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

Tratamientos poscosecha a base de calcio y silicio en hidro-enfriamiento sobre atributos básicos de calidad en cerezas (*Prunus avium* L.) dulces 'Bing' durante almacenamiento

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Abstract

Ca^{2+} and Si^{2+} treatments confer resistance to biotic and abiotic stresses in many fruits. In sweet cherries, Ca^{2+} improves shelf life extension during storage, but only $CaCl_2$ is used. On the other hand, there is scarce information on $CaCO_3$ as a source of Ca^{2+}, which has shown increased firmness in berries. This study evaluated different treatments based on Ca^{2+} ($CaCl_2$ and $CaCO_3$) + Si^{2+} (SiO_2) alone and combined with immersion in hydro-cooling (0°C) on physicochemical characteristics of 'Bing' sweet cherries (*Prunus avium* L.) during storage at low temperature (4°C). Results demonstrate that alone or combined treatments (Ca^{2+} and Si^{2+}) with hydro-cooling significantly affected skin and flesh color of sweet cherries. Chromaticity (C^*) was increased in treated fruits, indicating an intense red color, especially in those cherries treated with $CaCl_2$. Furthermore, firmness was increased during storage in treatments with Ca^{2+}, while SiO_2 treatment increased total soluble solids (TSS). Therefore, combined treatments of Ca^{2+} and Si^{2+} with hydro-cooling might be a promising postharvest strategy to maintain desirable physicochemical characteristics in sweet cherries during low-temperature storage.

Keywords
Prunus avium • fruit firmness • shelf life • non-climacteric fruit • total soluble solids • skin color

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Resumen

Se ha demostrado que los tratamientos con Ca^{2+} y Si^{2+} confieren resistencia al estrés biótico y abiótico en muchas frutas. En cerezas dulces, el Ca^{2+} mejora la extensión de la vida útil durante el almacenamiento, pero solo se ha utilizado $CaCl_2$. Por otro lado, existe escasa información sobre el $CaCO_3$ como fuente de Ca^{2+}, que ha mostrado un aumento de la firmeza en bayas. En este estudio, se evaluaron diferentes tratamientos a base de Ca^{2+} ($CaCl_2$ y $CaCO_3$) + Si^{2+} (SiO_2) solos y combinados por inmersión en hidro-enfriamiento (0°C) sobre características fisicoquímicas en cerezas dulces 'Bing' (*Prunus avium* L.) durante el almacenamiento a baja temperatura (4°C). Los resultados demuestran que los tratamientos solos o combinados (Ca^{2+} y Si^{2+}) en hidro-enfriamiento afectaron significativamente al color de la piel y pulpa de las cerezas dulces. Se aumentó la cromaticidad (C^*) en los frutos tratados, indicando un color rojo intenso, especialmente en aquellas cerezas tratadas con $CaCl_2$. Además, la firmeza aumentó durante el almacenamiento en los tratamientos con Ca^{2+}, mientras que el tratamiento con SiO_2 incrementó la acumulación de sólidos solubles totales (SST). Por lo tanto, los tratamientos combinados de Ca^{2+} y Si^{2+} con hidro-enfriamiento podrían ser una estrategia poscosecha prometedora para mantener las características fisicoquímicas deseables en cerezas dulces durante el almacenamiento a baja temperatura.

Palabras clave

Prunus avium • firmeza del fruto • vida útil • fruto no climatérico • sólidos solubles totales • color de la piel

Introduction

Sweet cherry (*Prunus avium* L.) is one of the most appreciated fruits worldwide. Attributes such as sweetness, color, size, and flavor add up to being a rich source of antioxidants and phytonutrients (14, 39, 40, 66). In Mexico, the current demand for sweet cherries exceeds the 1,249 tons imported (17). In this country, cherry production is 144.45 tons, with only 35.5 ha established in the states of Chihuahua and Puebla (50). However, Mexico has regions with high potential for its production (4).

