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Effects of putrescine and MAP on quality, phenolics, and organic acids in strawberry tree fruits

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Abstract

Background Strawberry tree (*Arbutus unedo* L.) fruits are rich in bioactive compounds but are highly perishable due to their high respiration rate and soft tissue structure, leading to rapid post-harvest quality losses. Therefore, developing sustainable strategies to maintain quality and extend shelf life is of great importance.

Methods In this study, the individual and combined effects of putrescine (1 mM) and modified atmosphere packaging (MAP) on the post-harvest quality and biochemical properties of strawberry tree fruits were investigated. Fruits harvested at full maturity were stored at 4 ± 1 °C and $90 \pm 5\%$ relative humidity for 15 days, and key quality parameters including weight loss, decay rate, respiration rate, soluble solids content, titratable acidity, vitamin C, organic acids, and phenolic compounds were periodically analyzed. Additionally, correlation analysis and principal component analysis (PCA) were performed to evaluate the relationships among variables.

Results Storage duration significantly increased weight loss and decay rate, while decreasing organic acids, vitamin C, and phenolic compounds ($p \leq 0.001$). At the end of storage, weight loss reached 2.97% in control fruits, whereas it decreased to 1.14% in the Put + MAP treatment, representing a reduction of approximately 61.6%. Similarly, decay rate decreased from 6.55% (control) to 3.34% (Put + MAP). Respiration rate was also significantly suppressed, with the lowest values observed in the combined treatment. Furthermore, malic acid (1.38 vs. 0.80 g/100 g) and vitamin C (36.90 vs. 28.37 mg/100 g) were better preserved in Put + MAP-treated fruits compared to control at day 15. PCA results confirmed that Put + MAP treatment maintained the most balanced profile between quality attributes and biochemical stability.

Conclusion The combined application of putrescine and MAP exhibited a strong synergistic effect by simultaneously reducing respiration, limiting water loss and decay, and preserving bioactive compounds. This study demonstrates that integrating a natural bioregulator (putrescine) with an environmentally friendly packaging system (MAP) represents an innovative and practical approach for extending the shelf life and maintaining the nutritional quality of strawberry tree fruits. This strategy also has high potential for application in other highly perishable soft fruits.

Keywords Modified atmosphere packaging, Organic acid, Phenolic stability, Respiration rate

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Background

Strawberry tree (*Arbutus unedo* L.) is an important wild or semi-cultivated fruit species native to the Mediterranean basin, but with a wide distribution extending to Western Europe, Ireland, and the Macaronesian Islands [1]. Strawberry tree that was used for both food and medicinal purposes since ancient Greek times, has been valued in traditional folk medicine for its antiseptic, diuretic, and laxative properties, and these uses have recently become a renewed focus of scientific research with the increasing interest in functional foods and natural bioactive compounds [2]. Strawberry tree fruits are rich in vitamin C, organic acids, carotenoids, and phenolic compounds, and exhibit high antioxidant capacity [3, 4]. Due to this rich biochemical composition, the fruits are used in the production of various traditional and industrial products such as jams, marmalades, jellies, fermented beverages, and aromatic distillates [2, 5]. The limited studies on this fruit species, high intraspecific genetic variation, limited selection and breeding efforts, and insufficient commercial varieties significantly restrict the widespread agricultural production of the strawberry tree and its marketing as fresh fruit, and this prevents the fruit from reaching consumers in sufficient quantities [6, 7]. One of the main factors limiting the commercial potential of strawberry tree fruits is their extremely short post-harvest shelf life and rapid quality loss during storage. Fruits generally only reach an acceptable aroma and taste profile at advanced maturity; at this stage, they spoil rapidly due to their soft tissue structure, high respiration rate, and fermentable sugar content [8, 9]. Post-harvest softening, loss of color and aroma, and microbial spoilage severely limit fresh consumption and often result in the fruit being processed. Furthermore, the susceptibility to overripening increases the risk of mechanical damage during transport and storage, further shortening the marketing period [6]. Therefore, the developing effective and sustainable practices to delay post-harvest quality losses, limit physiological deterioration, and extend the shelf life of strawberry trees is of great importance.

In recent years, the increasing restriction of the use of synthetic fungicides and chemical preservatives due to their potential negative effects on the environment and human health has increased interest in natural and biological post-harvest applications [10, 11]. In this context, polyamines are among the biostimulant groups that attract attention due to their multifaceted roles in plant metabolism and their regulatory effects on post-harvest physiological processes [12]. Polyamines such as putrescine, spermidine, and spermine play an active role in regulating cell division and elongation, embryogenesis, flowering, fruit development, and ripening processes, as well as tolerance mechanisms against biotic and abiotic stresses [13]. The decrease in endogenous polyamine

levels in fruits during the post-harvest period leads to an increase in respiration rate and ethylene production, faster degradation of cell wall polysaccharides, and consequently, tissue softening and quality losses [14]. Therefore, exogenous polyamine applications are reported to offer an effective and sustainable approach to maintaining post-harvest quality. Among polyamines, putrescine in particular can significantly slow down post-harvest physiological deterioration by suppressing respiration rate and ethylene biosynthesis, maintaining cell membrane integrity, and delaying the removal of the epicuticular wax layer, which plays a critical role in water loss from the bark [12]. Recent studies have shown that putrescine applications reduce weight loss and decay rates in fruits, maintain fruit flesh firmness for a longer period, and delay the ripening process by slowing down changes in soluble solids content and titratable acidity [12]. In addition, it has been reported that putrescine reduces oxidative stress by limiting the accumulation of reactive oxygen species (ROS); and makes significant contributions to the preservation of phenolic compounds, organic acids, and total antioxidant capacity during storage [15]. Indeed, the studies conducted on figs have clearly shown that putrescine applied at different doses reduces weight loss and decay rates, slows down the decrease in titratable acidity, and ensures that phenolic compounds remain more stable during cold storage [16].

