https://doi.org/10.17221/163/2025-CJFS

$CaCl_2$-cold storage combination: An efficient preservation approach for prolonging the shelf life of passion fruit (*Passiflora edulis*)

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Citation: Zhang X., Wang Y., Li J., Zhang Z., Chen C., Teng Y., Long X. (2026): CaCl2-cold storage combination: An effective preservation strategy for extending the shelf life of passion fruit (*Passiflora edulis*). Czech J. Food Sci., 44: 315–325.

Abstract: Passion fruit (*Passiflora edulis*) is a highly perishable climacteric fruit that is susceptible to rapid postharvest deterioration including pericarp shrinkage and pulp separation. In this study, six preservation treatments were assessed for maintaining the quality of 'Qinguo No. 9' passion fruit: control (20 °C), water + 20 °C, 4 °C alone, water + 4 °C, $CaCl_2$ + 20 °C, and their combination ($CaCl_2$ + 4 °C). The lowtemperature treatments markedly decreased significantly reduced cumulative weight loss and maintained higher edible rates, with 4 °C alone showing the strongest effect in reducing weight loss. In terms of nutritional attributes, the $CaCl_2$ + 4 °C treatment produced the highest soluble sugar content during the middle stage of storage. In addition, both $CaCl_2$ + 4 °C and $CaCl_2$ + 20 °C treatments significantly delayed flavonoid degradation and maintained elevated total phenolic levels during late storage, suggesting a synergistic interaction between calcium and low temperature in regulating secondary metabolism. Rather than simply optimising individual quality indicators, the combined treatment effectively balanced water retention, sugar accumulation, and antioxidant preservation throughout storage. These results indicate that $CaCl_2$ + 4 °C treatment represents a feasible strategy for extending the commercial shelf life of passion fruit while preserving both sensory and nutritional properties, particularly through improved mid-term sugar retention and enhanced latestage phenolic maintenance.

Keywords: climacteric fruit; postharvest physiology; cold storage; calcium treatment; secondary metabolism; shelf-life extension

The family *Passifloraceae* contains more than 500 species, the majority of which are distributed in tropical and subtropical regions (Dos et al. 2018). The principal cultivated species include purple pas-

Supported by the Guizhou Provincial Basic Research Program (Natural Science) under Grant No. QKHJC-ZK[2024]YB625, No. QKHJC-[2024]QN374, No. QKHJC-ZK[2022]YB292, No. QKHFQ[2024] 004-1, and No. QKHFQ[2024] 004-2, as well as the National Key R&D Projects of China (2021YFD1100303) and the Post-subsidy Project.

https://doi.org/10.17221/163/2025-CJFS

sion fruit (*Passiflora edulis* Sims), sweet passion fruit (*Passiflora alata*), and yellow passion fruit (*P. edulis* f. *flavicarpa*) (Corrêa et al. 2016). Among these, yellow passion fruit is currently the most extensively cultivated variety worldwide (Pereira et al. 2023). The global passion fruit market was valued at nearly USD 12 billion in 2024 and is projected to expand at a compound annual growth rate (CAGR) of 5.2% by 2031 (6Wresearch 2025). By 2022, the cultivation area in China alone had reached 45 000 hectares. This fruit variety is widely favoured by consumers because of its distinctive flavour and high nutritional content. At present, passion fruit is primarily consumed in the fresh form. The early fruit maturation period, occurring from late August to early September, generally coincides with conditions of high temperature and humidity. As a climacteric respiratory fruit, passion fruit exhibits accelerated respiration and transpiration rates after harvest, leading to continuous nutrient depletion. Consequently, several postharvest problems, including water loss, peel softening, shrinkage, decapsulation, and decay, frequently occur, thereby greatly reducing fruit quality and shortening storage duration. Therefore, the development of effective postharvest preservation and storage methods for passion fruit is of considerable importance.

Calcium ions perform diverse and essential functions in plant physiology, acting as important structural constituents of cell membranes and cell walls, where they help maintain membrane stability and cell wall integrity (Gao et al. 2019). Moreover, calcium ions have been reported to reduce fruit softening and browning while delaying the senescence process (Suriati et al. 2021). Calcium chloride, a highly water-soluble calcium salt, has been recognised as safe by the US Food and Drug Administration (FDA) (El-Beltagi et al. 2022). Previous studies have demonstrated that postharvest $CaCl_2$ can improve the antioxidant capacity of fruits and vegetables, delay tissue softening (Gao et al. 2020), and decrease the occurrence of physiological disorders and diseases (Pourahmadi et al. 2019). For instance, in papaya, both preharvest and postharvest calcium applications effectively delayed ripening and senescence, reduced postharvest disease incidence, and maintained overall fruit quality (Gao et al. 2020). Likewise, $CaCl_2$ treatment has been shown to preserve firmness, colour, and sugar and acid contents in tomatoes (Shehata et al. 2021), while also improving antioxidant activity in pears (Zhang et al. 2019). In addition, Pan et al. (2023) reported that calcium chloride treatment can retard down cell wall softening and prolong shelf life. In agreement with these findings, our previous study demonstrated that 2% $CaCl_2$ treatment produced the most favourable preservation effect (Zhang et al. 2024).