Fruit firmness, skin and pedicel color, acidity, and sugar content in fresh sweet cherries are major attributes influencing consumer acceptability (14). However, these attributes are often lost in between harvest, packaging, transportation, and storage, especially since sweet cherries are highly perishable and have a shorter post-harvest shelf life (40, 42, 49). Post-harvest strategies should avoid water loss, softening, color deterioration, and pedicel browning (14, 30, 53, 66). Nowadays, several technologies and practices, aimed at preserving post-harvest quality of sweet cherries, target respiration and senescence, increasing flesh firmness (10, 14, 54, 58, 66). In this regard, pre-harvest or at-harvest treatments with calcium (Ca^{2+}) and silicon (Si^{2+}) on sweet cherries extend storage life and improve flesh firmness by minimizing respiration and increasing fruit flesh resistance (14, 16, 31, 33, 46, 58, 63, 64).

Calcium is considered a critical, quality-defining nutrient in sweet cherries (63), mainly promoting firmness by acting in association with pectin molecules at cell-wall level (8, 38). $CaCl_2$ is the most widely used source of calcium in sweet cherries, both pre and post-harvest, preserving fruit quality and reducing physiological disorders like cracking (12, 14, 16, 27, 64). $CaCO_3$ is another less-known source of calcium for agriculture, shown to increase firmness of 'Shiraz' grapes after pre-harvest foliar application (32). On the other hand, silicon (Si^{2+}), although not considered an essential element for plant nutrition (7), has been suggested against various biotic and abiotic stresses in sweet cherry cultivation (2, 7, 28, 46). Si^{2+} improves strength and stiffness of plant tissues and increases wall extensibility (2, 23, 28). In addition, available literature demonstrates the safe use of physical treatments like hydro-cooling on vegetables and fruits to extend postharvest quality, especially by delaying firmness loss, reducing respiration rate and preserving fruit flavor (58, 60).

Therefore, chemical strategies like Ca^{2+} and Si^{2+} applications and physical treatments like hydro-cooling on freshly harvested sweet cherries might maintain storage quality (58, 59). However, studies considering a combination of Ca^{2+} and Si^{2+} with hydro-cooling and cool storage on post-harvest quality and shelf life of sweet cherries, are scarce (29, 53, 58).

Considering the aforementioned, the study aimed to evaluate the effect of post-harvest treatments with Ca^{2+} and Si^{2+} combined with hydro-cooling on physicochemical quality of 'Bing' sweet cherries during low-temperature storage.

Materials and methods

Fruits and chemical inputs

Sweet cherries 'Bing' (12 kg) were harvested from the commercial orchard "El Fulano" (28°26'46" N; 106°45'1.6" W and 2013 m above sea level) located in the "Tres Lagunas" ejido, in Cuauhtemoc, Chihuahua, Mex. Fruits were randomly collected from several trees on east-facing branches and from the center of the canopy. For the treatments of Ca^{2+} and Si^{2+}; food-grade $CaCl_2$, $CaCO_3$, and SiO_2 were purchased from Food Technologies Trading S.A. de C.V. Mexico.

Immersion of fruits

Before starting treatments, cherries were disinfected by immersion in a 1% (v/v) sodium hypochlorite for 5 min, washed twice with sterile distilled water, and left to dry at room temperature while packaged in commercial polyethylene boxes. Six treatments (solutions) simulated hydro-cooling, using distilled water and enough ice to keep the solutions at 0°C (58). Sweet cherries were immersed for 5 min in the evaluated solutions, all of them at 0.5% according to previous studies (58). The evaluated solutions were T1 ($CaCl_2$), T2 ($CaCO_3$), T3 (SiO_2), T4 ($CaCl_2$ + SiO_2), T5 ($CaCO_3$ + SiO_2) and a control treatment T6 (distilled water at 0°C). Thirty-two selected fruits were used in each treatment considering post-harvest evaluation dates 0, 7, 14 and 21 days after treatment. After the treatments, fruits were drained, placed on brown paper to dry at room temperature, packed in commercial polyethylene boxes (500 g) and immediately stored at 4°C with relative humidity of ~85%.