In addition to the positive effects of putrescine applications, MAP technology is also one of the widely used environmentally friendly methods for preserving fruit quality in the post-harvest period by regulating respiration rate and slowing down metabolic processes. In MAP applications, reducing the in-package O₂ concentration and increasing the CO₂ level suppresses respiration and ethylene production, thus delaying ripening and senescence processes. This results in reduced water loss, longer preservation of fruit flesh firmness, and limited microbial spoilage [17]. It has also been reported that MAP limits lipid peroxidation by preserving cell membrane integrity, thereby contributing to the reduction of oxidative stress. Recent studies have shown that MAP applications support the preservation not only of physical quality parameters but also of biochemical components such as phenolic compounds, flavonoids, and total antioxidant capacity. For example, the studies conducted on jujube fruit have reported that different MAP materials maintain higher levels of phenolic compounds and antioxidant activity during storage, and metabolic degradation is delayed in parallel with a decrease in respiration rate. Similarly, the studies on species such as grapes and persimmons have reported that MAP applications increase phenolic stability by suppressing oxidative enzyme activities such as polyphenol oxidase and peroxidase [12, 18]. When considering strawberry tree fruits, which are characterized

by their short shelf life and high respiration rate, the use of MAP applications in combination with natural bio-regulators such as putrescine stands out as a powerful synergistic preservation strategy that can more effectively limit physiological deterioration, delay quality losses, and extend marketability. However, studies on the combined use of putrescine and MAP applications are quite limited, and the effects of this combination on quality, biochemical compounds, and antioxidant systems, particularly in strawberry tree fruits, are not sufficiently elucidated. The aim of this study was to determine the effects of applying putrescine at different doses post-harvest in combination with MAP conditions on the physical quality characteristics and biochemical content of strawberry tree fruits during storage, and to evaluate the potential of this combination to extend shelf life.

Materials and methods

In this study, fully mature strawberry tree (*Arbutus unedo* L.) fruits were used as plant material. Samples were collected on a cepa basis from in Yalova province (approximately 40°39' N, 29°17' E) in northwestern Türkiye. The study area has a temperate climate, and fruit samples were harvested from similar altitudes (50–70 m) to minimize environmental variation. The orchard is a privately owned commercial production area, and the plant materials were obtained with the permission of the orchard owner. Since the samples were obtained from a cultivated source and not collected from the wild, no specific collection permits were required. The plant materials were taxonomically identified by the authors based on standard morphological descriptors, and no voucher specimens were deposited. Harvesting was planned considering criteria indicating that the fruits had reached marketable maturity, such as the change in peel color from green-yellow to red, the onset of slight softening in the fruit tissue, and the development of a typical aroma. Prior to harvesting, trees were selected from those grown under similar ecological conditions to minimize potential tree-specific variation. Harvesting was carried out in the early morning hours to keep fruit temperature and respiration activity low. After harvesting, the fruits were kept in the shade, and field-laboratory transportation was completed as quickly as possible. During transport, the fruit box were secured against shocks and impacts, preventing excessive vibration and compression. The fruits brought to the laboratory were processed rapidly without being left at room temperature before analysis and application, and any foreign materials on the surface were removed with a dry/clean material. The fruits were classified without washing; then, they were re-selected to ensure homogeneity in size and appearance and randomly distributed into experimental groups. At this stage, particular attention was paid to ensuring the reliability of quality

parameters to be measured during storage by creating similar starting material in each replicate.

Treatments

The study was conducted according to a full factorial experimental design, and treatments were planned based on the Put × MAP × Storage Time interaction. In this context, four different treatment groups were created to comparatively evaluate the effects of post-harvest treatments on the quality and biochemical properties of strawberry tree fruits during storage. In the experiment, the fruits that did not undergo any chemical or packaging treatment formed the control group; in the second group, fruits were treated with a 1 mM putrescine solution; in the third group, only MAP treatment was performed; and in the fourth group, storage under MAP conditions was carried out after putrescine treatment. For putrescine application, homogeneously selected fruits were immersed in a putrescine solution prepared at a concentration of 1 mM for 5 minutes. To ensure optimization between experimental conditions and applications, both the control and MAP groups were immersed in water for 5 minutes, as was the case with putrescine applications. The selection of the 1 mM putrescine concentration was based on previous studies reporting that low to moderate doses of the preservation of bioactive compounds, such as phenolics and flavonoids, along with organic acids as key quality-related primary metabolites, was significantly affected by the treatments; putrescine are effective in maintaining post-harvest quality without causing phytotoxic effects. In particular, earlier studies conducted on various fruit species such as fig, hawthorn, and peach have demonstrated that concentrations around 1 mM significantly reduce respiration rate, delay softening, and preserve biochemical compounds during storage [12, 15, 16]. Therefore, 1 mM was chosen as an optimal and widely accepted concentration to evaluate the effectiveness of putrescine under the present experimental conditions. After application, the excess solution remaining on the surface was removed, and the fruits were briefly dried at room temperature before being ready for packaging. Fruits in the control group and the group treated only with MAP were subjected to similar treatment steps by being immersed in distilled water for the same duration to eliminate any potential treatment effects related to putrescine application. Thus, the differences between the treatments were ensured to be due only to the effects of putrescine and MAP. In the MAP application, the fruits were placed in commercially available MAP packaging with controlled gas permeability and stored under passive MAP conditions. The packaging material consisted of low-density polyethylene (LDPE) film with a thickness of approximately 30–40 µm, which is commonly used for fresh fruit packaging due to its suitable gas transmission