Low-temperature storage is generally considered one of the most effective and practical approaches for prolonging the shelf life of fruits and vegetables (Moretti et al. 2010). Previous studies have indicated that low temperatures can significantly reduce respiration rates (Lv et al. 2022), inhibit the activities of enzymes such as lipoxygenase and polyphenol oxidase in pears (Li et al. 2023), slow down metabolic activity, and delay sucrose degradation (Wang et al. 2022). Furthermore, low-temperature storage can suppress microbial proliferation and reduces mass loss (Qadri et al. 2015). For instance, studies on sweet corn has demonstrated that low temperature storage effectively reduced respiration intensity and sugar depletion (Xiao et al. 2023). However, passion fruit is particularly sensitive to postharvest temperature conditions. Previous studies showed that storage at 4 ± 1 °C effectively maintained fruit quality by slowing the decline in soluble solids, titratable acidity, and vitamin C content, while inhibiting superoxide anion production and delaying changes in antioxidant enzyme activities (Ren et al. 2024). Despite these advantages, limited information is available regarding the combined influence of calcium chloride and low temperature on the postharvest quality of passion fruit. Therefore, the present study used 'Qinguo No. 9' to investigate the effects of a combined treatment consisting of 2% $CaCl_2$ and low temperature (4 °C) on fruit quality during different storage periods. The low-temperature treatment (4 °C) was selected according to the experimental design adopted in previous cold storage studies (Ren et al. 2024), with the objective of evaluating the preservation efficacy of lower storage temperature in combination with calcium chloride treatment. Clarifying the postharvest quality changes of passion fruit and its responses to calcium ions and low temperature may provide valuable insights for improve the preservation and quality maintenance of this economically valuable fruit.

MATERIAL AND METHODS

Sample collection

The study was conducted using one-year-old grafted 'Qinguo No. 9' passion fruit seedlings cultivated at a passion fruit plantation in Zhongchen Town, Rongjiang County, Guizhou Province, China (25° 94' N, 108° 53' E, 291 m above sea level). This area is characterised by a subtropical humid monsoon climate, with an average annual temperature of 18.1 °C, annual

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sunshine duration of 1 141 h, and mean annual precipitation of 1 211 mm, most of which occurs between April and September. The zonal soil was classified as yellow loam and contained 0.68 g·kg^{-1} total nitrogen, 23.56 mg·kg^{-1} hydrolysable nitrogen, 16.85 g·kg^{-1} total potassium, 113.73 mg·kg^{-1} available potassium, 0.33 g·kg^{-1} total phosphorus, with a soil pH of 6.5. In the experimental field, the orchard was established using high-ridge cultivation techniques, with a ridge height of 60 cm, ridge width of 1 m, and ridge spacing of 3 m. In addition, a flat-shed vertical curtain trellis system was constructed using steel pipes spaced 4 m apart and steel wires with a diameter of 4 mm. 'Qinguo No. 9' passion fruits were harvested at commercial maturity, which was defined as fruits exhibiting 75–80% yellow peel colour. Only mature fruits without visible mechanical injury or pest damage were selected and analysed on the day of harvest.

Experimental treatment

The experiment included six treatment groups: a control group (Control 20 °C) without immersion treatment and stored at 20 °C; a water immersion control group (Water + 20 °C), in which fruits were immersed in distilled water at 20 °C and subsequently stored at 20 °C; a low-temperature storage group (4 °C), where fruits were directly stored at 4 °C without immersion; a water immersion combined with low-temperature storage group (Water + 4 °C), where fruits were immersed in distilled water at 20 °C and then transferred and stored at 4 °C; a $CaCl_2$ treatment at ambient temperature ($CaCl_2$ + 20 °C), in which fruits were immersed in a 2% $CaCl_2$ solution (Sinopharm Chemical Reagent Co., Ltd., China, analytical grade) at 20 °C and then stored at 20 °C; and a combined $CaCl_2$ and low-temperature treatment group ($CaCl_2$ + 4 °C), where fruits were immersed in 2% $CaCl_2$ solution at 20 °C before storage at 4 °C. For each treatment, 25 fruits were immersed for 10 min with continuous turning to ensure uniform treatment of the fruit surface. Following immersion, the fruits were naturally air-dried, packed into fresh-keeping PE film bags, sealed, and stored for 10 days under controlled conditions. The ambient-temperature groups were maintained at 20 ± 1 °C, whereas the low-temperature groups were maintained at 4 ± 1 °C. Relative humidity under all storage conditions was controlled at 80–85%. Fruit quality parameters were evaluated at two-day intervals. The edible portions were rapidly frozen in liquid nitrogen and preserved at –80 °C for subsequent analyses.

