Applied Food Research 6 (2026) 101775

Contents lists available at ScienceDirect

Applied Food Research

journal homepage: www.elsevier.com/locate/afres

Postharvest quality of purple passion fruit in packaging alone or combined with fungicide and wax during ripening under ambient conditions

Fariborz Habibi, Uzman Khalil, Steven A. Sargent, Ali Sarkhosh *

Department of Horticultural Sciences, University of Florida, Gainesville, FL 32611, USA

ARTICLE INFO

Keywords:
Antioxidant activity
Color
Firmness
Packaging
Phenolic content
Total soluble solids

ABSTRACT

Purple passion fruit (*Passiflora edulis* f. edulis) is highly perishable and often stored at ambient temperature, which accelerates quality loss. This study aimed to evaluate the effects of different postharvest treatments on the physicochemical and biochemical quality of 'Possum Purple' passion fruit during 21 days of storage at simulated ambient conditions (20 °C). Treatments included open container (OC), carnauba wax coating (W), perforated plastic packaging (P), carnauba wax + packaging (WP), fungicide dipping (F), fungicide + wax (FW), fungicide + packaging (FP), and a combination of fungicide, wax, and packaging (FWP). After 21 days, results showed that non-packaged or unwaxed fruit (OC and F treatments) experienced the highest weight loss and shriveling, along with a rapid decline in firmness. In contrast, packaging-based treatments, especially FWP, effectively maintained fruit weight, reduced shriveling, and preserved firmness. Non-packaged treatments (OC, W, F) showed higher total soluble solids (TSS), titratable acidity (TA), total phenolic content (TPC), and total antioxidant activity (TAA), but showed greater physical quality deterioration. The TSS/TA ratio and pH increased over time, with F, FW, and FP treatments showing the highest final ratios. Color parameters of both peel and juice were better preserved in packaging-based treatments. Overall, based on multivariate statistical analyses, the application of packaging alone or in combination with fungicide and wax proved most effective in preserving the fruit quality of passion fruit during storage by reducing physiological deterioration and maintaining key nutritional attributes.

1. Introduction

Passion fruit (*Passiflora* spp.) belongs to the Passifloraceae family and grows in warm tropical and subtropical regions. Passion fruit is classified by the pericarp color as purple (*P. edulis* f. edulis) or yellow (*P. edulis* f. flavicarpa) types (Schotsmans & Fischer, 2011). Pulp of the purple type is typically eaten fresh because it tastes sweeter, while that of the yellow type is more sour and is mostly used for juice processing due to its higher juice content (Dos Reis et al., 2018).

Passion fruit pulp is appreciated among consumers for its unique aroma, flavor, taste, and rich source of bioactive compounds and high antioxidant capacity. It contains vitamins A and C, thiamin, riboflavin, and niacin and minerals including potassium, zinc, iron, and magnesium. The fruit is also an excellent source of dietary fiber, carotenoids (β-carotene), flavonoids, and polyphenols (Fonseca et al., 2022). Furthermore, it contains phytochemicals including triterpenoids, glycosides (passiflorine and cyanogenic glycosides), flavonoid glycosides (luteolin-6-C-chinovoside), saponins, and alkaloids. Other important bioactive compounds reported in passion fruit include ascorbic acid, resveratrol, piceatannol, choline, γ-lactones, esters, essential volatile oils such as eugenol, and various amino acids (Naranjo-Durán et al., 2023). These compounds contribute not only to human health by preventing oxidative stress and inflammation, but also to the fruit's sensory qualities and overall appeal (Weyya et al., 2024).

Passion fruit is highly perishable and susceptible to postharvest physiological deterioration, which significantly limits its distribution, marketability, and shelf life, especially in ambient storage conditions. One of the major postharvest challenges of passion fruit is its rapid water loss, shriveling, and firmness loss during ripening (Nxumalo & Fawole, 2022). These changes, along with declines in titratable acidity, firmness, color, bioactive compound, and antioxidant activity, are the major causes of quality loss and economic losses for growers, exporters, and retailers (de Oliveira Militão et al., 2025). To address these challenges, there is an increasing interest in developing and applying postharvest strategies that can extend shelf life while maintaining passion fruit quality and nutritional value (Yang et al., 2024).

Several postharvest treatments have been studied to reduce quality loss of horticultural crops during handling and storage. Cooling is the

---

* Corresponding author.
E-mail address: sarkhosha@ufl.edu (A. Sarkhosh).

https://doi.org/10.1016/j.afres.2026.101775
Received 1 November 2025; Received in revised form 27 December 2025; Accepted 9 February 2026

most effective means for commercially extending postharvest quality of these crops. Supplemental treatments, including edible coatings, packaging systems, and chemical treatments can also be used for maintaining fruit quality after harvest (Palumbo et al., 2022). Edible coatings including carnauba wax serve as semi-permeable barriers that reduce water loss, delay ripening, suppress respiration, and enhance the visual appeal of fruit (Devi et al., 2022). Carnauba wax, derived from Brazilian palm leaves, is a popular fruit coating that reduces moisture loss, slows ripening by lowering respiration, and enhances the visual appeal of fruit by adding a glossy sheen to the surface (Devi et al., 2022). Perforated plastic films limit moisture loss while modified atmosphere packaging (MAP) modifies the atmosphere around the fruit, both minimizing development of anaerobic conditions; perforated films do not establish a true MAP due to their high gas transmissivity (Palumbo et al., 2022). Chemical treatments are widely used to prevent postharvest diseases, especially in fruits that are prone to fungal infections. However, the efficacy of these combined treatments varies depending on the fruit type, cultivar, and storage conditions (Zhang et al., 2025).

Understanding the effects of postharvest treatments on quality attributes, physical and biochemical properties is essential for developing practical strategies that can maintain fruit quality during storage and transport (Zhang et al., 2025). Synergistic effects can be ensured by integrated physical and chemical postharvest treatment techniques to reduce postharvest loss (You et al., 2022). This information is valuable not only for commercial growers and exporters but also for understanding consumer references and developing postharvest standards for passion fruit (Yang et al., 2024). Due to the perishable nature of passion fruit, it is crucial to develop cost-effective and efficient postharvest treatment strategies (Nxumalo & Fawole, 2022).

Passion fruit responds well to cooling after harvest, and purple cultivars can be stored for up to five weeks when held at 3–5 °C (Paull & Chen, 2016). During commercial handling, passion fruit are often stored at ambient temperature to promote ripening. However, this can accelerate moisture loss, leading to excessive shriveling and darkening of the pericarp. There is limited information on the comparative performance of individual and combined postharvest treatments under such simulated ambient conditions, especially in situations where refrigeration is unavailable or not economically feasible. Although refrigerated storage is commonly used for long-distance export markets, passion fruit intended for local distribution or short-term marketing is often held at ambient temperature, particularly in regions lacking adequate cold chain infrastructure. Therefore, this study aimed to evaluate the effects of different postharvest treatments (applied individually or in combination) on the physical and biochemical quality of ‘Possum Purple’ passion fruit under simulated ambient storage conditions at 20 °C to reflect typical handling practices and storage in local and domestic supply chains.

2. Materials and methods

2.1. Treatments and storage conditions

In this study, fruit of purple passion fruit, cv. Possum Purple, were harvested from 1-year-old vines at the commercial maturity stage, corresponding to the color break stage, where the fruit peel exhibits the initial transition from green to purple, with approximately 10–20 % of the peel surface displaying purple coloration at the University of Florida’s Institute of Food and Agricultural Sciences, Plant Science Research and Education Unit (UF/IFAS PSREU), Citra, Florida, USA. Immediately after harvest, the fruit were transported approximately 32 km in an air-conditioned vehicle within 20 min of harvest to the Postharvest Physiology Laboratory at the University of Florida, Gainesville, for treatment and analysis. Then, fruit were carefully inspected and only uniform, damage-free fruit without visible defects or mechanical injuries were selected, washed with tap water and allowed to air-dry to remove any excess water on fruit peel. Eight postharvest treatments were applied to evaluate their effects on fruit quality during storage including: 1) control (open container, OC), 2) carnauba wax (Agri Gloss Carnauba - 100 % Carnauba, HDH Agri Products, Tavares, FL, USA) coating in the open container (W), 3) packaging in a perforated plastic clamshell with twelve ventilation holes (P), 4) carnauba wax coating combined with packaging (WP), 5) fungicide dipping in the open container (F), 6) fungicide treatment combined with carnauba wax coating in the open container (FW), 7) fungicide treatment in perforated packaging (FP), and 8) a combined treatment of fungicide, carnauba wax coating, and packaging (FWP). For fungicide treatments, fruit were dipped in Scholar® SC (fludioxonil-based, Syngenta Crop Protection, Greensboro, NC, USA) fungicide solution (0.37 g L^{-1}) for 30 s. Similarly, for wax coating, fruit were dipped for 30 s in a ready-to-use commercial carnauba wax (food-grade) solution. Packaged fruit were placed in clamshell containers (16 × 16 × 8 cm) with twelve perforations (0.5 cm in diameter) to allow for ventilation. All treated fruit were stored at 20 °C with 50–60 % relative humidity (RH) in walk-in environmental rooms (Conviron, Pembina, ND, USA) equipped with a dry fog humidification system (Smart Fog, Inc., Reno, NV, USA), for 21 days to simulate ambient (room) storage conditions. The experiment was conducted twice using fruit from two independent harvests (July 18 and July 24, 2024), with treatments applied one day after each harvest. Each treatment consisted of four replicate clamshells, with four fruit per replicate. Postharvest quality evaluations were conducted at harvest (day 0) and after 7, 14, and 21 days of storage.