Basic physicochemical properties

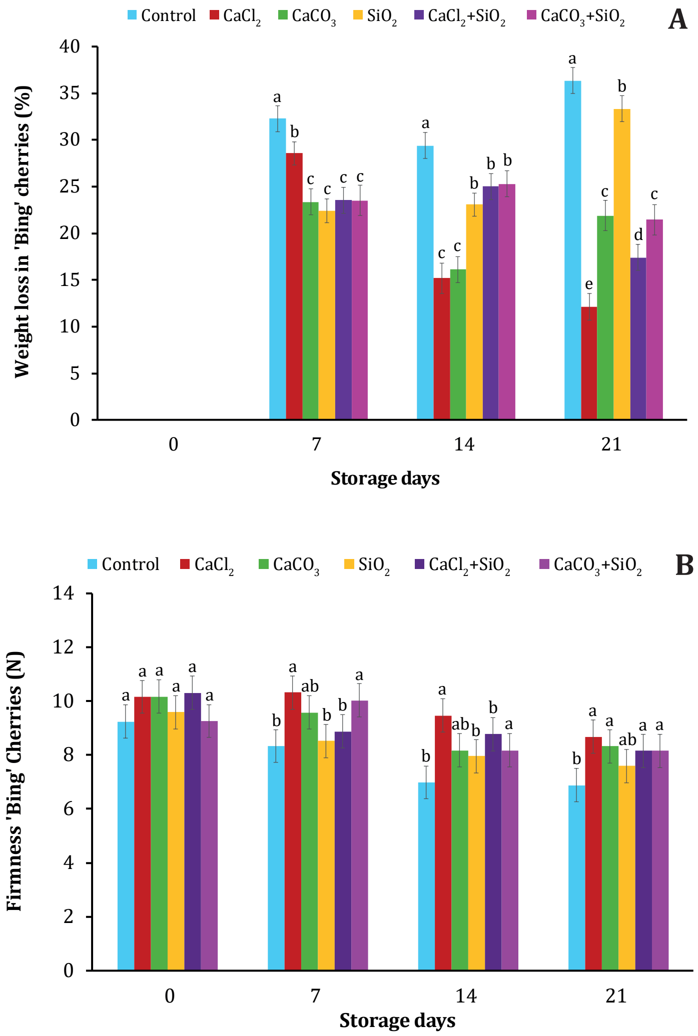
Physicochemical changes were measured by monitoring weight, firmness, color, total soluble solids (TSS; °Brix), and titratable acidity (TA). Measurements were expressed as the average of 32 fruits. The standard error (SE) was estimated at each evaluation time. Fruit weight was determined with an electronic balance, 0.01g precision, Precisa BJ 610C (Precisa Gravimetrics AG/Switzerland). Fruit firmness was evaluated as fruit resistance to a deformation of 15% of fruit diameter using a plunger of Ø=6 mm on a stationary steel plate, attached to a Universal Texture Analyzer TA-XT2i (Texture Technologies Corp. USA) according to previous studies (6). Data were expressed in Newtons (N) using the Texture Exponent Lite program. Skin color (CIELab parameters L^*, C^* and h^*) was measured at opposite sites of each fruit with a colorimeter CR-300, Minolta, (Japan). Total soluble solids content (TSS= °Brix) was determined in fruit juice with a digital refractometer PAL-1 pocket (Atago, Japan). Finally, titratable acidity (TA expressed as g 100 g^{-1} of fresh weight 'FW') was measured by diluting 1 g of flesh in 9 mL of distilled water, followed by 3 drops of phenolphthalein and titrated with 0.1 N NaOH until pH 8.2 (6). The maturity index was expressed as the ratio of TSS: TA (34).

Experimental design and statistical analysis

Results were statistically evaluated according to a split-plot in-time design. ANOVA and LSD mean tests were used to detect significant differences among treatments at $p \leq 0.05$ using SAS System for Windows 9.0 (SAS Institute. Inc. Cary, N.C., USA, 2002) after testing assumptions. All experiments were conducted using four replicates.