Measuring indexes

Single fruit weight. During storage, 15 fruits from each treatment group were selected, and individual fruit weight was measured every two days using an electronic balance with an accuracy of 0.01 g. The average fruit weight was subsequently calculated. Cumulative weight loss was calculated according to the following equation:

$$\textit{Cumulative weight loss (\%)} = [(\textit{first measured average} - \textit{measured average})/\textit{first measured average}] \times 100 \quad (1)$$

Edible rate. Five fruits were randomly collected from each treatment group for determination of edible rate. The total mass of each intact fruit was first recorded, after which the pulp was separation from the peel and the peel mass was measured. The edible rate was calculated using the following formula:

$$\textit{Editable rate (\%)} = [(\textit{whole fruit mass} - \textit{peel mass})/\textit{whole fruit mass}] \times 100 \quad (2)$$

Soluble solids. A PAL-1 handheld digital refractometer was used to determine soluble solids content. During the storage period, five fruits from each treatment were selected every two days for measurement, and the average soluble solids value (%) was calculated.

Soluble sugar and titratable acid. Soluble sugar content (g·kg^{-1}) was determined using the anthrone method (Wang et al. 2015). Briefly, 0.5 g fresh fruit pulp was extracted with 80% ethanol in a water bath maintained at 80 °C, after which the extract was reacted with anthrone reagent at 90 °C for 15 min. The absorbance of the final solution was measured at 620 nm. Glucose was used as the standard, and the results were expressed as mg glucose equivalent per gram fresh weight. Titratable acid content (g·kg^{-1}) was measured using the NaOH titration method (Wang et al. 2024). A 1 g sample was homogenised with distilled water. After centrifugation at 4 000 rpm for 10 min, the supernatant volume was adjusted to 25 mL. Following thorough mixing, a 5 mL aliquot was titrated using 0.1 mol·L^{-1} NaOH standard solution and the volume of NaOH consumed was recorded for subsequent calculation.

Determination of vitamin C, total flavonoids, total phenol content

The vitamin C [*Vc* ()] content [mg·(100 g)$^{-1}$] was determined using the 2,6-dichlorophenol indophenol (DCPIP) method (Borba et al. 2021). In brief, fresh

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fruit pulp was extracted using 1% oxalic acid solution, and the obtained supernatant was titrated with DCPIP solution until a persistent pink endpoint appeared. Vitamin C content was calculated according to the volume of DCPIP consumed and expressed as mg of ascorbic acid per 100 g fresh weight. Total flavonoid content ($mg \cdot kg^{-1}$) was determined using the ultraviolet absorption method, whereas the total phenol content ($mg \cdot kg^{-1}$) was analysed using the Folin–Ciocalteu method (Matić et al. 2017). Briefly, fruit pulp samples were extracted with 70% ethanol. For determination of total flavonoids, the extract was reacted sequentially with $NaNO_2$, $AlCl_3$, and NaOH, and absorbance was measured at 510 nm. The results were expressed as mg rutin equivalent (RE) per gram fresh weight. For total phenol analysis, the extract was mixed with Folin–Ciocalteu reagent and Na_2CO_3, incubated in darkness, and absorbance was measured at 765 nm. The results were expressed as mg gallic acid equivalent per gram fresh weight.

Data statistical analysis

All experiments were performed in sextuplicate, and the obtained results are expressed as mean ± standard deviation. Data processing was carried out using Microsoft Excel 2010, while graphical visualisation was prepared using GraphPad Prism (version 10.2.0, GraphPad Software, LLC, San Diego, USA). Statistical significance among treatments was analysed using the SPSS software (version 22.0, IBM SPSS, USA).

RESULTS AND DISCUSSION

Effects of calcium compound low-temperature treatment on cumulative weight loss and edible rate of postharvest passion fruit. The cumulative weight loss of fruits is mainly associated with metabolic activities such as respiration and transpiration. Previous studies have demonstrated that calcium chloride treatment can effectively reduce the cumulative weight loss rate in fruits (Chen et al. 2011; Turmanidze et al. 2016). In the present study, compared with the Control and Water + 20 °C groups, the treatments at 4 °C, Water + 4 °C, $CaCl_2$ + 20 °C, and $CaCl_2$ + 4 °C treatments significantly decreased the cumulative weight loss of passion fruit, among which the 4 °C treatment showed the strongest inhibitory effect ($P \leq 0.05$). This phenomenon may be related to the fact that passion fruit is classified as a berry, while $CaCl_2$ activates related enzymatic activities and metabolic regulation in plants, thereby alleviating chilling injury during low-temperature storage (Zhang et al. 2022). After 10 days of storage, the cumulative weight loss of the control treatment reached 13.00%. In contrast, the cumulative weight losses under 4 °C, Water + 4 °C, and $CaCl_2$ + 4 °C treatments were 6.25, 9.02, and 9.66%, respectively, corresponding to reductions of 51.94, 30.59, and 25.68% relative to the control (Figure 1A). These findings are generally consistent with previous reports on tomato and strawberry storage (Shahzad et al. 2020; Nuhu and Zarami 2023).