2.2. Weight loss

Fruit weight loss (WL) was determined by recording the initial weight (IW) of each replicate before storage and the final weight (FW) after storage using a digital balance with 0.01 g precision. The WL was calculated as a percentage using the formula: WL (%) = [(IW - FW) / IW] × 100 (Razzaq et al., 2014).

2.3. Shrivel severity rating

Shriveling severity was hedonically rated using a visual scoring 5-scales ranging from 0 to 4, where 0 = no visible shriveling, 1 = minimal, 2 = moderate, 3 = extensive, and 4 = severe shriveling.

2.4. Firmness

Fruit firmness was measured at the equator of intact fruit using a texture analyzer (Texture Analyzer, Texture Technologies Corp., Surrey, UK) equipped with a 5-kg load cell and a 45-mm diameter flat plate. Each fruit was compressed to a depth of 3 mm, and the maximum force was recorded in Newtons (N) (Plaza et al., 2004).

2.5. Color parameters

Peel and juice color were measured for each replicate using a colorimeter (Minolta CR-300, Tokyo, Japan). Peel color was assessed externally at the equator on opposite sides of the intact fruit. For juice color, 3 mL of extracted juice was placed in a plastic cap with a 10 mm diameter opening. Color values were recorded using the CIE$L^*a^*b^*$ system, and the L^*, a^*, and b^* readings were later converted to hue angle ($h°$) and chroma (C^*) for clearer interpretation (McGuire, 1992).

2.6. Juice attributes

Total soluble solids (TSS), total titratable acidity (TA), the TSS/TA ratio (flavor index), and juice pH were evaluated using juice extracted from the fruit in each treatment. Fruit were cut in half, and the whole pulp (arils and juice sacs with seeds) was collected in a zip-lock plastic bag. The pulp was gently hand-pressed to release the juice, which was then filtered through a double layer of cheesecloth to separate the juice without seeds. TSS was determined using a handheld digital refractometer (Reichert AR200, Depew, NY, USA) with automatic temperature compensation. TA and pH were measured using an automatic titrator (Metrohm 814 USB Sample Processor, Herisau, Switzerland). TA was expressed in percent, citric acid basis. The flavor index was calculated as the TSS/TA ratio (Shahkoomahally et al., 2021).

2.7. *Total carotenoid content (TCC)*

The TCC was evaluated according to the method described by Talcott and Howard (1999). In this case, 2 mL of fruit juice was mixed with 20 mL of an extraction solution consisting of ethanol and hexane (1:1, v/v). The mixture was vortexed thoroughly and then centrifuged at 20,000 × *gn* for 20 min at 4 °C. After centrifugation, the samples were stored at −20 °C for 24 h. The hexane phase was then carefully separated using a transfer pipette. This extraction step was repeated with fresh extraction solution, followed by a wash with deionized (D.I.) water to remove any remaining residues. After completely removing the hexane phase, 20 mL of D.I. water was added to the tubes, vortexed, and the tubes were again stored at −20 °C for 2 h. The hexane phase was then transferred to a clean tube and adjusted to a consistent volume using the extraction solution. Subsequently, 250 μL of each extract, along with a blank (extraction solution only), was loaded in triplicate onto a microplate, and absorbance was measured at 470 nm using a microplate reader (SYNERGY HTX, Biotek, USA). TCC was calculated and expressed as β-carotene (mg 100 g^{-1}).

2.8. *Total phenolic content (TPC)*

The TPC was determined using the Folin-Ciocalteu colorimetric method (Singleton & Rossi, 1965). Briefly, 500 μL of diluted juice was mixed with 2.5 mL Folin-Ciocalteu reagent under yellow light. After an 8-minute incubation, 2.0 mL sodium carbonate was added. The mixture was then heated at 45 °C for 15 min, cooled to room temperature, and the absorbance was measured at 765 nm. Gallic acid (GA) was used to generate the standard curve, and results were expressed as mg L^{-1} of gallic acid equivalents (GAE).

2.9. *Total antioxidant activity (TAA)*

The TAA was evaluated using the ferric reducing antioxidant power (FRAP) assay, following the method of Benzie and Strain (1996). The FRAP reagent was prepared by mixing acetate buffer (pH 3.6), TPTZ solution in HCl, and $FeCl_3$ solution in a 10:1:1 ratio. Under yellow light, 50 μL of the sample and Trolox standards were each combined with 180 μL of FRAP reagent. Absorbance was then measured at 595 nm. TAA was calculated using a standard curve based on varying concentrations of Trolox equivalents (TE) and expressed as μmol TE L^{-1}.

2.10. *Statistical analyses*

Both tests were designed using a completely randomized design (CRD) with two factors (treatments and storage times), each with four replicates. Measurements for each replicate were repeated three times to ensure accuracy. Statistical analysis was conducted to compare the two experiments, and no significant differences were found between them ($P < 0.05$). Therefore, data from the two experiments were pooled and analyzed using SAS software (version 9.4). The least significant difference (LSD) test ($P < 0.05$) and standard errors (SE) of the means were used for mean comparisons. Principal component analysis (PCA) and hierarchical cluster analysis (HCA) were conducted using Minitab version 21 (Minitab, LLC, State College, PA, USA). Pearson’s correlation coefficients were calculated and visualized using the corrplot package in R.

3. Results

3.1. *Weight loss, shriveling, and firmness*

Weight loss (WL) varied significantly among treatments, with the highest losses observed in non-packaged treatments. The OC and F treatments showed the highest WL with 28.5 % and 27.8%, respectively. Application of wax alone (W) moderately reduced weight loss, though still significantly higher than packaged treatments. Packaging-based treatments including either alone (P), combined with wax (WP), fungicide (FP), or both (FWP) consistently maintained the lowest WL values, all below 11 %, with no significant differences among them (Fig. 1).

Fruit shriveling increased significantly with storage time, particularly under non-packaged treatments, similar to the trend observed for WL. The OC and F treatments exhibited the highest shriveling scores from day 7 onward, reaching the maximum level by day 21. In contrast, packaging treatments (P, WP, FP, and FWP) effectively reduced shriveling, with the lowest scores observed in FWP during storage (Fig. 2).

Fruit firmness decreased progressively across all treatments, with significant differences occurring by day 7 in OC and F treatments. The highest firmness levels throughout storage were consistently maintained by the P and WP treatments, followed closely by FP and FWP. Fruit stored in OC, W, F, and FW treatments, showed a rapid decline in firmness; the lowest values were observed at the final sampling date, with no significant differences among them (Fig. 2).

3.2. *Juice compositional attributes*

TSS declined gradually in all treatments from an initial value of 16.1 % to a range of 13.1–15.0 % by day 21 (Fig. 3). Fruit stored in the OC treatment had the higher TSS levels (15.0 %) compared with other treatments, particularly the P (13.4 %), WP (13.1 %), FP (13.2 %), and FWP (13.3 %) treatments, which exhibited the lowest TSS values with no significant differences among them (Fig. 3).