Results and discussion

In hydro-cooling, calcium and silicon treatments (alone or combined) significantly influenced some quality parameters and shelf life in sweet cherries during low-temperature storage (figure 1, figure 2, page 118 and figure 3, page 119). Various studies have extensively documented that Ca^{2+} applications in fruits favor storage conservation. In sweet cherries, it has been documented that Ca^{2+} delays deterioration, favorably influencing physicochemical attributes like weight, color, firmness, TSS, TA, pH, respiration rate, and anthocyanin content, especially during storage (14, 31, 57, 58, 59, 60). Shelf life extension in sweet cherries could be attributed to Ca^{2+} increase in the cell walls, favored by rapid absorption of Ca^{2+} by the fruit flesh under hydro-cooling immersion (19, 27, 59, 61).

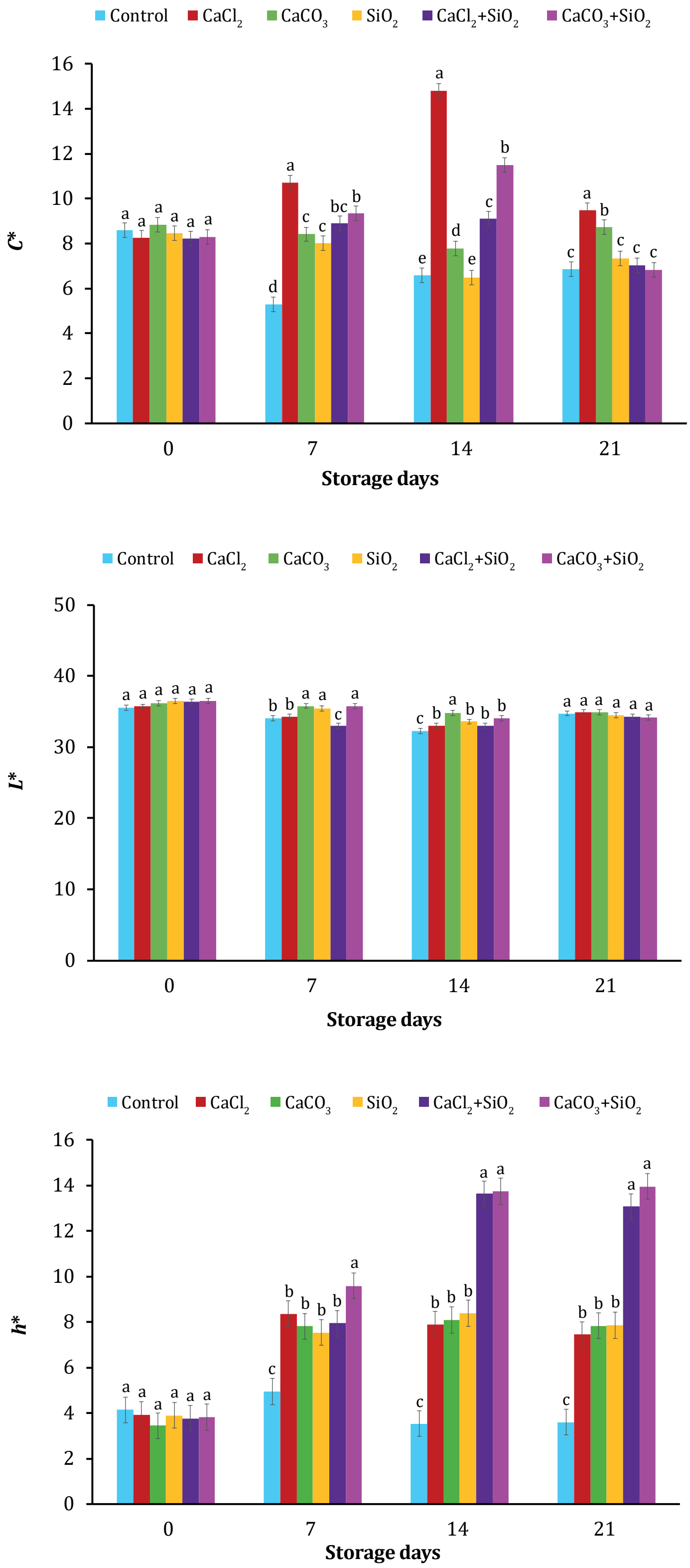


Different letters indicate significant differences ($p \leq 0.05$) between treatments for each storage date.