properties. The film exhibited an oxygen permeability of approximately 8000–10000 mL m⁻² day⁻¹ atm⁻¹ and a carbon dioxide permeability of 20000–30000 mL m⁻² day⁻¹ atm⁻¹. During storage, the internal atmosphere composition of the packages was formed passively by fruit respiration, and no external gas injection was applied. Based on typical equilibrium conditions observed in passive MAP systems for similar fruits, the in-package gas composition was estimated to reach approximately 3–5% O₂ and 5–10% CO₂, with the balance being N₂. The packaging material used allows for natural changes in the O₂ and CO₂ concentrations inside the packaging due to the respiration activity of the fruits, and no external gas injection was performed. In this way, the effects of modified atmosphere conditions created by fruit-packaging interaction during storage on quality parameters were evaluated. Fruits in all treatment groups were stored in cold storage adjusted to 4 ± 1°C temperature and 90 ± 5% relative humidity. The storage period was set at 15 days, and samples were taken on the harvest day (day 0), as well as on days 5, 10, and 15. Analyses were performed in triplicate at each treatment and sampling time, with 15 fruits used in each replicate. At the sampling times, the fruits were removed from cold storage and immediately processed for the relevant physical, physiological, and biochemical analyses. During storage, on each sampling day (harvest/day 0, days 5, 10, and 15), the fruits in each replicate were first evaluated for physical and physiological analyses, and then representative samples were set aside for biochemical analyses. Physical analyses were performed on the same fruits; for biochemical analyses, the fruits were separated from their seeds and homogenized. All analyses were carried out using three replicates (*n* = 3), and each replicate consisted of 15 fruits, resulting in a total of 45 fruits per treatment group at each sampling time.”

Weight loss

Weight loss was determined by weighing the fruit at the beginning of storage in each replicate and reweighing it on the respective sampling days. Weighings were performed using a digital balance with an accuracy of 0.01 g. Weight loss was calculated as a percentage (%) and the following equation was used: $WL (\%) = [(Initial\ weight - Weight\ on\ measurement\ day) / Initial\ weight] \times 100$. The obtained values were used to evaluate the effects of the treatments on water loss and transpiration.

Decay rate

The decay rate was determined by dividing the number of fruits showing softening, tissue collapse, leakage, mold growth, or significant deterioration during storage by the total number of fruits in each replicate. Results are

expressed as percentages (%). The decay assessment was based on visual and tactile criteria.

Respiration rate

In respiration rate measurement, the specified number of fruits from each replicate were placed in airtight glass jars, and after a 2-hour incubation period, the CO₂ concentration in the headspace of the jars was measured using Headspace Gas Analyzer (GS3/L, Systech Illinois, USA). Respiration rate was calculated using the following equation, and the results were expressed in nmol CO₂ / kg/h: $RR = (V_j - V_f) \times \%CO_2 \times 10 / (FW \times T)$. *V_j* = jar volume (mL), *V_f* = fruit volume (mL), *FW* = fruit weight (kg), *T* = incubation time (hours) are defined.

SSC, TA, pH ve vitamin C

For use in SSC, TA, pH, and vitamin C analyses, the fruits in each replicate were first washed with tap water, their surface moisture was dried, and their pits were removed. The fruits were homogenized using a laboratory-type blender; the resulting fruit puree was filtered through double-layered cheesecloth to remove fiber, peel, and large particles, thus obtaining clear fruit juice. Analyses were performed using freshly prepared filtrate on each sampling day, and all measurements were taken from the same extract. SSC content was determined using a Model PAL-1 digital refractometer (Atago, Tokyo, Japan), and results were expressed as % (°Brix). pH measurement was performed using a digital pH meter (HI 2211, Hanna Instruments, USA) with the same fruit juice extract. Prior to measurement, the pH meter was calibrated with pH 4.00 and 7.00 buffer solutions. Following calibration, the electrode was directly immersed in the fruit juice sample, allowed to stabilize until the reading was stable, and the pH value was recorded. Measurements were repeated at least twice in each test, and the average values were used for evaluation. For TA analysis, 10 mL of the prepared fruit juice filtrate was taken and 10 mL of pure water was added. The mixture was homogenized on a magnetic stirrer and then titrated with 0.1 N NaOH solution. The titration process was monitored using a digital pH meter, and the endpoint was accepted as pH 8.2. TA was calculated based on the amount of NaOH consumed in the titration, and the results were expressed as malic acid equivalents. Values were reported in grams of malic acid in % fresh weight. In each replicate, the analysis was performed in at least two replicates, and the average values were used.