TA decreased gradually in all treatments from an initial value of 1.79

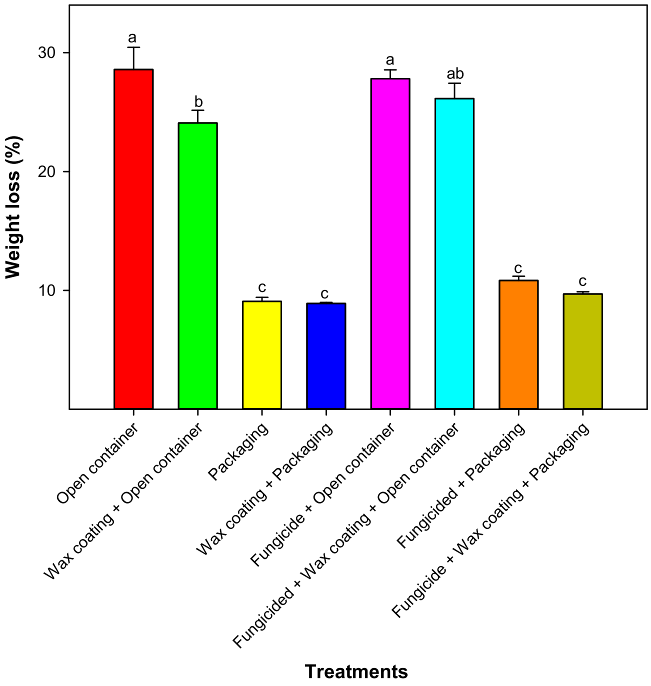

Fig. 1. Effect of different postharvest treatments on weight loss of ‘Possum Purple’ passion fruit. Different letters above bars indicate significant differences among treatments and storage durations according to LSD test ($p < 0.05$). Data are presented as mean ± SE ($n = 4$).

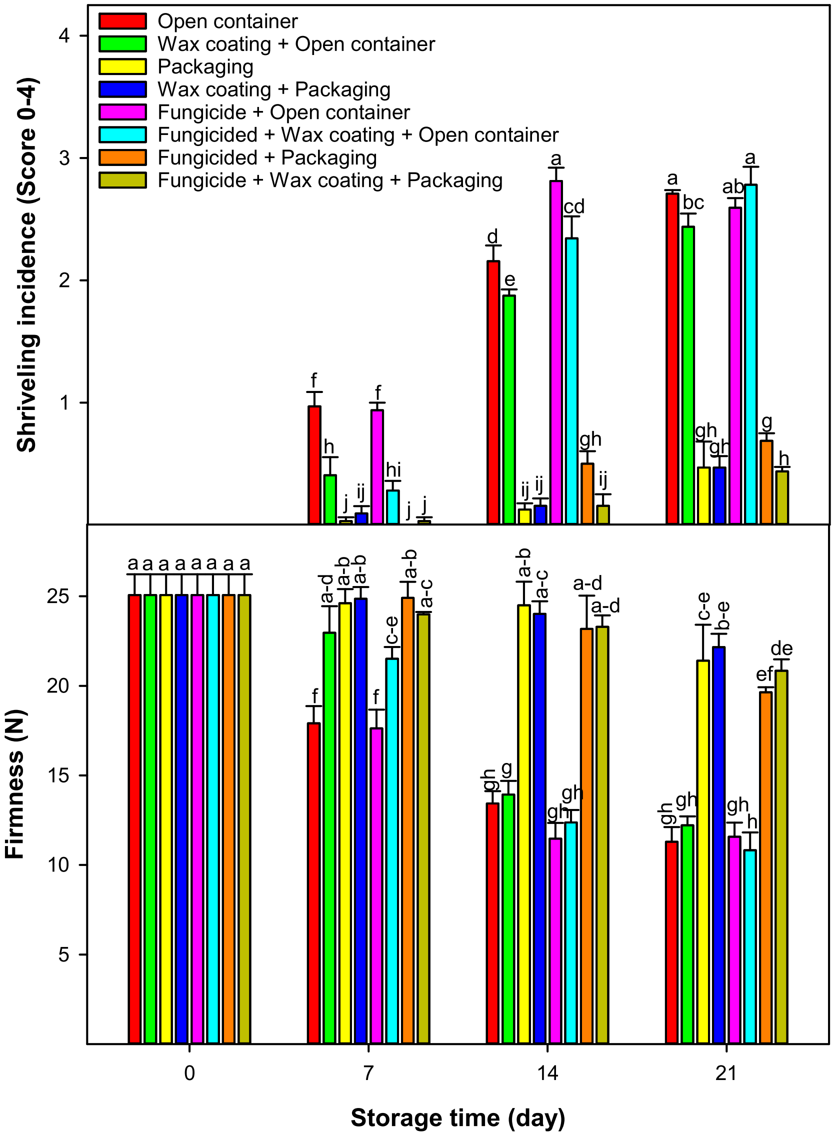

Fig. 2. Effect of different postharvest treatments on shriveling incidence and firmness of 'Possum Purple' passion fruit. Different letters above bars indicate significant differences among treatments and storage durations according to LSD test ($p < 0.05$). Data are presented as mean ± SE ($n = 4$).

% to approximately 1.01–1.15 % by day 21 (Fig. 3). Significant differences among treatments occurred after day 7, with the OC (1.81 %) and W (1.71 %) treatments maintaining higher TA levels compared to others, including FP (1.42 %) and FWP (1.46 %). By day 21, no significant differences were observed among treatments (Fig. 3).

The TSS/TA ratio increased significantly across all treatments. The OC treatment showed the lowest TSS/TA ratio on days 7 (8.77) and 14 (10.6). However, at the final sampling date, the ratio had increased sharply, reaching the highest values in the F (13.15), FW (13.58), and FP (13.1) treatments, with no significant differences among them. At the final sampling date, the WP and FWP treatments exhibited the lowest TSS/TA ratios, 12.1 and 12.11, respectively, also without significant differences among them (Fig. 3).

Juice pH increased significantly across all treatments from 3.57 to 3.91–4.00 by day 21, indicating a reduction in acidity over time (Fig. 3). By day 21, the FWP treatment maintained a significantly lower pH (3.91) compared to the OC (3.97), FW (4.00), WP (3.97), and F (4.00) treatments, which exhibited higher pH values with no significant differences among them (Fig. 3).

3.3. *Total carotenoid content (TCC)*

TCC increased progressively across all treatments from 3.54 mg 100 g^{-1} to 7.13–7.82 mg 100 g^{-1} by day 21 (Fig. 4). By day 7, the highest TCC values were observed in the OC (6.71 mg 100 g^{-1}) and WP (6.36 mg 100 g^{-1}) treatments, while the P (5.22 mg 100 g^{-1}) and FW (5.16 mg 100 g^{-1}) treatments showed lower levels. At the final sampling date, no significant differences in TCC were found among the treatments, with values ranging from 7.13 mg 100 g^{-1} (FP) to 7.82 mg 100 g^{-1} (W) (Fig. 4).

3.4. *Total phenolic content (TPC)*

TPC increased markedly across all treatments from 19.38 mg L^{-1} GAE on day 0 to 21.66–24.71 mg L^{-1} GAE by day 7 (Fig. 4). On day 7, the highest TPC levels were observed in the OC (24.68 mg L^{-1} GAE), W (24.71 mg L^{-1} GAE), and WP (24.65 mg L^{-1} GAE) treatments, while the FP (22.26 mg L^{-1} GAE) and FWP (21.66 mg L^{-1} GAE) treatments showed the lowest levels. At the final sampling date, the FWP treatment exhibited the lowest TPC (22.13 mg L^{-1} GAE). While the OC (26.25 mg L^{-1} GAE) and W (26.12 mg L^{-1} GAE) treatments had the highest TPC levels, with no significant differences between them (Fig. 4).