Las letras diferentes indican diferencias significativas ($p \leq 0,05$) entre tratamientos para cada fecha de almacenamiento.

Figure 1. Effect of post-harvest treatments based on calcium (Ca^{2+}) and silicon (Si^{2+}) sources, alone and combined with hydro-cooling on weight loss (A) and firmness (B) in 'Bing' sweet cherries during storage at low temperature.

Figura 1. Efecto de los tratamientos poscosecha basados en fuentes de calcio (Ca^{2+}) y silicio (Si^{2+}) solas y combinadas con hidro-enfriamiento sobre la pérdida del peso (A) y la firmeza (B) en cerezas dulces 'Bing' durante el almacenamiento a baja temperatura.

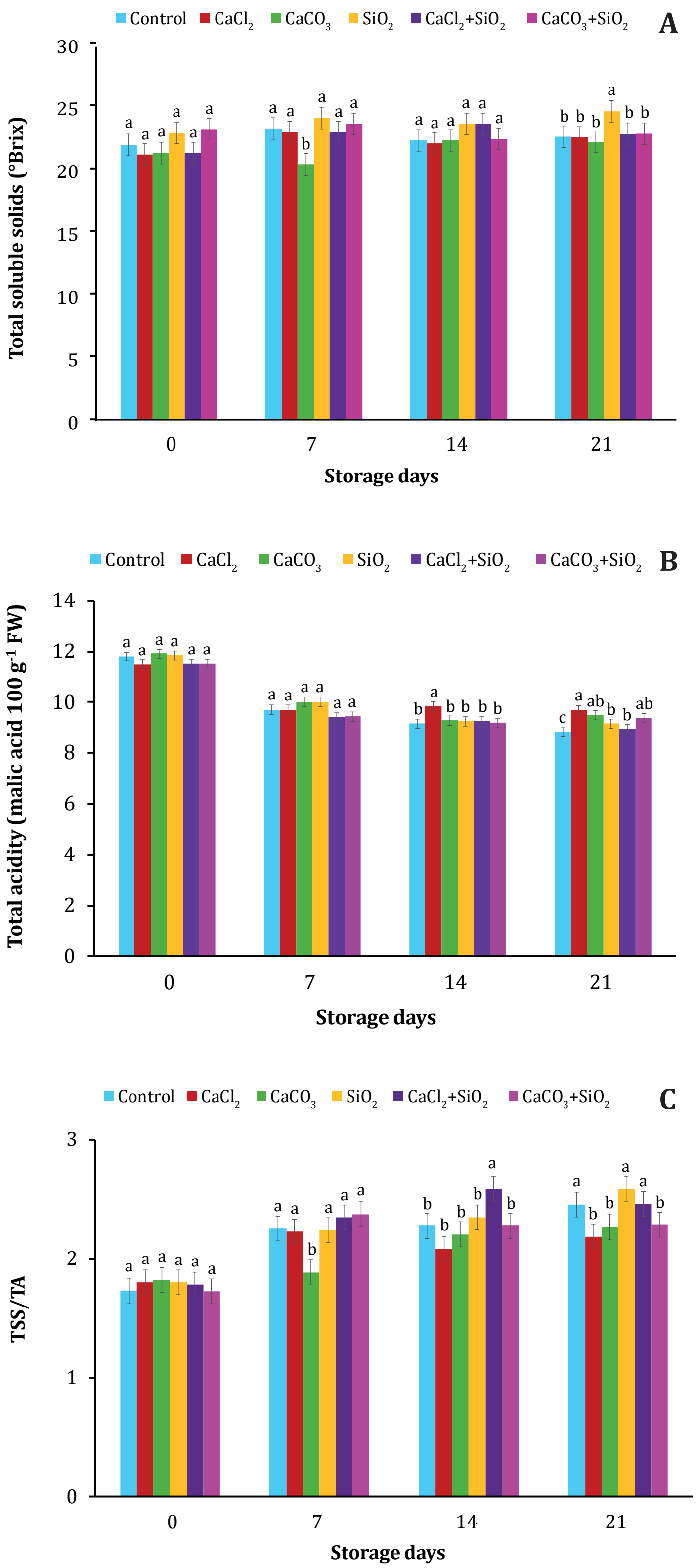


Different letters indicate significant differences ($p \leq 0.05$) between treatments for each storage date.

Las letras diferentes indican diferencias significativas ($p \leq 0,05$) entre tratamientos para cada fecha de almacenamiento.

Figure 2. Effect of post-harvest treatments of calcium (Ca^{2+}) and silicon (Si^{2+}) sources alone and/or combined with hydro-cooling on skin color (L^* C^* $h°$) in 'Bing' sweet cherries during low-temperature storage.

Figura 2. Efecto de los tratamientos poscosecha de fuentes de calcio (Ca^{2+}) y silicio (Si^{2+}) solas y/o combinadas con hidro-enfriamiento sobre el color de la piel (L^* C^* $h°$) en cerezas 'Bing' dulces durante el almacenamiento a baja temperatura.



Different letters indicate significant differences ($p \leq 0.05$) between treatments for each storage date.

Las letras diferentes, indican diferencias significativas ($p \leq 0,05$) entre tratamientos para cada fecha de almacenamiento.

Figure 3. Effect of post-harvest treatments of calcium (Ca^{2+}) and silicon (Si^{2+}) sources alone and/or combined with hydro-cooling on total soluble solids (TSS; A), titratable acidity (TA; B) and maturity index (TSS/ TA; C) in 'Bing' sweet cherries during low-temperature storage.