During the entire storage period, the edible rate of the Control (20 °C) treatment continuously declined, whereas the remaining treatments generally exhibited an initial decrease followed by a subsequent increase. Compared with the control, all treatments significantly improved the edible rate of the fruits after 8 and 10 days of storage ($P \leq 0.05$) (Figure 1B). This improvement may be associated with the berry characteristics of passion fruits, where the applied treatments effectively reduced juice water loss during the later storage stage, thereby maintaining a higher edible proportion of the pulp (Zhang et al. 2024).

A clear difference in cumulative weight loss was observed between the Control and Water + 20 °C treatments (13.00% vs. 15.63%), whereas the variation in edible rate was much greater (51.94% vs. 67.75%). These results indicate that cumulative weight loss alone cannot fully explain the variation in edible rate. In the control group, the lack of any preservation treatment caused severe pericarp shrinkage, pulp adhesion, and a relatively high decay incidence, directly resulting in a marked reduction in edible pulp proportion. By comparison, although the Water + 20 °C treatment exhibited slightly greater cumulative weight loss, it maintained improved fruit integrity and lower decay occurrence, thereby preserving a comparatively higher edible rate. Among all tested treatments, storage at 4 °C alone was the most effective in minimising cumulative weight loss, showing superior performance compared with water treatment alone, or $CaCl_2$ treatment alone. This result may be explained by the ability of low temperature to suppress respiration and transpiration rates, thereby reducing metabolic activity and lowering the water vapour pressure gradient, which directly limits moisture loss from the fruit surface (Gidado et al. 2024). In contrast, the Water + 20 °C treatment failed to reduce cumulative weight loss, probably because of increased surface moisture evaporation under ambient conditions. $CaCl_2$ treatment alone ($CaCl_2$ + 20 °C) mainly improves cell wall integrity and membrane stability (Eroğul et al. 2024) rather

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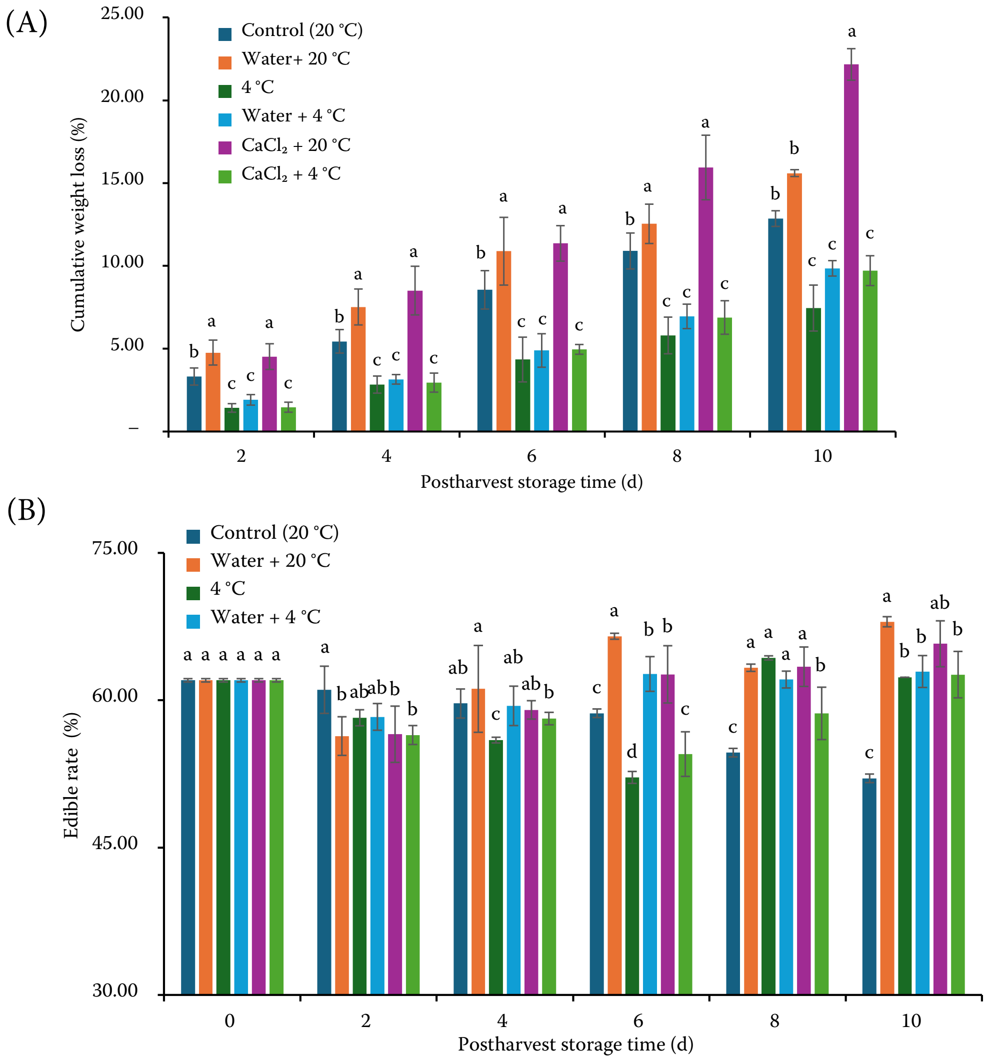