Organic acids and bioactive compounds

For the analysis of Vitamin C organic acids and individual phenolic compounds, strawberry tree fruits, representatively selected from each replicate, were first washed with tap water, surface moisture was removed, and the seeds were separated. The fruits were homogenized and pureed

using a laboratory-type blender. Specific samples were taken from the resulting homogenate, according to the type of analysis, and treated with the relevant extraction solutions. After the extraction process, all samples were centrifuged at 4 °C at 12,000 rpm for 15 min. The clear supernatant obtained after centrifugation was carefully collected, passed first through a coarse filter, and then filtered through a 0.45 µm membrane filter to prepare it for HPLC analysis. The extracts were stored at low temperature and in a dark environment until analysis.

Vitamin C

2.5% meta-phosphoric acid solution was homogenized with 10 g of fruit sample and filtered through a 0.45 µm Teflon membrane filter. Chromatographic separation was then performed using an HPLC system (Agilent 1100 Series, Agilent Technologies, USA) on a Phenomenex Luna C18 column (250 × 4.60 mm, 5 µm) maintained at 25 °C. The mobile phase, consisting of ultrapure water acidified to pH 2.2 with sulfuric acid (H₂SO₄), was applied at a constant flow rate of 1 mL/min. Results were detected using a diode array detector (DAD) tuned to 254 nm [19].

Organic acids

To determine the main organic acids (citric, malic, succinic, and oxalic acid) in strawberry tree fruits, samples taken from the prepared homogenate were extracted using the acidic aqueous extraction method. As an extraction solution, the distilled water containing 0.1–0.5% (v/v) phosphoric acid or formic acid was used to maintain the stability of organic acids and prevent oxidative degradation. The mixtures prepared after extraction were subjected to centrifugation and filtration before being analyzed by HPLC. Quantitative analysis of organic acids was performed using an HPLC system (Agilent 1100 Series, Agilent Technologies, USA) equipped with a reversed-phase C18 column (ODS, 250 × 4.6 mm, 4–5 µm). An acidified water–methanol mixture was generally preferred as the mobile phase; the flow rate was adjusted to 0.8–1.0 mL min⁻¹. The detection was performed at a wavelength of 210–220 nm, where organic acids exhibit maximum absorbance. Identification and quantification were carried out using external standard curves prepared for each organic acid; results were expressed in g/100 g fresh weight [20].

Specific phenolic compounds

For the analysis of individual phenolic compounds, the portions taken from homogenized fruit samples were treated with acidified aqueous or methanolic solution to ensure efficient extraction of phenolic compounds. The clear extracts obtained after extraction, centrifugation, and filtration were used in HPLC analyses. Separation

and quantitative analysis of phenolic compounds were performed using an Agilent 1100 HPLC system (Agilent Technologies, USA) with a diode array detector (DAD). The separation was performed on an ODS column (250 × 4.6 mm, 4 µm); a gradient elution program was applied using acidified water (A) and methanol or acetonitrile (B) as the mobile phase. The flow rate was set to 1.0 mL min⁻¹ and the column temperature to 25–30 °C. The identification of phenolic compounds was based on retention times, UV-Vis spectra, and comparison with external standards. In this study, individual phenolic compounds such as gallic acid, catechin, quercetin, rutin, ferulic acid, chlorogenic acid, protocatechic acid, syringic acid, p-coumaric acid, and fluorizin were determined. The detection was performed at wavelengths specific to the compounds. Quantitative determination was carried out using standard curves prepared for each phenolic compound, and the results were expressed in mg/100 g fresh weight [21].

Statistical analysis

The experiment was evaluated according to the full factorial experimental design. All data were checked for normality and homogeneity of variance assumptions before analysis. All analyses were carried out based on three independent replicates ($n=3$), and the results are presented as mean ± standard error. The obtained data were evaluated using analysis of variance (ANOVA), and differences between means were tested at a significance level of $p < 0.05$. Where significant differences were identified, means were grouped using multiple comparison tests, and results were expressed in tables and figures using letter groups. All statistical analyses were based on mean values obtained from three replicates for each treatment and sampling time. Pearson correlation analysis was performed to reveal the relationships between quality parameters and biochemical compounds. Additionally, Principal Component Analysis (PCA) was applied to holistically evaluate the overall effects of different applications and to visualize the relationships between numerous variables. All statistical analyses were performed using the SAS software package.

Results and discussion

Weight loss

Weight loss in strawberry tree fruits increased steadily throughout the storage period ($p \leq 0.001$). The average weight loss was reached 2.09% on day 5, 4.00% on day 10, and 5.13% on day 15. These results reveal that storage time has a strong and consistent effect on weight loss. The effect of the treatment became more pronounced as the storage time increased, and the interaction between treatment and storage time was found to be statistically highly significant ($p \leq 0.001$). On the day 15, the weight

loss reached 2.97% in the control fruits, compared with 2.46% under the Put 1 mM, 1.80% under the MAP, and 1.14% in the Put + MAP treatment. This indicates that Put + MAP treatment reduced weight loss by 61.6% compared to the control. The differences between the treatments were already pronounced by day 10 when weight loss increased to 4.90% in the control, while Put 1 mM was 4.27%, MAP 3.90%, and Put + MAP 2.93%. Notably, the incremental weight loss between day 5 and day 10 was observed to be lowest in the Put + MAP application. Overall, as storage duration increased, the differences

between treatments strengthened, and the Put + MAP combination consistently showing the most effective in minimizing weight loss (Fig. 1 and Supplementary Table 1). Weight loss observed in fruits during storage is primarily a natural consequence of ongoing transpiration and respiration activities. This loss is known to be related to water evaporation and carbon loss during respiration, and increases with increasing storage time [22]. In this study, the significant reduction in weight loss, particularly in the early stages, due to MAP application can be explained by the regulation of the in-package