Figura 3. Efecto de los tratamientos poscosecha de fuentes de calcio (Ca^{2+}) y silicio (Si^{2+}) solas y/o combinadas con hidro-enfriamiento sobre los sólidos solubles totales (SST; A), la acidez titulable (AT; B) y el índice de madurez (SST/AT; C) en cerezas dulces 'Bing' durante el almacenamiento a baja temperatura.

Weight loss is the most important parameter for horticultural crops and fruit quality and shelf life. All treatments based on Ca^{2+} and Si^{2+} sources, alone and combined with hydro-cooling, affected weight loss of sweet cherries during storage (figure 1, page 117). According to previous studies (51, 66), weight loss in stored fruits mainly depends on transpiration and respiration. Interestingly, cherries treated with Ca^{2+} lost less weight during storage compared to untreated cherries (figure 1, page 117), suggesting that Ca^{2+} ions increased cell wall stability. Other studies mention increased cell wall stability after Ca^{2+} ions bind non-esterified pectins and stabilize cell membranes, preventing electrolyte leakage and consequently preventing fruit moisture and weight loss (1, 38, 41). The observed weight values in fruits treated with Ca^{2+} could have been influenced by the amount of this element absorbed through the skin (through the lenticels and peduncle pores) during the 5-minutes exposure (44). Similarly, previous studies (15) documented that combined Ca-Glu (calcium gluconate) treatment, limited weight loss in sweet cherries.

Sweet cherries treated with SiO_2 showed rapid weight loss on day 21 of storage, however less evident than for control fruits (figure 1A, page 117). Similarly, other studies (3) have documented that SiO_2 was less effective in preventing weight loss in post-harvest fruits of *Citrus* × *sinensis,* while Rombolà *et al.* (2023) found that foliar sprays with sodium silicate (Na_2SiO_3) decreased cherry weight at harvest.