Figure 1. Effects of calcium compound low-temperature treatment on cumulative weight loss and edible rate of postharvest passion fruit

[a–c]different letters within the same day indicate significant differences among treatments ($P < 0.05$); error bars indicate standard error

than directly suppressing transpiration or respiration. Under ambient temperature conditions, its protective effects were insufficient to offset the rapid water loss caused by active transpiration. This response may also be related to the hygroscopic characteristics of $CaCl_2$ and the temporary water film formed on the fruit surface after treatment, which could alter water exchange dynamics. Nevertheless, the combined treatment exhibited better performance in other quality parameters, including edible rate and nutritional composition (El-Bana and Ennab 2023), suggesting that the synergistic interaction between calcium and low temperature play a more important role in preserving overall fruit quality rather than merely reducing cumulative weight loss.

Effect of calcium compound low-temperature treatment on sugar-acid metabolism of postharvest passion fruit. During storage, soluble solids content (SSC) showed an initial increase followed by a gradual decrease, whereas cumulative weight loss consistently increased throughout the storage period. This trend reflects the dynamic balance between moisture loss and respiratory substrate consumption. During the early storage stage, transpiration-induced water loss caused a concentration effect, resulting in increased SSC. At the later stage, intensified respiration consumed soluble sugars and organic acids, eventually exceeding the concentration effect and leading to a decline in SSC. Cumulative weight loss, caused by both moisture evaporation and respiratory CO_2 release, continu-

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ously accumulated during storage (Wang et al. 2025). Low-temperature treatments significantly increased the soluble solids content of passion fruit. The soluble solids content of the Water + 4 °C treatment reached its peak at day 2, whereas $CaCl_2$ + 4 °C showed the highest value at day 6. The remaining treatments also reached maximum value at day 6. After 8 and 10 days of storage, the 4 °C, Water + 4 °C, $CaCl_2$ + 20 °C, and $CaCl_2$ + 4 °C treatments significantly increased soluble solids content compared with the control ($P \leq 0.05$) (Figure 2A). Previous studies on strawberries reported that low-temperature storage combined with a 2% $CaCl_2$ treatment significantly increases soluble solids content (El-Sayed et al. 2023), which is in agreement with the present results. Similarly, Xu et al. (2023) observed that $CaCl_2$ treatment alone enhanced soluble solid retention in passion fruit, although low-temperature storage was not included in their study. In contrast, the combined $CaCl_2$ + 4 °C treatment in the present study not only delayed the SSC peak but also maintained relatively higher SSC levels during the later storage stage, indicating a synergistic effect between calcium treatment and low temperature. This increase may be associated with the role of $CaCl_2$ in preserving total sugar during fruit senescence, thereby maintaining a higher soluble solids content (Sharma et al. 2006).

El-Sayed et al. (2023) reported that fruits treated with 2% calcium chloride exhibited significantly higher soluble sugar content than untreated controls. In the current study, soluble sugar content in passion fruit generally showed a trend of initial increase followed by decline across most treatments, although the timing of peak values varied among treatments (Figure 2B). In the Control treatment, soluble sugar content increased rapidly during the early stage, declined sharply during mid storage, and increased again afterwards. The Water + 20 °C treatment showed a gradual upward trend eventually reached the highest soluble sugar level among all treatments at the end of storage. Both the 4 °C and $CaCl_2$ + 20 °C peaked during the middle storage stage and then gradually declined. The Water + 4 °C treatment exhibited an early peak, followed by a sharp decrease and a later secondary increase. Meanwhile, the $CaCl_2$ + 4 °C treatment reached its highest soluble sugar content at mid storage, and subsequently decreased substantially. Significant differences among treatments were observed at several storage periods ($P \leq 0.05$). During mid storage, $CaCl_2$ + 4 °C and $CaCl_2$ + 20 °C treatments showed the highest soluble sugar contents, both significantly exceeding those of the other treatments. At the end of storage, the Water + 20 °C treatment exhibited the highest soluble sugar content, significantly higher than all other groups. Notably, although $CaCl_2$ + 4 °C treatment maintained the highest soluble sugar content during mid storage, the sugar level declined rapidly during the later storage stage, indicating that the combined effect of calcium and low temperature promotes medium-term sugar accumulation but may not sustain this advantage during prolonged storage. This enhancement was mainly attributed to low temperature, which reduced the respiration rate, and to the ability of $CaCl_2$ to interact with pectin and form calcium pectate thereby limiting total sugar consumption and extending the storage period (Eroğul et al. 2024). During passion fruit storage, the titratable acid content generally showed an initial decline followed by an increase, except in the Water + 4 °C treatment. At day 4 of storage, Water + 20 °C, 4 °C, $CaCl_2$ + 20 °C, and $CaCl_2$ + 4 °C exhibited the lowest organic acid contents, with the greatest reduction observed in $CaCl_2$ + 4 °C. In the later storage stage, the organic acid content increased substantially. After day 10 of storage, the titratable acid content in Water + 4 °C was 15.78% lower than that in the Control (Figure 2C), which was consistent with previous observations reported for strawberries (Lu et al. 2024).