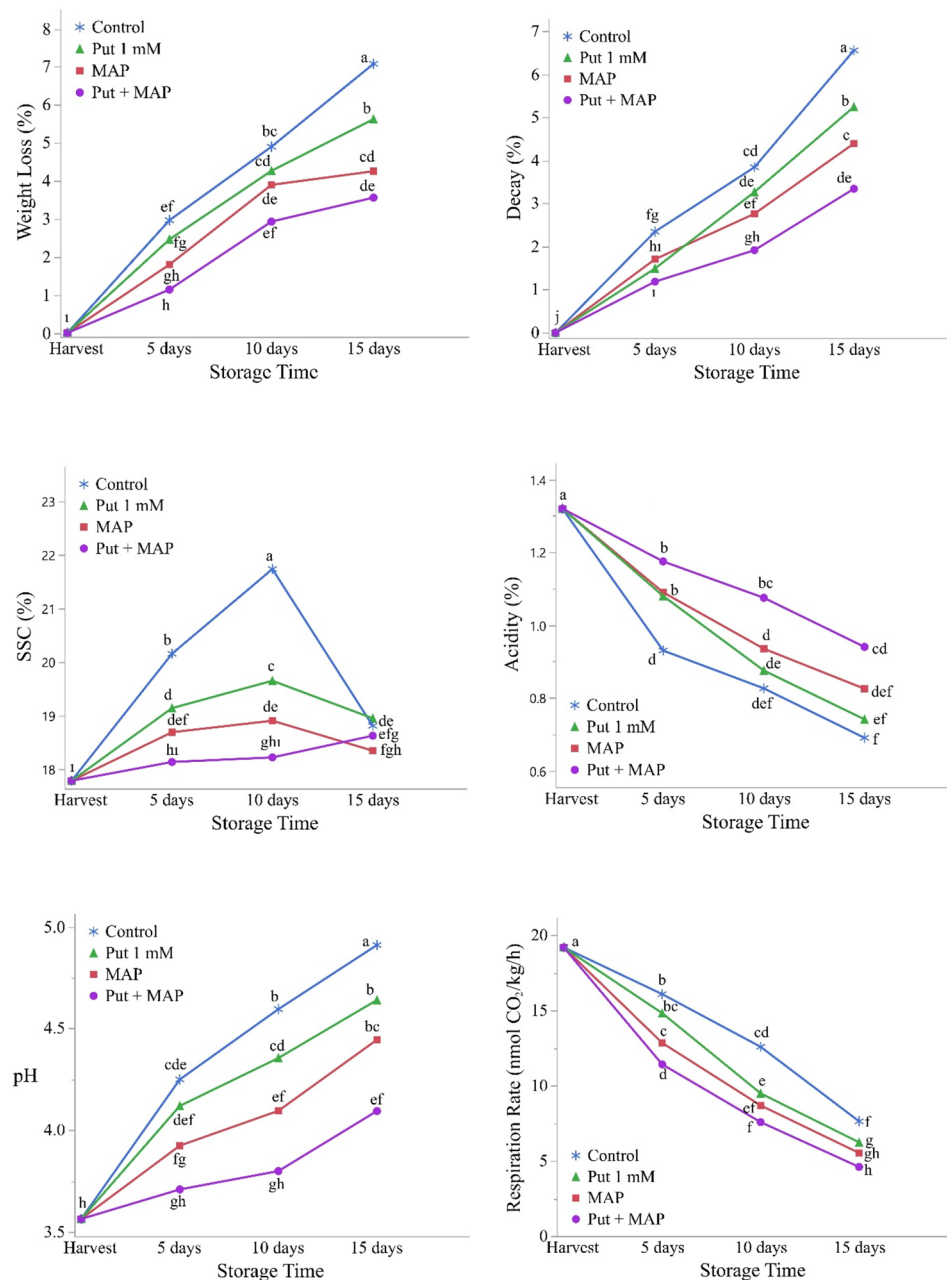


Fig. 1 Effect of putrescine and MAP application on changes in fruit quality characteristics during storage. Different letters on top of the storage periods indicate significant differences at $p \leq 0.05$

atmosphere, the decrease in respiration rate, and the increase in relative humidity. Indeed, it has been stated in the literature that the low O₂ and high CO₂ environment created under MAP conditions suppresses respiration and slows transpiration by reducing the surface water vapor gradient [23, 24]. The reduction in weight loss by putrescine application alone compared to the control group is related to the cell wall and membrane stability-enhancing effect of polyamines. These compounds are known to reduce tissue permeability and limit water loss by forming ionic bonds with pectic substances [25–29]. However, the fact that this effect is more limited compared to MAP is due to putrescine acting more through intracellular mechanisms. The lowest weight loss was observed in the Put + MAP combination, indicating that these two applications act through different but complementary mechanisms. While MAP suppresses respiration and transpiration by regulating environmental conditions, putrescine strengthens the cell structure, making water loss more difficult. This synergistic effect has been similarly reported in different fruit types [30–33]. Furthermore, the low rate of increase in weight loss in the Put + MAP application shows that this combination controls not only the total loss but also the rate of loss. When evaluated together with the simultaneous decrease in respiratory rate, this reveals that metabolic activity is sustainably slowed down. Indeed, it is known that the decrease in respiratory rate is one of the fundamental mechanisms in limiting weight loss [34, 35].