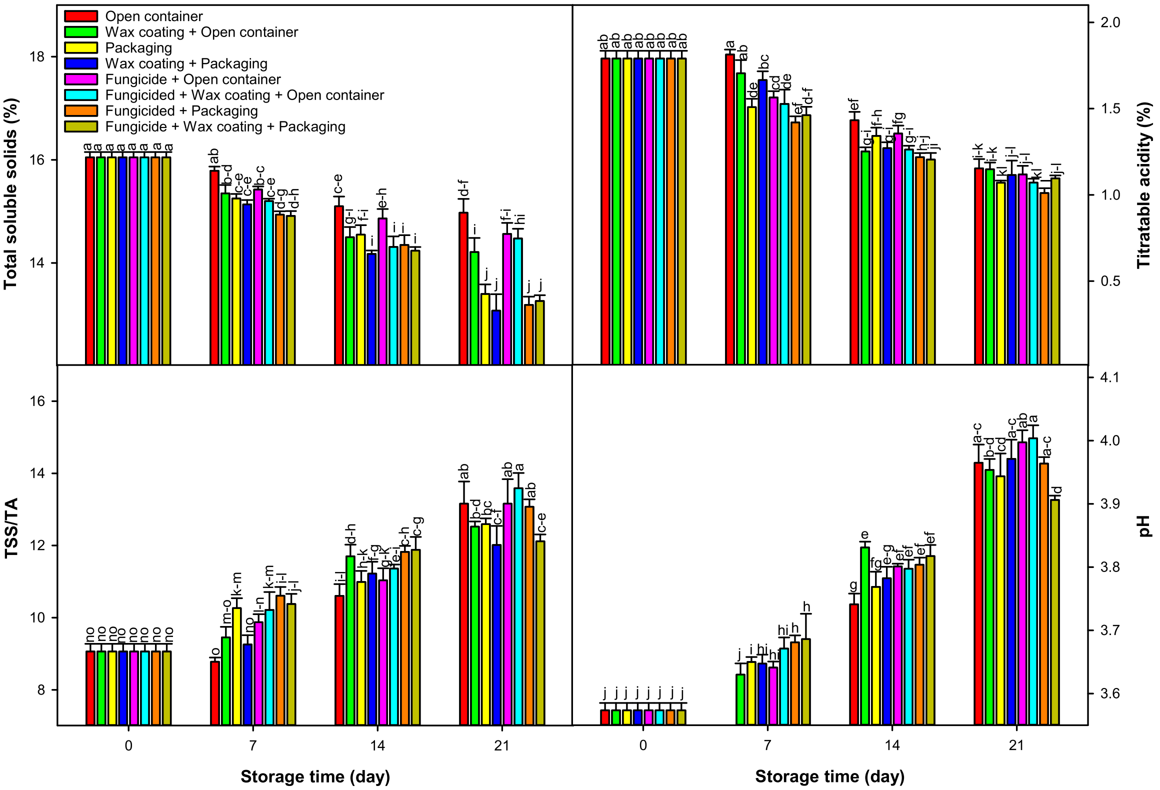

Fig. 3. Effect of different postharvest treatments on total soluble solids (TSS), titratable acidity (TA), TSS/TA, and pH of 'Possum Purple' passion fruit juice. Different letters above bars indicate significant differences among treatments and storage durations according to LSD test ($p < 0.05$). Data are presented as mean ± SE ($n = 4$).

3.5. Total antioxidant activity (TAA)

TAA increased sharply across all treatments from 9.64 µmol TE L^{-1} on day 0 to 28.90–36.83 µmol TE L^{-1} by day 14, followed by a decline to 27.48–31.41 µmol TE L^{-1} by day 21 (Fig. 4). On day 7, the highest TAA was observed in the OC treatment (36.29 µmol TE L^{-1}), while the FWP treatment had the lowest (26.07 µmol TE L^{-1}). By day 14, the FW treatment exhibited the lowest TAA (28.90 µmol TE L^{-1}), whereas the OC (34.06 µmol TE L^{-1}), W (33.87 µmol TE L^{-1}), P (36.83 µmol TE L^{-1}), FP (35.08 µmol TE L^{-1}), and FWP (32.77 µmol TE L^{-1}) treatments showed the highest values, with no significant differences among them. At the final sampling date, TAA declined across all treatments, with no significant differences among them (Fig. 4).

3.6. Color parameters

Peel color attributes changed significantly during the storage period (Fig. 5). The values of L^*, b^*, C^*, and $h°$ decreased across all treatments over time. At the final sampling date, peel L^* showed no significant differences among treatments. The most pronounced decreases in b^*, C^*, and $h°$ were observed in the WP, FW, FP, and FWP treatments by day 14, after which the values remained stable through day 21, with no significant differences among these treatments at that time. Peel a^* increased significantly in all treatments up to day 14, then either stabilized or declined slightly in some treatments. At the final sampling date, the P, WP, FP, and FWP treatments exhibited the highest a^* values, with no significant differences among them (Fig. 5).

Juice color parameters changed significantly during storage across all treatments (Fig. 5). Both juice L^* and $h°$ values decreased over time, with more pronounced declines observed in the OC and W treatments, indicating darker, deeper yellow color. Juice a^* values increased significantly in the OC treatment up to day 14, reaching the highest levels among all treatments. At the final sampling date, the OC treatment also showed the lowest juice b^* and C^* values, while no significant differences were observed among the other treatments (Fig. 5).

3.7. Multivariate statistical analyses

Principal component analysis (PCA) was conducted to explore the multivariate relationships among postharvest treatments and fruit quality attributes. The first two principal components (PC1 and PC2) accounted for 61.3 % and 22.6 % of the total variance, respectively, explaining 83.9 % of the variability in the dataset (Fig. 6A). PC1 primarily separated the treatments based on changes in physicochemical and nutritional attributes. Treatments including OC, W, and F were located on the positive side of PC1 and associated strongly with TA, TSS, TPC, weight loss, shriveling, and certain peel (L^*, b^*, $h°$, C^*) and juice (a^*) color parameters. Treatments combining wax coating and packaging (e.g., FP, FW) were correlated with TSS/TA ratio, pH, and juice color (L^*, b^*, $h°$) parameters. In contrast, P, WP, and FWP treatments were located on the negative side of PC1 were positioned at the lower side of PC2 and showed associations with firmness, peel a^*, and juice C^* (Fig. 6A).

To further explore the similarities among postharvest treatments based on fruit quality attributes, hierarchical cluster analysis (HCA) was performed using Ward's method and Euclidean distance as a dissimilarity measure (Fig. 6B). The resulting dendrogram clearly separated the treatments into two main clusters. The first cluster grouped all treatments involving open containers, including OC, F, W, and FW. These treatments were closely associated and formed a distinct group. The second major cluster consisted of treatments that included packaging, either alone or in combination with wax coating and/or fungicide application. Treatments including P, WP, FP, and FWP showed high similarity and were grouped together, indicating their effectiveness in preserving fruit quality.

The Pearson correlation matrix was employed to assess the linear

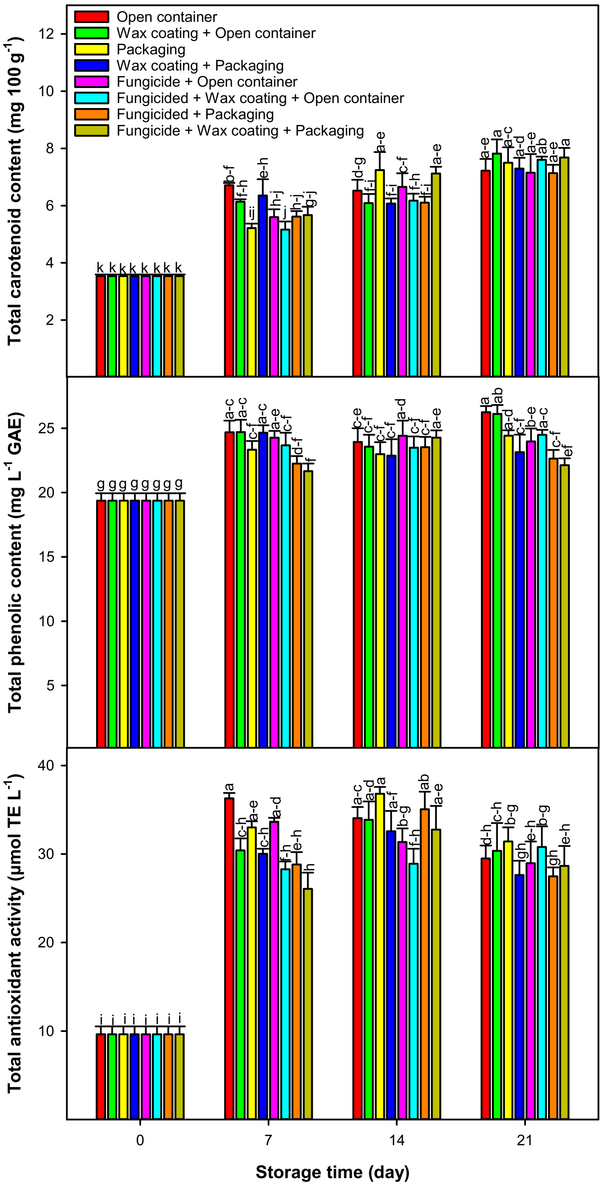

Fig. 4. Effect of different postharvest treatments on total carotenoid content (TCC), total phenolic content (TPC), and total antioxidant activity (TAA) of 'Possum Purple' passion fruit juice. Different letters above bars indicate significant differences among treatments and storage durations according to LSD test ($p < 0.05$). Data are presented as mean ± SE ($n = 4$).

relationships among the evaluated quality parameters (Fig. 7). In this graphical representation, the direction and strength of the correlations are illustrated using colored circles, where purple tones indicate positive correlations and orange tones indicate negative correlations. The size and intensity of the circles are proportional to the correlation coefficients, with larger and darker circles representing stronger and more significant correlations. Strong positive correlations were observed among antioxidant-related traits, including TAA, TPC, and TCC. Similarly, juice *a**, peel *a**, and TAA exhibited strong positive associations. Conversely, notable negative correlations were found among shriveling, TSS, and TA, with TAA and TCC.