The sugar-acid ratio of passion fruit initially increased and subsequently decreased during storage, which is commonly observed in postharvest fruits and is closely related to the balance between sugar accumulation and organic acid consumption (Han et al. 2024). At day 4 of storage, the sugar-acid ratio of $CaCl_2$ + 4 °C reached its maximum value and was significantly higher than those of the Control and Water + 20 °C treatments. This effect may be associated with the combined influence of calcium treatment and low temperature. $CaCl_2$ likely promoted sugar retention through stabilisation of cell membranes and reduction of respiratory substrate consumption, while low temperature further suppressed respiration activity (El-Sayed et al. 2023; Eroğul et al. 2024). At day 6 of storage, the Control, Water + 4 °C, 4 °C, and $CaCl_2$ + 20 °C treatments reached their respective peak values, among which 4 °C showed the highest sugar-acid, significantly exceeding those of the Control and Water + 20 °C treatments. This findings suggested that low temperature alone was highly effective in maintaining a relatively high sugar-acid ratio during the middle stage of storage, likely because of its strong inhibitory effect on respiration and organic acid degradation (Lu et al. 2024).

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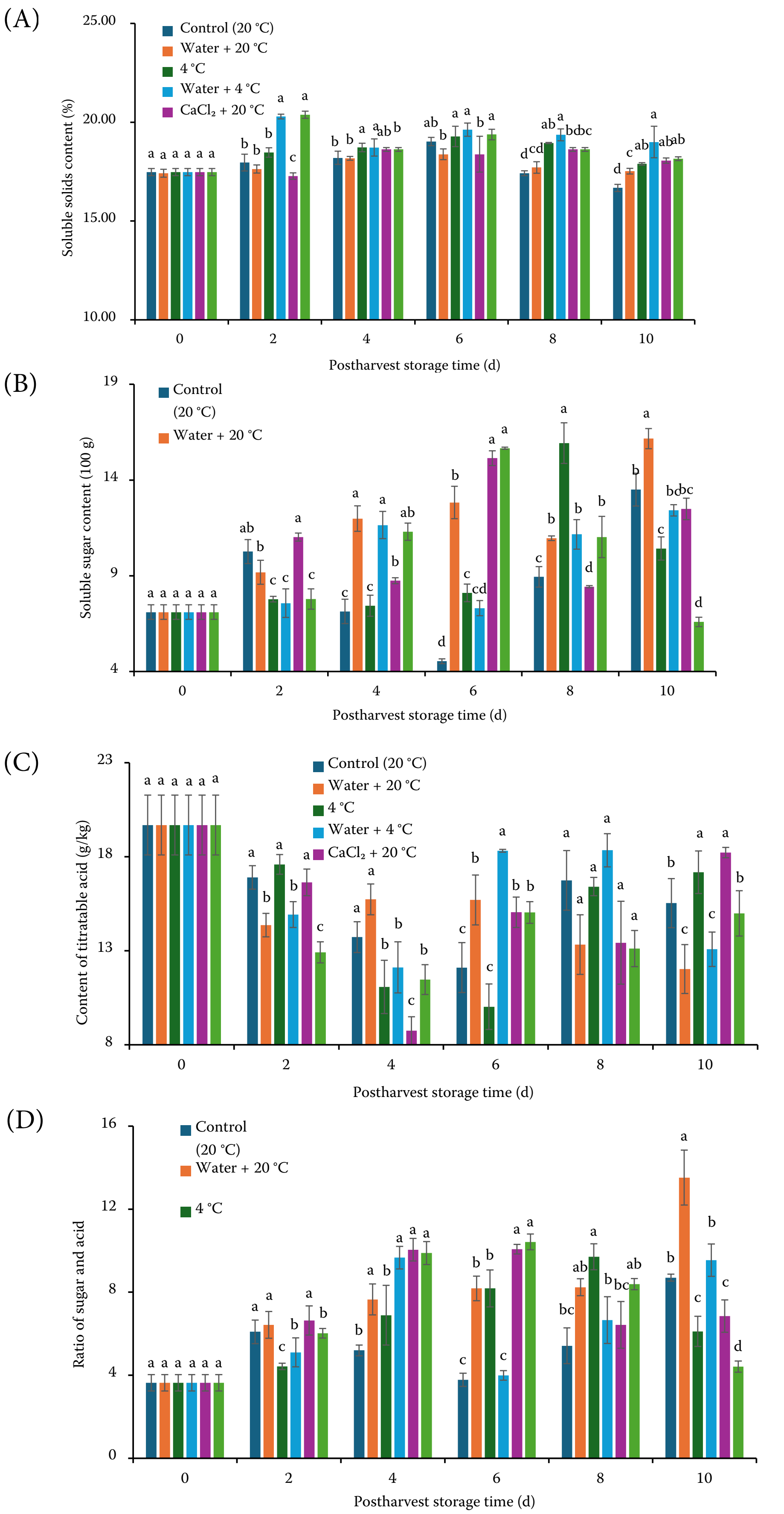