Firmness is a major attribute in fruits (43). Broadly, our study showed a gradual loss of firmness concerning storage time indicating senescence, with significant differences among monitoring dates and treatments. According to previous studies (14), decreases in this parameter are more noticeable during storage. Softening of sweet cherries is attributed to enzymatic degradation of pectic compounds in the middle lamella of the cell walls by polygalacturonases, pectin methyl esterases, cellulases, and β-galactosidases (62). All sweet cherries treated with Ca^{2+} and Si^{2+} were firmer than control fruits (figure 1B, page 117). Studies have suggested that pre- and post-harvest treatments with Ca^{2+} and Si^{2+} favor greater firmness in fruits at harvest time and during storage (27, 55). Sweet cherries containing insufficient Ca^{2+} are softer, and, therefore, more susceptible to quality losses during storage (10). Fruits treated with $CaCl_2$ were the firmest compared to control fruits after 21 days of storage (figure 1B, page 117). It has been evidenced that $CaCl_2$ applied before and/or after cherry harvest increases firmness values up to 0.6 N (14, 63, 64). Our study is consistent with previous studies (10, 14, 15, 27, 55), reporting increased fruit firmness in treatments with Ca^{2+} before harvest and/or in recently harvested cherries. The treatments ($CaCO_3$ and $CaCO_3$+SiO_2) also favored greater firmness of sweet cherries but to a lesser extent than $CaCl_2$ (figure 1B, page 117). Similarly, other studies (32) documented firmer 'Shiraz' grapes after pre-harvest foliar treatment with $CaCO_3$. In our study, the treatment with SiO_2 alone was the least effective, although slightly superior to the control.

The greater firmness of sweet cherries treated with Ca^{2+} is attributed to the ability of this element to maintain cell wall mechanical properties and integrity during storage, which consequently delays softening (14, 44, 47). According to previous studies (38), Ca^{2+} acts in association with pectin molecules in fruit cell walls. It has also been suggested that Ca^{2+} maintains fruit firmness by reducing water loss and stabilizing the membrane, given this ion is responsible for binding phosphate and carboxylate groups of membrane phospholipids and proteins (62, 65).

Surface color of cherries is determined by factors such as radiation at the end of fruit development, and temperatures near harvest (13). Recently, it has been documented that color of sweet cherries is influenced by post-harvest treatments based on Ca^{2+} and Si^{2+} (14, 46). On the other hand, according to other studies (21, 36), the chromatic functions L^*, C^* and $h°$ are closely correlated with color change and anthocyanin accumulation in sweet cherries during ripening. Interestingly, after 21 days of storage, sweet cherries treated with Ca^{2+} or Si^{2+} showed increased chromaticity (figure 2, page 118), redder and intensity (C^*), especially in cherries treated with $CaCl_2$. This effect could be due to the inhibition of skin color development by Ca^{2+} or Si^{2+}. The delayed skin color darkening may be related to senescence inhibition (58, 59). Control fruits showed a darker red color attributed to chlorophyll degradation and accumulation of anthocyanins during storage (5, 18). Coincidentally, other studies (21) reported that the higher the anthocyanin content in sweet cherries, the lower the values of L^* and $h°$.

The *L** value in sweet cherries decreased during storage in all treatments, not showing significant differences among treatments (figure 2, page 118). Sweet cherries treated with $CaCO_3$+SiO_2 and $CaCl_2$+SiO_2 showed a higher *h*° angle (figure 2, page 118), indicating reduced red tones (*h*°) than control fruits and suggesting lower skin anthocyanin content (21, 37). In contrast, Rombolà *et al.* (2023) documented that Si^2+ reduced hue (*h*°), brightness (*C*), and saturation of cherry skin/flesh, while, Karagiannis *et al.* (2021) documented that foliar sprays with Si^2+ induced skin color development in apples by stimulating anthocyanin accumulation. In this experiment, sweet cherries treated with $CaCO_3$+SiO_2 and $CaCO_3$ showed higher *L** and *h*° values (figure 2, page 118) compared with control fruits, probably given to suppression of respiratory processes by $CaCO_3$, as previously established in cherries treated with Ca^2+ at harvest (14). The positive effect of $CaCO_3$ on skin and flesh color in sweet cherries is given by Ca^2+ activation of ABA biosynthesis, which influences anthocyanin biosynthesis in non-climacteric fruits such as cherries (20, 32).