4. Discussion

Information on how postharvest treatments affect the physical and biochemical attributes of passion fruit is essential for improving postharvest management and commercial handling. Since passion fruit is highly perishable and prone to quality losses after harvest, developing cost-effective and efficient postharvest strategies is crucial to extend shelf life and maintain fruit quality. However, limited information is available on the comparative performance of individual and integrated postharvest treatments, particularly under ambient conditions where refrigeration may not always be available or economically feasible. Therefore, this study investigated the effects of different postharvest treatments, including OC, W, F, FW, FP, and FWP, on the physicochemical and biochemical quality of 'Possum Purple' passion fruit during storage at 20 °C.

Weight loss (WL) is a key indicator of physiological deterioration in passion fruit during storage. In passion fruit, WL and subsequent shriveling are primarily caused by water loss through the porous peel, compounded by a high surface area-to-volume ratio and elevated respiratory activity (Pongener et al., 2014). In addition, the cuticle, composed of both cutin and wax, is closely correlated to postharvest water loss in passion fruit. A reduction in the thickness and content of cutin, along with a decrease in wax content and its main components, contributes to increased water loss (Yang et al., 2024). These factors accelerate water vapor loss, especially under ambient storage conditions. As internal moisture decreases, cell turgor pressure drops, leading to surface shriveling, a major visual indicator of senescence that directly reflects internal moisture loss (Nxumalo et al., 2022). Our results showed that packaging treatments (P, WP, FP, and FWP), alone or in combination, were highly effective in reducing both weight loss (WL) and shriveling, as compared with fruit stored without packaging (OC and F). Properly designed packaging creates a high-humidity, non-condensing microenvironment that reduces the vapor pressure deficit between the fruit and surrounding air, thus slowing down transpiration (Chen et al., 2018). Additionally, wax coatings enhance this barrier by partially closing lenticels and decreasing cuticular permeability to water vapor (Pongener et al., 2014).

Fruit firmness is a critical indicator of postharvest quality in purple passion fruit, reflecting changes in cellular integrity, water status, and enzymatic activity (Fu et al., 2024). In this study, all treatments exhibited progressive softening, with the most significant losses in firmness occurring by day 7 in the non-packaged OC and F groups. In contrast, packaging treatments, especially P and WP, effectively maintained higher firmness levels during storage. At the final sampling date, fruit in non-packaged treatments in W and FW had the lowest firmness values. This reduction is likely attributable to increased moisture loss, reduced cell turgor, and the enhanced activity of cell wall-degrading enzymes including polygalacturonase, pectin lyase, pectin methylesterase, and cellulose, all of which are stimulated by elevated respiration rates and senescence (Zhong et al., 2022). These changes were slightly less pronounced in packaging alone or combined with wax compared to OC treatment, leading to better water maintenance and the preservation of cell turgor (Liu et al., 2024).

In this study, significant changes in juice biochemical attributes including TSS, TA, TSS/TA ratio, and pH occurred in passion fruit due to the postharvest treatments applied prior the 21-day storage period. During storage, a gradual decline in TSS was observed across all treatments. Fruit stored in OC consistently maintained higher TSS levels compared with packaged treatments, especially after 21 days. This trend may be attributed to water loss through transpiration under open conditions, which concentrates soluble solids within the juice (You et al., 2022).

In passion fruit, TA reflects the concentration of organic acids like citric and malic acids, generally changes during ripening and after harvest (Tang et al., 2025). In this study, TA also declined gradually in all treatments. Differences among treatments became noticeable from day 7, with OC and W maintaining higher TA levels than those subjected to packaging. However, at the final sampling date, no significant differences in TA were observed among treatments, and non-packaged treatments had a significant TA reduction in compared to day 7 likely due to the overall depletion of acids as senescence advanced (Xu et al.,

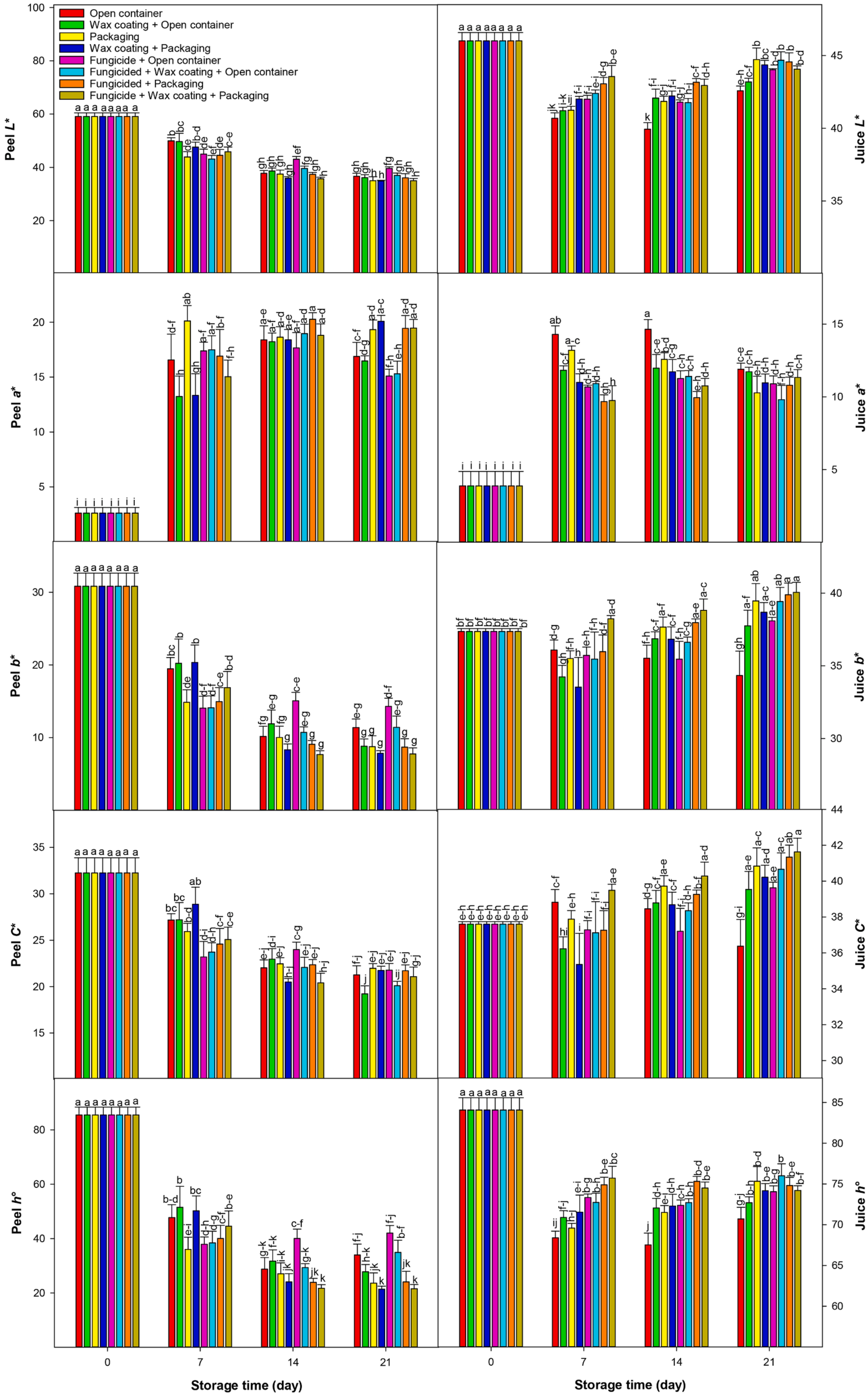

Fig. 5. Effect of different postharvest treatments on peel and juice CIELAB color parameters of ‘Possum Purple’ passion fruit. Different letters above bars indicate significant differences among treatments and storage durations according to LSD test ($p < 0.05$). Data are presented as mean ± SE ($n = 4$).

2023).