Figure 2. Effect of calcium compound low-temperature treatment on sugar-acid metabolism of postharvest passion fruit

[a–d]different letters within the same day indicate significant differences among treatments ($P < 0.05$); error bars indicate standard error

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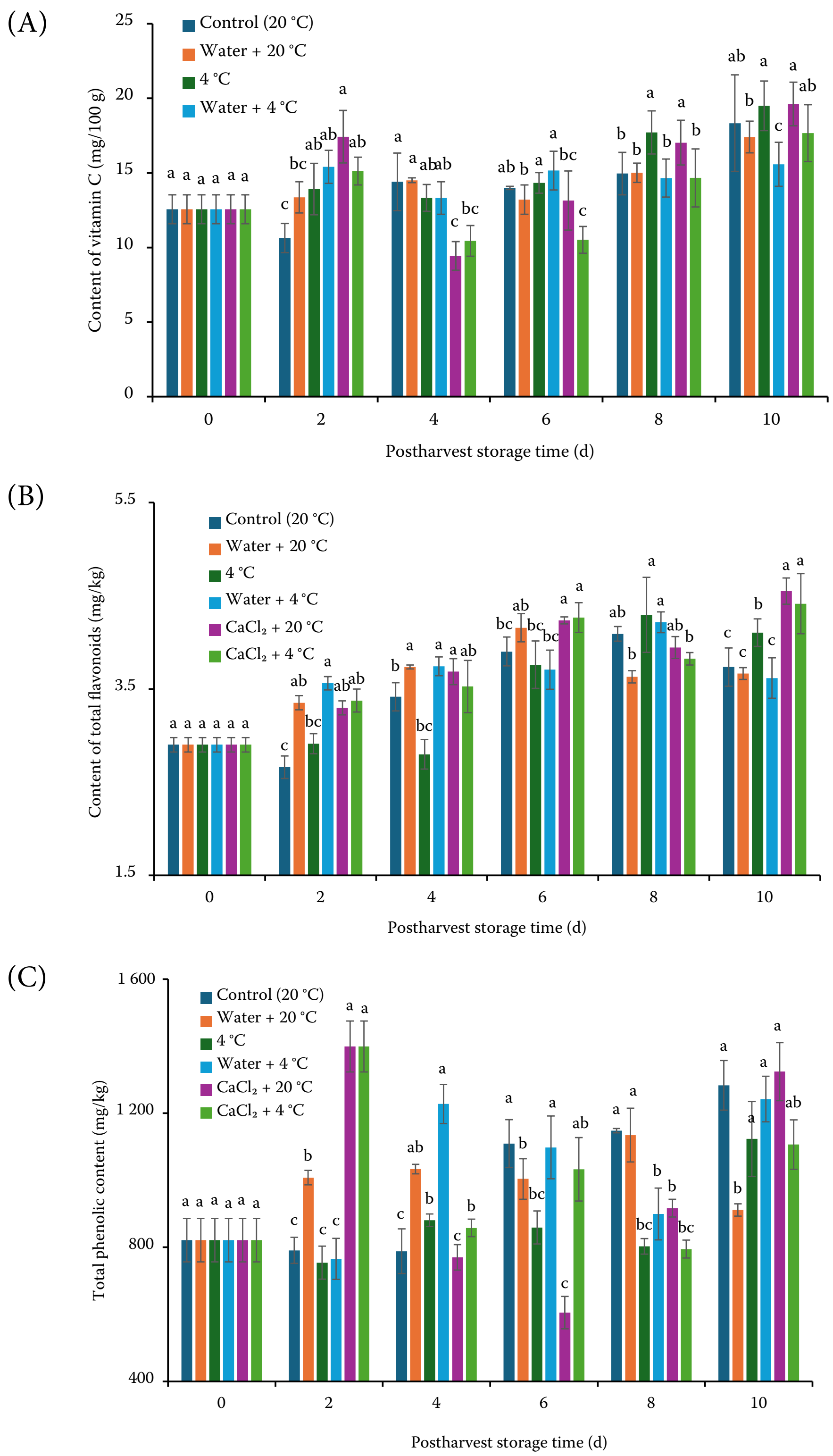

Figure 3. Effect of calcium compound low temperature-treatment on antioxidant activity of postharvest passion fruit

[a–c]different letters within the same day indicate significant differences among treatments ($P < 0.05$); error bars indicate standard error

Effect of calcium compound low-temperature treatment on antioxidant activity of postharvest passion fruit. Previous studies on strawberries and peaches demonstrated that treatment with 2% $CaCl_2$ solution significantly increased Vc content (Turmanidze et al. 2016). In the present study, the Vc content of passion fruit showed a general increasing trend during postharvest storage, and reached the highest level at 10 days after harvest. At 6 days postharvest, all treatments except Water + 20 °C promoted Vc accumulation compared to the initial value. By day 10 of storage, significant differences were detected among