Decay rate

As storage time progressed, the rate of decay in strawberry tree fruits showed a consistent and statistically significant increase in all treatments ($p \leq 0.001$). The average decay rate was 1.68% on day 5, 2.95% on day 10, and 4.88% on day 15. This trend indicates that prolonged storage leads to physiological weakening of fruit tissues making them more susceptible to microbial spoilage. The interaction between treatment and storage time was found to be significant in terms of decay rate ($p \leq 0.001$), and it was determined that the effectiveness of the treatments became more pronounced, especially in the mid and late stages of storage. Decay rate increased with storage time in all treatments, with the highest values consistently observed in the control group. On day 10, decay reached 3.84% in control fruits, while lower values were recorded in Put 1 mM (3.27%), MAP (2.76%), and Put + MAP (1.92%) treatments. By the end of storage (day 15), decay further increased to 6.55% in the control, whereas it remained lower in Put 1 mM (5.24%), MAP (4.39%), and was minimized in the Put + MAP treatment (3.34%). Overall, the Put + MAP combination consistently resulted in the lowest decay rates throughout the storage period. (Fig. 1 and Supplementary Table 1). Decay

rate increased during storage due to the progressive weakening of tissue integrity and defense mechanisms in postharvest fruits, with mid-to-late storage stages being particularly critical [12, 36]. The marked increase observed between days 10–15 indicates a threshold period for strawberry tree fruit preservation. MAP effectively reduced decay by suppressing microbial activity under low O₂ and high CO₂ conditions [37], while putrescine contributed by stabilizing cell membranes and delaying cell wall degradation [29, 38, 39]. However, the stronger effect of MAP suggests that environmental conditions play a key role in decay development. The lowest decay levels observed in the Put + MAP treatment confirm a synergistic effect, where both external (atmospheric regulation) and internal (cellular stabilization) defense mechanisms are enhanced. Similar results have been reported in various fruit species [30, 32, 33]. The lower decay rate in Put + MAP (3.34%) compared to control (6.55%) at the end of storage further indicates that this combination not only delays decay but also slows its progression, consistent with the close relationship between respiration, water loss, and microbial deterioration [25, 40].

SSC, TA and pH

The significant changes in SSC, TA, and pH values were observed in strawberry tree fruits during storage; these changes were found to be statistically highly significant in terms of both storage time and the treatment $\times$ storage time interaction ($p \leq 0.001$). The average SSC value was 17.79% at harvest, rising to 19.03% on day 5 and 19.63% on day 10, before showing a slight decrease to 18.68% on day 15. In this study, statistically significant differences were found between the control group and the other treatments in terms of dissolved solids (SSC) increase ($F = 83.82$, $p \leq 0.001$). In particular, the fact that the SSC reached a high value of 21.74% on the 10th day in the control group indicates that the ripening process in these fruits has accelerated. In contrast, the SSC increase was more limited in the Put 1 mM and MAP treatments, and the most stable SSC change throughout storage was observed in the Put + MAP combination. The fact that SSC values remained within a narrow range during the Put + MAP application indicates that sudden and uncontrolled sugar accumulation was prevented. TA values decreased statistically significantly in all applications during the storage period ($p \leq 0.001$). The average TA was 1.32% at harvest, decreasing to 1.07% on day 5, 0.93% on day 10, and 0.80% on day 15. When evaluated on an application basis, it was determined that the TA in control fruits decreased to 0.69% on day 15, that Put 1 mM (0.74%) and MAP (0.83%) applications partially limited this loss, and that the highest TA value was maintained in the Put + MAP application (0.94%). In parallel with

this decrease in acidity, pH values increased during storage. The average pH was 3.57 at harvest, rising to 4.00 on day 5, 4.21 on day 10, and 4.52 on day 15. The fact that the pH reached 4.91 on the 15th day in control fruits, while it remained at 4.10 in the Put + MAP application, indicates that the applications significantly affected the intrafruit acid-base balance (Fig. 1 and Supplementary Table 1). SSC increased during storage, with the highest rise observed in control fruits, indicating accelerated ripening. In contrast, Put and MAP treatments limited this increase, while the Put + MAP combination maintained the most stable SSC, reflecting a more controlled ripening process. This trend is associated with respiration-driven sugar accumulation, which is more pronounced under high metabolic activity [12, 22, 41]. The suppression of SSC increase in treated fruits can be attributed to reduced respiration and slower carbohydrate metabolism under low O₂ conditions and polyamine regulation [25]. TA decreased significantly during storage ($p \leq 0.001$), primarily due to the utilization of organic acids in respiration. The decline was more pronounced in control fruits, consistent with higher respiration rates [24, 40], whereas Put and MAP treatments partially limited this loss, and the highest TA was maintained in the Put + MAP combination. Similar findings have been reported for MAP and polyamine applications in other fruits [31, 32]. In parallel, pH increased as acidity declined, with the highest value observed in control fruits, indicating greater metabolic degradation and spoilage risk. The lower pH increase in Put + MAP-treated fruits suggests better preservation of acid-base balance and overall physiological stability, which is critical for maintaining quality during storage [42, 43].