The TSS/TA ratio, a key indicator of flavor and consumer acceptability, increased significantly during storage in all treatments, reflecting the combined effect of sugar loss and acid degradation (You et al., 2022). At the final sampling date, OC, F, FW, and FP treatments exhibited lower TSS/TA ratios, suggesting a more stable balance between sweetness and acidity. This likely resulted from accelerated sugar loss or organic acid reduction (Xu et al., 2023). Interestingly, at the final

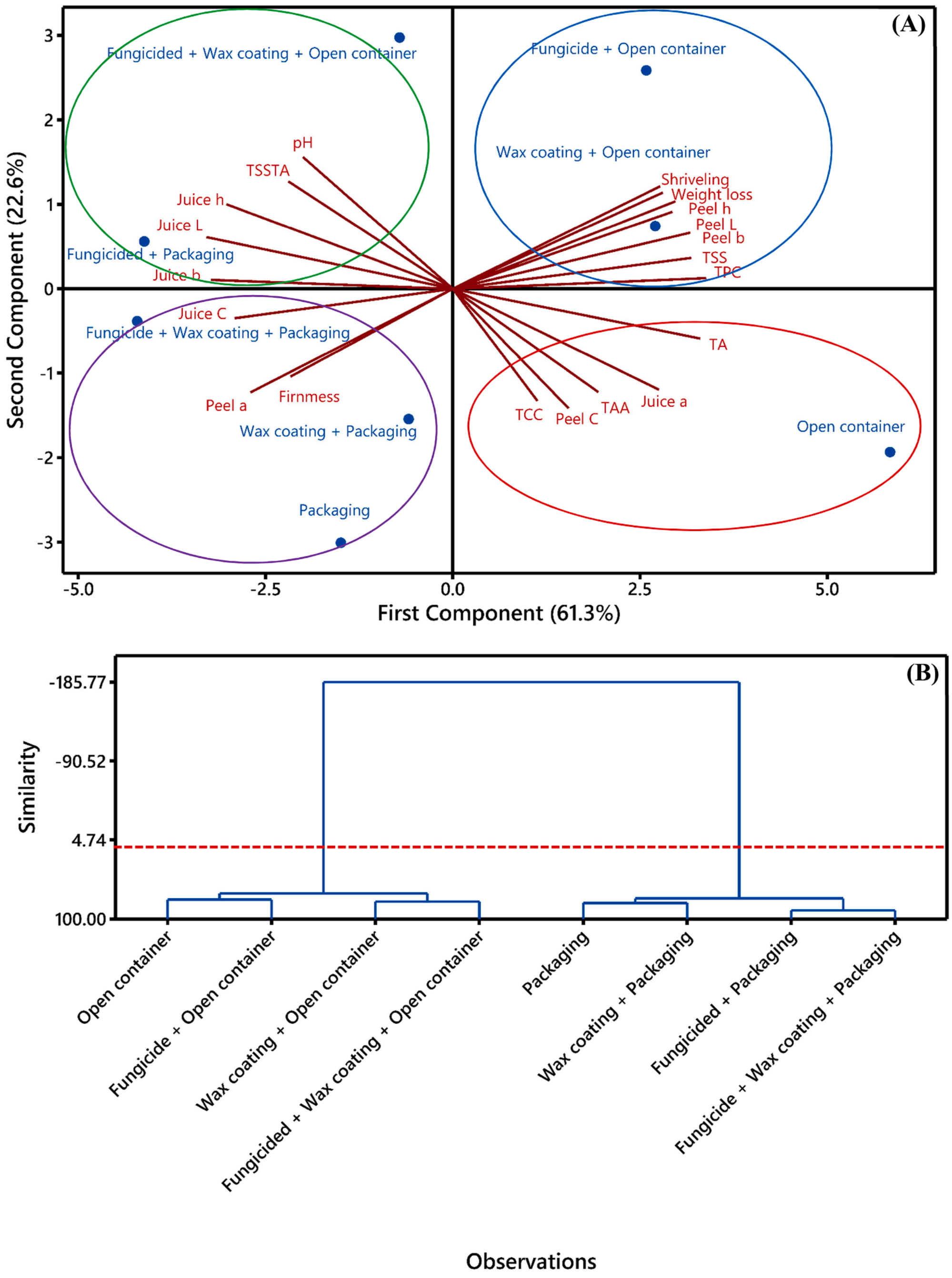

Fig. 6. Principal component analysis (PCA) including score plot and biplot (A) showing the relationship among postharvest treatments and fruit quality parameters. Hierarchical clustering analysis (HCA) (B) dendrogram based on the similarity of postharvest treatments in relation to fruit quality parameters.

sampling date, fruits from WP and FWP treatments had the lowest TSS/TA ratios among all, possibly due to a more moderate decline in TA relative to the sharper reduction in TSS, highlighting the influence of wax and packaging in slowing down metabolic changes (Nxumalo et al., 2022).

Juice pH increased significantly during the storage period in all treatments. The organic acids are progressively metabolized as respiratory substrates and this acid degradation reduces the hydrogen ion concentration in the juice, leading to a gradual increase in pH (Araujo et al., 2017).

The TCC increased progressively during storage in all treatments, reflecting the ongoing ripening and pigment biosynthesis during postharvest storage. The initial rise in TCC, particularly notable by day 7, was most pronounced in fruit stored under OC treatment. This condition may have facilitated ripening and carotenoid accumulation due to improved gas exchange and senescence (Li et al., 2020). However, at the final sampling date, no significant variations in TCC were observed among treatments. This suggests that despite initial differences in metabolic activity, the biosynthetic processes continued or stabilized over time, leading to comparable carotenoid accumulation under all conditions, eventually leading to comparable carotenoid levels (Pongener et al., 2014). These results indicate that while postharvest treatments can modulate the rate of carotenoid accumulation, the final carotenoid content may be more dependent on the actual harvest maturity that affects the ripening potential of the fruit than on the specific storage treatment.

The TPC increased significantly during the initial storage period across all treatments. Passion fruit is a climacteric fruit and continues to