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treatments, with the $CaCl_2$ + 20 °C and 4 °C treatments exhibiting the highest Vc contents ($P \leq 0.05$) (Figure 3A). The variation in treatment responses may be associated with the unique physiological characteristics of passion fruit as a berry fruit. Compared with strawberries and peaches, which possess relatively stronger pericarp structures, passion fruit has a thin leathery peel and a high pulp moisture content, making it more vulnerable to rapid metabolic fluctuations and postharvest senescence (Chen et al. 2011). The marked increase in Vc content under $CaCl_2$ + 20 °C and 4 °C treatments at the later storage stage may also be explained by the combined role of calcium in preserving cell membrane integrity and low temperature in alleviating oxidative stress, thereby delaying Vc degradation (Eroğul et al. 2024). In addition, the relatively high Vc levels observed in these treatments were consistent with the higher total phenolic contents (Figure 3C), implying a synergistic contribution to antioxidant capacity during the late storage period.

The total flavonoid content of passion fruit first increased and then gradually decreased during the postharvest storage. The flavonoid peaks in Water + 20 °C, $CaCl_2$ + 4 °C, and $CaCl_2$ + 20 °C treatments appeared two days earlier than those in the remaining treatments. This earlier response suggests that calcium treatment and low temperature may accelerate the activation of phenylpropanoid metabolism. After 10 days of storage, $CaCl_2$ + 4 °C and $CaCl_2$ + 20 °C treatments significantly suppressed flavonoid degradation, and maintained higher flavonoid contents than the other treatments ($P \leq 0.05$) (Figure 3B). This sustained preservation effect indicates that calcium may play a more critical role in delaying flavonoid degradation during extended storage, possibly through stabilisation flavonoid-related enzyme activities or reduction of oxidative turnover (Zhang et al. 2024). The ability of $CaCl_2$ or CaM genes to induce the activities of enzymes involved in phenylpropanoid metabolism further supports the regulatory role of calcium in promoting flavonoid accumulation (Xu et al. 2023).

The total phenolic content generally exhibited an upward trend during postharvest storage. However, the trends following $CaCl_2$ + 4 °C and $CaCl_2$ + 20 °C treatments showed a fluctuating pattern characterised by an initial increase, followed by a decrease and then another increase. This dynamic change may reflect a biphasic stress response. The early increase was probably associated with activation of phenylalanine ammonia lyase (PAL) activity induced by low-temperature stress and calcium signalling, whereas the decline during mid storage may have resulted from oxidative consumption of phenolic compounds. The subsequent increase at the later stage could be associated with secondary metabolic adjustments during fruit senescence, potentially associated with lignin accumulation or the synthesis of other stressrelated phenolic substances (Ma et al. 2023). At day 2 of storage, the total phenolic content in the $CaCl_2$ + 20 °C treatment was significantly higher than that of the control ($P \leq 0.05$) (Figure 3C). This increase may be associated with low-temperature stress responses in the fruit together with the role of calcium ions in stimulating active oxygen metabolism, thereby promoting the accumulation of total phenolics (Ma et al. 2023). Notably, although the combined $CaCl_2$ + 4 °C treatment did not exhibit the highest total phenolic content at any single storage point, it showed a distinctive biphasic variation and maintained comparatively high phenolic levels throughout storage. This observation suggests that the synergistic effect between calcium and low temperature is more evident in sustaining phenolic metabolism rather than simply increasing peak phenolic accumulation.

CONCLUSION

The results of this study demonstrate that the combined application of calcium chloride and low-temperature storage (4 °C) represents as an effective postharvest preservation strategy for maintaining the quality of passion fruit (*Passiflora edulis* cv. 'Qinguo No. 9'). Compared with the control, low-temperature treatments (4 °C, Water + 4 °C, and $CaCl_2$ + 4 °C) significantly reduced cumulative weight loss and maintained relatively higher edible rates, with 4 °C treatment alone showing the strongest effect in minimising weight loss. Regarding nutritional quality, $CaCl_2$ + 4 °C treatment achieved the highest soluble sugar content during mid storage (day 6). In addition, both $CaCl_2$ + 4 °C and $CaCl_2$ + 20 °C treatments significantly inhibited flavonoid degradation and maintained high total phenolic levels during late storage (day 10), indicating a synergistic interaction between calcium application and low temperature in regulating secondary metabolism. The combined treatment did not merely maximise individual quality indicators but effectively balanced water retention, sugar accumulation, and maintenance of antioxidant compounds throughout the storage period. These findings suggest that the $CaCl_2$ + 4 °C treatment has considerable potential for commercial application in extending the shelf life of passion fruit, reducing postharvest losses, and preserving market quality.

https://doi.org/10.17221/163/2025-CJFS

Acknowledgement. All authors are grateful for the help of other colleagues during the course of the study.

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Received: September 23, 20025
Accepted: May 27, 2026
Published online: July 16, 2026