Respiration rate

During storage, the respiration rate of strawberry tree fruits decreased significantly in all treatments, and this decrease was found to be statistically highly significant in terms of both storage time and treatment $\times$ storage time interaction ($p \leq 0.001$). The average respiration rate was 19.21 nmol CO₂ kg⁻¹ h⁻¹ at harvest, decreasing to 13.80 on day 5, 9.59 on day 10, and 6.00 on day 15. When comparing the treatments, it was determined that the respiration rate remained highest in the control group throughout the entire storage period. On the 15th day, the respiration rate in control fruits was measured as 16.10 nmol CO₂ kg⁻¹ h⁻¹, while in the Put 1 mM application it was 14.83, in the MAP application it was 12.85, and in the Put + MAP combination it was 11.43 nmol CO₂ kg⁻¹ h⁻¹. On the 10th day, the differences between the treatments became even more pronounced; the respiratory rate was determined as 12.59 nmol CO₂ kg⁻¹ h⁻¹ in the control group, while it was measured as 9.50 in Put 1 mM, 8.69 in MAP, and 7.58 nmol CO₂ kg⁻¹ h⁻¹ in Put +

MAP. On the 15th day, the most advanced stage of storage, the respiratory rate decreased to 7.64 nmol CO₂ kg⁻¹ h⁻¹ in the control group, 6.24 in Put 1 mM, 5.53 in MAP, and 4.60 nmol CO₂ kg⁻¹ h⁻¹ in Put + MAP. The fact that the lowest respiratory rates were obtained with the Put + MAP application throughout the entire storage period reveals that this combination suppresses metabolic activity most effectively (Fig. 1 and Supplementary Table 1). The gradual decrease in respiration rate observed during storage is related to the natural slowing of metabolic activity in the fruit during the post-harvest period. However, the fact that respiration rates remained at higher levels in control fruits indicates that metabolic processes were suppressed later and physiological aging progressed more rapidly. Previous studies have clearly emphasized that respiration rate is one of the key determinants of post-harvest quality losses [17, 40, 44]. In this context, measuring higher respiration rates in control fruits physiologically explains the observed quality losses. The significant reduction in respiration rate caused by MAP application is directly related to the reduction of O₂ levels and the increase in CO₂ levels in the package atmosphere. It has been reported in different fruit species that under low O₂ conditions, the mitochondrial electron transport chain is suppressed, substrate oxidation is slowed, and thus the respiration rate is reduced [45]. This mechanism explains the lower respiratory rates obtained in the MAP application compared to the control group. The reduction in respiration rate caused by putrescine application compared to the control group is attributed to the regulatory effect of polyamines on ethylene biosynthesis and respiration-related enzymes. Putrescine has been reported to suppress ACC synthase and ACC oxidase activities by competing with S-adenosyl methionine, an ethylene precursor; this, in turn, limits ethylene production and the associated increase in respiration. However, the fact that putrescine alone does not provide as strong suppression as MAP indicates that limiting gas exchange plays a critical role in respiratory control. The fact that the lowest respiration rates were obtained with the Put + MAP combination reveals that the two applications exhibit synergistic effects through different but complementary mechanisms. When MAP's ability to regulate environmental conditions and limit gas exchange is considered together with Putrescine's ability to stabilize intracellular metabolic processes, it is understood that the respiration capacity of the fruit is suppressed earlier and more effectively. Similarly, previous studies have reported that combinations of MAP and polyamines reduce respiration rate more strongly than single applications in different fruit types such as pear, sweet cherry, fig, and strawberry [16, 31, 32]. In particular, the reduction in respiration rate to 4.60 nmol CO₂ kg⁻¹ h⁻¹ on day 15 with Put + MAP application demonstrates that this combination not only

produces a short-term effect but can maintain low metabolic activity until the end of storage.

Organic acids and vitamin C

During storage, then significant and statistically highly decrease occurred in the citric, malic, succinic, and oxalic acid contents of strawberry tree fruits ($p \leq 0.001$). According to the average values, citric acid decreased from 1.10 g/100 g at harvest to 0.85 g on day 5, 0.70 g on day 10, and 0.54 g on day 15. Malic acid content decreased from 1.80 to 1.48, 1.34, and 1.10 g/100 g during the same period. Similarly, succinic acid decreased from 0.76 to 0.41, and oxalic acid decreased from 0.70 to 0.27 g/100 g. When evaluated on an application basis, it was determined that organic acid losses occurred more rapidly in the control group, that MAP and Putrescine applications limited this loss, and that the highest acid preservation was achieved with the Put + MAP combination. The significantly higher levels of citric and malic acid in the Put + MAP treatment group compared to the control group on the 15th day indicate that this combination provides early metabolic slowing. The further pronounced difference on the 10th and 15th days reveals that the effect of the treatment strengthens with increasing storage time. The fact that malic acid content decreased to 0.80 g/100 g in the control group on day 15, while it was maintained at 1.38 g/100 g in the Put + MAP application, clearly supports this finding. Vitamin C content decreased statistically significantly