The TSS concentration in sweet cherries significantly increased according to storage time in all treatments (figure 3A, page 119). Increasing TSS concentrations during storage is only frequent in climacteric fruits (22, 35). Therefore, the highest TSS concentrations in non-climacteric sweet cherries might be favored by a pronounced weight/moisture loss in SiO_2 treated and control fruits (figure 1A, page 117). The SiO_2 and $CaCl_2$+SiO_2 treatments significantly increased TSS in sweet cherries (figure 3A, page 119), like previously documented by Rombolà *et al.* (2023), who suggested that Si^{2+} forms a protective film covering fruit surface and preventing transpiration, slowing down phloem translocation, and subsequent sugar accumulation. The high concentration of TSS (figure 3A, page 119) in SiO_2-treated fruits might also be due to sugar concentration after greater weight loss (figure 1A, page 117) (11), something not observed in $CaCl_2$-, treated ones.

On the contrary, lower TSS values were observed in sweet cherries treated with $CaCl_2$ compared with control fruits. This coincides with other studies (9, 15), documenting low TSS contents in Ca^{2+}-treated cherries. Both studies attributed these results to lower respiration rates in treated cherries, leading to cell wall and membrane stabilization. This could also be attributed to delayed moisture and weight loss (figure 1A, page 117) after pectin stabilization and consequent effects on cell wall and membrane structure (32).

TA in sweet cherries also decreased over time during storage for control, Ca^{2+} and Si^{2+} treatments evidencing significant differences (figure 3B, page 119). Similar results were documented in 'Sweetheart' and 'Lapins' sweet cherries during storage (58). Low acidity mainly depends on ripeness state (45); however, during storage, organic acids might be used as carbon source during respiration (15, 25, 26, 60). After 21 days of storage, sweet cherries treated with Ca^{2+} and Si^{2+} maintained TA above values recorded for control cherries. However, the highest TA values were measured in $CaCl_2$-treated fruits (figure 3B, page 119). Sweet cherries treated with $CaCO_3$ and $CaCO_3$+SiO_2 also showed high TA values. Coincidentally, treatments with Ca^{2+} (such as $CaCl_2$ and Ca-Glu/calcium gluconate) in pre-harvest and/or before storage of sweet cherries, also preserved or retarded TA loss during storage, compared to control fruits (14, 15, 48, 55, 58).

Delayed loss of TA during storage of sweet cherries treated with Ca^{2+} sources could be due to the suppressive effect on fruit metabolic activity, especially respiration (15, 35, 56).

The maturity index TSS/TA indicates commercial and organoleptic maturity of fruits (34, 45). High contents of both TSS and TA are associated with good flavor in sweet cherries (52, 53). The TSS/TA ratios in 'Bing' sweet cherries treated with Ca^{2+} and Si^{2+} were statistically different (figure 3C, page 119), however increasing over time in all treatments and indicating a higher acid *vs.* sugar content ratio. TSS/TA ratio in sweet cherries treated with $CaCO_3$+SiO_2, $CaCO_3$, and $CaCl_2$ remained lower than control after 21 days of storage, indicating diminished respiration rates. While TSS/TA ratios in SiO_2 treatments remained above control values.

Conclusions

Immersion of freshly harvested 'Bing' sweet cherries with hydro-cooled solutions of Ca^{2+} ($CaCl_2$ and $CaCO_3$) and Si^{2+} (SiO_2) alone and combined markedly improved quality properties and extended storage capacity at low temperatures. All treatments based on Ca^{2+} and Si^{2+} alone reduced weight loss while maintaining firmness, and acidity in sweet cherries. Skin color of sweet cherries treated with Ca^{2+} and Si^{2+} was more intense than control fruits. Sweet cherries treated with $CaCl_2$ were the firmest and had the highest TA values. SiO_2 increased TSS concentration in sweet cherries, while $CaCl_2$ decreased it.

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