (*Fragaria chiloensis*) fruit. *Food Chem., 132*(4), 2014-2022. https://doi.org/10.1016/j.foodchem.2011.12.041
43. Gapper, N.E., McQuinn, R.P., & Giovannoni, J.J. (2013). Molecular and genetic regulation of fruit ripening. *Plant Mol. Biol., 82*(6), 575-591. https://dx.doi.org/10.1007/s11103-013-0050-3
44. Choi, H.-G., & Park, K.S. (2023). Ripening process of tomato fruits postharvest: Impact of environmental conditions on quality and chlorophyll a fluorescence characteristics. *Horticulturae*, 2023, 9, 812. https://doi.org/10.3390/horticulturae9070812.
45. Antala, P.A., Chakote, A., Varshney, N., Suthar, K., Singh, D., Narwade, A., Patel, K., Gandhi, K., Singh, S., & Karmakar, N. (2025). Phytochemical and metabolic changes associated with ripening of *Lycopersicon esculentum*. *Sci. Rep*., 15, 10692 (2025). https://doi.org/10.1038/s41598-025-95255-9.
46. Kapoor, L., Simkin, A.J., George Priya Doss, C., & Siva, R. (2022). Fruit ripening: dynamics and integrated analysis of carotenoids and anthocyanins. *BMC Plant Biol 22, 27*(2022). https://doi.org/10.1186/s12870-021-03411-w.
47. Zhu F., Wen W., Cheng Y., & Fernie AR. (2022). The metabolic changes that affect fruit quality during tomato fruit ripening. *Mol. Hortic. 2022 20;2*(1):2. doi: 10.1186/s43897-022-00024-1.
48. Lopez-Camelo, A.F., & Gomez, P.A. (2004). Comparison of color indexes for tomato ripening. *Hortic. Bras*., 22, 534–537. https://doi.org/10.1590/S0102-05362004000300006.
49. Wang, S., Qiang, Q., Xiang, L., Fernie, A.R. & Yang, J. (2023). Targeted approaches to improve tomato fruit taste. *Hortic. Res. 10*(1): 10: uhac229. https://doi.org/10.1093/hr/uhac229.

50. Xu, M., Ji, S., Pang, S., Lu, Y., Li, S., & Xu, W. (2025). Regulatory mechanisms of total soluble solids in tomato: From QTL mapping to gene editing. *Foods*, 2025, 14, 3692. https://doi.org/10.3390/foods14213692.
51. Hatami, M., Kalantari, S., & Delshad, M. (2013). Responses of different maturity stages of tomato fruit to different storage conditions. *Acta Hortic*., 1012, 857-864. https://doi.org/10.17660/ActaHortic.2013.1012.116
52. Kaygısız, T., Sen, F., Gundogdu, M., Ejaz, S., & Aglar, E. (2025). Effect of postharvest melatonin and salicylic acid applications on quality characteristics and primary and secondary metabolite physiology of tomato fruits. *BMC Plant Biol.* 25, 1090. https://doi.org/10.1186/s12870-025-07013-8.
53. Kaur, G., Abugu, M. & Tieman, D. (2023). The dissection of tomato flavor: biochemistry, genetics, and omics. *Front. Plant Sci*. 14:1144113. doi: 10.3389/fpls.2023.1144113.