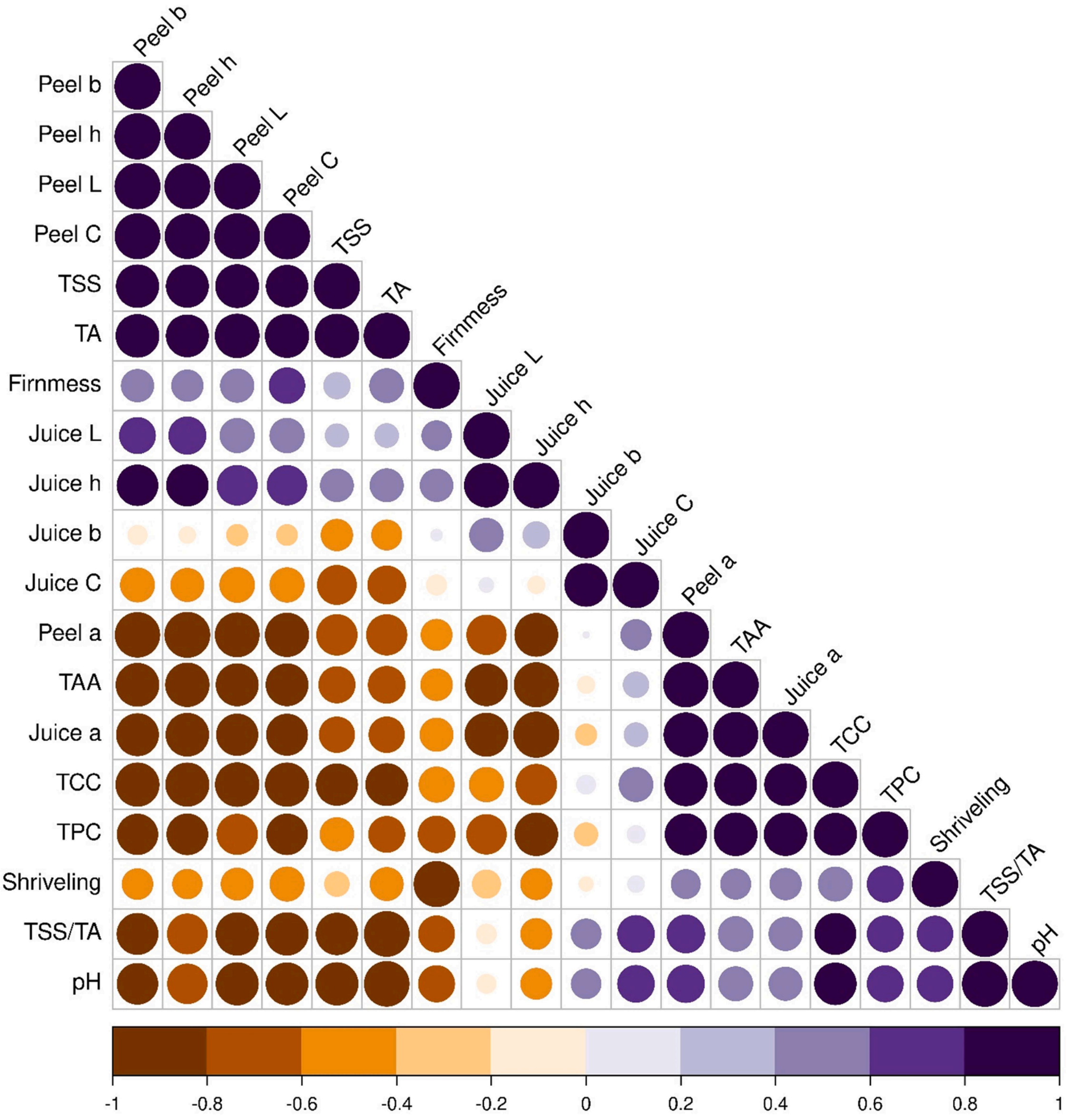

Fig. 7. Pearson correlation coefficients among variables. Positive and negative correlations are represented by purple and orange, respectively. The circle size and color intensity are proportional to the values of the correlation coefficients. Large circles indicate significant correlation coefficients, reflecting strong linear relationships, small circles represent the smallest, insignificant correlation coefficients.

ripen after harvest, as evidenced by increased respiration and ethylene production. These physiological changes can affect the levels of bioactive compounds, including phenolics (Nxumalo et al., 2022). In addition, phenolic compounds act as antioxidants to mitigate damage to cell membranes by accumulation of excessive reactive oxygen species (ROS), and their levels can be influenced by postharvest treatments (de Oliveira Militão et al., 2025). In this study, by day 7 the highest TPC levels were detected in fruit stored in OC, may have facilitated moderate abiotic stress response at the beginning of senescence processes, triggering the biosynthesis of phenolic compounds as defense mechanisms. For this reason, packaging treatments exhibited the lowest TPC at the final sampling date. This suggests that the packaging treatments may have alleviated oxidative stress and delayed senescence, thereby limiting the activation of biochemical pathways involved in phenolic accumulation (Xu et al., 2023). This suggests that they also may have collectively limited phenolic accumulation by reducing oxidative stress and slowing senescence (Li et al., 2020).

The TAA increased during early storage, peaking around day 14 across treatments, likely due to the accumulation of bioactive compounds like phenolics and carotenoids, as also shown in TPC and TCC results (Barbosa Santos et al., 2021). However, by day 21, TAA reduced in all treatments, probably because of antioxidant breakdown and the natural senescence of the fruit. As storage progresses, enzymatic and non-enzymatic antioxidant systems may become depleted or less effective, and the loss of antioxidants can become greater than their production (Cai et al., 2024).

Significant changes in peel and juice color parameters occurred during storage, reflecting ripening progression and pigment degradation. The consistent decline in peel L^*, b^*, C^*, and h° across all treatments indicates a gradual loss of brightness, yellowness, and chroma, which is commonly associated with anthocyanin accumulation and peel maturation (de Jesus et al., 2023). The marked increase in peel a^* values up to day 14 in all treatments suggests the development of reddish hues, likely linked to anthocyanin biosynthesis. Juice color changes also exhibited treatment-dependent trends. The observed reductions in juice L^* and h° values indicate increasing darkness and a shift in hue over time, possibly due to carotenoid biosynthesis. A notable increase in juice a^* values was observed in the OC treatment, potentially reflecting accelerated pigment synthesis or faster senescence. In contrast, packaging-based treatments more effectively preserved juice color stability, possibly by delaying oxidative processes and slowing senescence processes (Araujo et al., 2017).

5. Conclusion

In conclusion, postharvest treatments significantly influenced the physicochemical and biochemical quality of purple passion fruit during storage. Among the treatments, packaging when combined with carnauba wax and fungicide application (FWP) proved most effective in preserving overall fruit quality by reducing weight loss, shriveling, and softening. Although open-container treatments (OC, W, F) exhibited higher levels of TSS, TA, TPC, and TAA, they also showed accelerated physical deterioration over time. Open container treatments, particularly those without wax coatings or packaging, were linked to more pronounced senescence indicators and quality degradation. Multivariate analyses further supported these findings, indicating that OC, W, and F treatments clustered with markers of quality loss, while packaging-based treatments (P, WP, FWP) correlated with better retention of firmness, color, and juice quality. These results highlight the benefits of combining packaging with simple preservation strategies to extend shelf life and maintain fruit quality. These findings provide valuable insights for developing sustainable postharvest storage strategies for purple passion fruit to enhance marketability and nutritional value by minimizing postharvest losses.

Funding

This work was supported by the Southern Sustainable Agriculture Research and Education (S-SARE) Research and Education award number LS23–380.

Ethical statement

No Humans or animals were used in this research.

CRediT authorship contribution statement

Fariborz Habibi: Writing – original draft, Visualization, Software, Methodology, Formal analysis. **Uzman Khalil:** Writing – review & editing, Visualization, Methodology. **Steven A. Sargent:** Writing – review & editing, Visualization, Validation, Supervision, Resources, Conceptualization. **Ali Sarkhosh:** Writing – review & editing, Visualization, Validation, Supervision, Resources, Funding acquisition, Data curation, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgment

The authors acknowledge Southern Sustainable Agriculture Research and Education (S-SARE) for providing the fund. We are grateful to HDH Agri Products LLC (Tavares, FL, USA, http://hdhagri.com/) for supplying Carnauba Wax. We also sincerely appreciate the invaluable support and collaboration of the Postharvest and Fruit Crops Labs in the Department of Horticultural Sciences at the University of Florida during our laboratory experiments.

Data availability

Data will be made available on request.

References

Araujo, L. D. S., COSTA, E. M. R., Soares, T. L., SANTOS, I. S. D., & JESUS, O. N. D (2017). Effect of time and storage conditions on the physical and physico-chemical characteristics of the pulp of yellow and purple passion fruit. *Food Science and Technology, 37*, 500–506. https://doi.org/10.1590/1678-457X.20616

Barbosa Santos, T., De Araujo, F. P., Neto, A. F., De Freitas, S. T., de Souza Araújo, J., de Oliveira Vilar, S. B., Brito Araújo, A. J., & Lima, M. S. (2021). Phytochemical compounds and antioxidant activity of the pulp of two Brazilian passion fruit species: Passiflora cincinnata Mast. And passiflora edulis Sims. *International Journal of Fruit Science, 21*(1), 255–269. https://doi.org/10.1080/15538362.2021.1872050

Benzie, I. F., & Strain, J. J. (1996). The ferric reducing ability of plasma (FRAP) as a measure of "antioxidant power": The FRAP assay. *Analytical Biochemistry, 239*(1), 70–76. https://doi.org/10.1006/abio.1996.0292

Cai, S., Zhang, Z., Wang, J., Fu, Y., Zhang, Z., Khan, M. R., & Cong, X. (2024). Effect of exogenous melatonin on postharvest storage quality of passion fruit through antioxidant metabolism. *LWT, 194*, Article 115835. https://doi.org/10.1016/j.lwt.2024.115835

Chen, F. P., Xu, X. Y., Luo, Z., Chen, Y., Xu, Y., & Xiao, G. (2018). Effect of high O2 atmosphere packaging on postharvest quality of purple passion fruit (Passiflora edulis Sims). *Journal of Food Processing and Preservation, 42*(9), Article e13749. https://doi.org/10.1111/jfpp.13749

de Jesus, O. N., Lima, L. K. S., dos Santos, I. S., dos Santos, M. A., & Rosa, R. C. C. (2023). Bright red passion fruit - evaluation of colorimetry and physicochemical quality for the fresh fruit market. *Scientia Horticulturae, 317*, Article 112016. https://doi.org/10.1016/j.scienta.2023.112016

de Oliveira Militão, A., da Silva, T. I., do Nascimento, A. M., da Costa, F. B., de Castro, A. K. G., Macêdo, L. F., Alcântara, C. M., Evangelista, M. E. M., Sales, G. N. B., Lopes, K. P., & Santos, S. C. L. (2025). Storage increases soluble sugars and decreases bioactive compounds in wild passion fruit (Passiflora cincinnata). *Horticulture, Environment, and Biotechnology*, 1–16. https://doi.org/10.1007/s13580-025-00676-0

Devi, L. S., Kalita, S., Mukherjee, A., & Kumar, S. (2022). Carnauba wax-based composite films and coatings: Recent advancement in prolonging postharvest shelf-life of fruits and vegetables. *Trends in Food Science & Technology, 129*, 296–305. https://doi.org/10.1016/j.tifs.2022.09.019

Dos Reis, L. C. R., Facco, E. M. P., Salvador, M., Flôres, S. H., & de Oliveira Rios, A. (2018). Antioxidant potential and physicochemical characterization of yellow, purple and orange passion fruit. *Journal of Food Science and Technology, 55*, 2679–2691. https://doi.org/10.1007/s13197-018-3190-2

Fonseca, A. M., Geraldi, M. V., Junior, M. R. M., Silvestre, A. J., & Rocha, S. M. (2022). Purple passion fruit (Passiflora edulis f. edulis): A comprehensive review on the nutritional value, phytochemical profile and associated health effects. *Food Research International, 160*, Article 111665. https://doi.org/10.1016/j.foodres.2022.111665

Fu, D., Wang, J., Chen, Y., Hu, Z., & Tang, W. (2024). Predicting storage time of passion fruit using pericarp change index: A study on size, mass and texture parameters. *Journal of Food Measurement and Characterization, 18*(5), 3893–3905. https://doi.org/10.1007/s11694-024-02463-4

Li, C., Xin, M., Li, L., He, X., Liu, G., Li, J., Sheng, J., & Sun, J. (2020). Transcriptome profiling helps to elucidate the mechanisms of ripening and epidermal senescence in passion fruit (Passiflora edulia Sims). *PLOS ONE, 15*(9), Article e0236535. https://doi.org/10.1371/journal.pone.0236535

Liu, J., Wang, Y., Zhong, Z., Zhou, L., & Liu, W. (2024). Proteomic investigation of metabolic changes of passion fruit treated with microporous packaging combined with chitosan coating during storage. *Food and Bioprocess Technology, 17*(11), 4278–4289. https://doi.org/10.1007/s11947-024-03392-2

McGuire, R. G. (1992). Reporting of objective color measurements. *HortScience : A Publication of the American Society for Horticultural Science, 27*, 1254–1255. https://doi.org/10.21273/HORTSCI.27.12.1254

Naranjo-Durán, A. M., Quintero-Quiroz, J., Ciro-Gómez, G. L., Barona-Acevedo, M. J., de, Carmen, & Contreras-Calderón, J. (2023). Characterization of the antioxidant activity, carotenoid profile by HPLC-MS of exotic colombian fruits (goldenberry and purple passion fruit) and optimization of antioxidant activity of this fruit blend. *Heliyon, 9*(7), Article e17819. https://doi.org/10.1016/j.heliyon.2023.e17819

Nxumalo, K. A., & Fawole, O. A. (2022). Effects of chitosan coatings fused with medicinal plant extracts on postharvest quality and storage stability of purple passion fruit (Passiflora edulis var. Ester). *Food Quality and Safety, 6*, fyac016. https://doi.org/10.1093/fqsafe/fyac016

Palumbo, M., Attolico, G., Capozzi, V., Cozzolino, R., Corvino, A., de Chiara, M. L. V., Pace, B., Pelosi, S., Ricci, I., Romaniello, R., & Cefola, M. (2022). Emerging postharvest technologies to enhance the shelf-life of fruit and vegetables: An overview. *Foods (Basel, Switzerland), 11*(23), 3925. https://doi.org/10.3390/foods11233925

Paull, R. E., & Chen, C. C. (2016). Passion fruitK. C. Gross, C. Y. Wang, & M. Saltveit (Eds.), Passion fruit. *The commercial storage of fruits, vegetables and florist and nursery stocks. (USDA-ARS agric. handbook no. 66)*, 460–462.

Plaza, P., Sanbruno, A., Usall, J., Lamarca, N., Torres, R., Pons, J., & Viñas, I. (2004). Integration of curing treatments with degreening to control the main postharvest diseases of clementine mandarins. *Postharvest Biology and Technology, 34*(1), 29–37. https://doi.org/10.1016/j.postharvbio.2004.03.012

Pongener, A., Sagar, V., Pal, R. K., Asrey, R., Sharma, R. R., & Singh, S. K. (2014). Physiological and quality changes during postharvest ripening of purple passion fruit (Passiflora edulis Sims). *Fruits, 69*(1), 19–30. https://doi.org/10.1051/fruits/2013097

Razzaq, K., Khan, A. S., Malik, A. U., Shahid, M., & Ullah, S. (2014). Role of putrescine in regulating fruit softening and antioxidative enzyme systems in 'Samar Bahisht

Chaunsa' mango. *Postharvest Biology and Technology, 96*, 23–32. https://doi.org/10.1016/j.postharvbio.2014.05.003

Schotsmans, W. C., & Fischer, G. (2011). Passion fruit (Passiflora edulis Sims.). In E. M. Yahia (Ed.), *Postharvest biology and technology of tropical and subtropical fruit* (pp. 125–143). Sawston, UK: Woodhead Publ.. https://doi.org/10.1533/9780857092618.125

Shahkoomahally, S., Sarkhosh, A., Richmond-Cosie, L. M., & Brecht, J. K. (2021). Physiological responses and quality attributes of muscadine grape (Vitis rotundifolia Michx) to CO_2-enriched atmosphere storage. *Postharvest Biology and Technology, 173*, Article 111428. https://doi.org/10.1016/j.postharvbio.2020.111428

Singleton, V. L., & Rossi, J. A. (1965). Colorimetry of total phenolics with phosphomolybdic-phosphotungstic acid reagents. *American Journal of Enology and Viticulture, 16*(3), 144–158. https://doi.org/10.5344/ajev.1965.16.3.144

Talcott, S. T., & Howard, L. R. (1999). Phenolic autoxidation is responsible for color degradation in processed carrot puree. *Journal of Agricultural and Food Chemistry, 47*(5), 2109–2115. https://doi.org/10.1021/jf981134n

Tang, Y., Wang, P., Chen, J., Li, L., Tang, L., Huang, W., Wei, X., & Xu, J. (2025). The accumulation pattern of sugars and organic acids in diverse fruit pulps coordinates sweet-sour taste of passion fruit. *LWT, 225*, Article 117948. https://doi.org/10.1016/j.lwt.2025.117948

Weyya, G., Belay, A., & Tadesse, E. (2024). Passion fruit (Passiflora edulis Sims) by-products as a source of bioactive compounds for non-communicable disease prevention: Extraction methods and mechanisms of action: A systematic review. *Frontiers in Nutrition, 11*, Article 1340511. https://doi.org/10.3389/fnut.2024.1340511

Xu, H., Qiao, P., Pan, J., Qin, Z., Li, X., Khoo, H. E., & Dong, X. (2023). CaCl2 treatment effectively delays postharvest senescence of passion fruit. *Food Chemistry, 417*, Article 135786. https://doi.org/10.1016/j.foodchem.2023.135786

Yang, H., Li, X., Tan, Y., & Pan, Y. (2024). Revealing the crucial role of cuticular wax components in postharvest water loss in passion fruit (Passiflora edulis Sims. *Postharvest Biology and Technology, 213*, Article 112974. https://doi.org/10.1016/j.postharvbio.2024.112974

You, M., Duan, X., Li, X., Luo, L., Zhao, Y., Pan, H., Gong, W., Yang, L., Xiang, Z., & Li, G. (2022). Effect of 1-methylcyclopropene combined with chitosan-coated film on storage quality of passion fruit. *Sustainable Chemistry and Pharmacy, 27*, Article 100679. https://doi.org/10.1016/j.scp.2022.100679

Zhang, Y., Zhang, W., Wu, W., Farag, M. A., Wang, L., Xiao, S., Gao, H., & Jiang, W. (2025). Critical assessment of the delivery methods of chemical and natural postharvest preservatives for fruits and vegetables: A review. *Critical Reviews in Food Science and Nutrition, 65*(6), 1070–1092. https://doi.org/10.1080/10408398.2023.2289071

Zhong, Z., Zhou, L., Yu, K., Jiang, F., Xu, J., Zou, L., Du, L., & Liu, W. (2022). Effects of microporous packaging combined with chitosan coating on the quality and physiological metabolism of passion fruit after harvest. *Food and Bioprocess Technology, 15*(8), 1836–1850. https://doi.org/10.1007/s11947-022-02845-w