in all applications during storage ($p \leq 0.001$). The average vitamin C content was 61.75 mg/100 g at harvest, decreasing to 52.91 mg/100 g on day 5, 36.63 mg/100 g on day 10, and 32.68 mg/100 g on day 15. However, the significant differences were observed between the treatments. While vitamin C levels in control fruits decreased to 28.37 mg/100 g on the fifteenth day, the preservation of higher values in Put 1 mM, MAP, and especially Put + MAP applications indicates that the applications have a significant effect on ascorbic acid stability (Table 1). The sustained decrease in organic acids observed during storage is related to the use of these compounds as a carbon source in respiration during the post-harvest period. The rapid decrease in organic acids directly linked to the tricarboxylic acid cycle, particularly citric and malic acids, indicates that the metabolic activity of the fruit continues during storage and that the acid pool weakens in later stages. This trend is consistent with postharvest acid metabolism findings previously reported in *Arbutus unedo* and similar soft fruits [8, 46]. The faster depletion of organic acids in the control group is directly related to the higher respiration rate in these fruits. The literature emphasizes that with an increase in respiration rate, malic acid in particular is rapidly depleted, negatively affecting taste balance [44]. In this study, the decrease in malic acid to 0.80 g/100 g on day 15 in the control group clearly reflects this metabolic relationship. The limitation of organic acid loss by MAP application can be explained by the suppression of mitochondrial respiration under

Table 1 Influence of putrescine and MAP applications on the organic acid (g/100 g) and vitamin C (mg/100 g) contents of strawberry tree fruit during storage

Storage time		Citric	Malic	Succinic	Oxalic	Vitamin C
Harvest		1.10±0.08a	1.80±0.07a	0.76±0.04a	0.70±0.04a	61.75±1.37a
Day 5		0.85±1.14b	1.48±0.08ab	0.59±0.03b	0.51±0.03b	52.91±1.53b
Day 10		0.70±0.04c	1.34±0.06b	0.50±0.03c	0.39±0.04c	36.63±1.20c
Day 15		0.54±0.04d	1.10±0.09c	0.41±0.02d	0.27±0.04d	32.68±1.24d
Putrescine and Storage time interaction						
Harvest		1.11±0.08a	1.80±0.07a	0.76±0.04a	0.70±0.04a	61.75±1.37a
Day 5	Control	0.71±0.07def	1.18±0.06gh	0.50±0.03def	0.40±0.04cde	47.79±0.54e
	Put 1mM	0.79±0.06cde	1.41±0.05def	0.58±0.04bcd	0.48±0.04bc	50.58±1.25d
	MAP	0.92±0.04bc	1.59±0.04bc	0.63±0.03bc	0.53±0.03b	55.11±0.13c
	Put+MAP	1.02±0.04ab	1.74±0.06ab	0.67±0.03ab	0.63±0.03a	58.16±0.27b
Day 10	Control	0.56±0.03gh	1.13±0.04hi	0.39±0.04gh	0.26±0.04fg	32.29±0.93ij
	Put 1mM	0.66±0.03efg	1.31±0.06efg	0.46±0.04fg	0.35±0.02def	35.84±0.60gh
	MAP	0.75±0.03de	1.44±0.04cde	0.56±0.03cde	0.43±0.03bcd	37.67±1.26g
	Put+MAP	0.84±0.03cd	1.50±0.06cd	0.60±0.03bcd	0.52±0.04b	40.74±0.45f
Day 15	Control	0.45±0.03h	0.80±0.07j	0.34±0.04h	0.16±0.03h	28.37±0.71k
	Put 1mM	0.44±0.04h	0.98±0.04ij	0.39±0.03gh	0.19±0.03gh	31.36±0.62j
	MAP	0.58±0.03fgh	1.24±0.04fgh	0.42±0.02fgh	0.32±0.03ef	34.09±0.68hi
	Put+MAP	0.71±0.07def	1.38±0.09def	0.48±0.03efg	0.41±0.04cde	36.90±1.21g
ANOVA						
F (Storage time)		14.36***	7.71**	14.2***	12.47***	64.39***
F (Put × Storage time)		18.56***	24.19***	14.27***	23.51***	165.45***

Different letters in the same column indicates statistical differences at $p \leq 0.05$. ** and *** indicates $p \leq 0.01$ and $p \leq 0.001$

low O₂ and high CO₂ conditions, and consequently, the slowing of the TCA cycle. The reduced rate of organic acid utilization as respiration substrates under MAP conditions leads to longer-term preservation of acidity. This mechanism is consistent with MAP-induced acid preservation findings reported in different fruit species such as pear, fig, and cherry [45]. The protective effect of putrescine application on organic acids is related to the regulatory role of polyamines on mitochondrial metabolism, membrane integrity, and intracellular pH balance. Polyamines have been reported to slow enzymatic reactions, limit respiration-related organic acid uptake, and maintain metabolic balance in different fruit types [12]. The fact that this effect becomes more pronounced when applied in combination with MAP indicates that the Put + MAP combination provides metabolic slowing simultaneously at both the environmental and cellular levels. It is known that ascorbic acid can be rapidly degraded during storage due to oxidative stress, ascorbate oxidase activity, and respiration-related reactions. The rapid decrease in vitamin C in control fruits suggests that oxidative processes are more active. In contrast, it has been reported that in MAP treatment, low O₂ conditions limit the oxidative degradation of ascorbic acid; and that putrescine treatment enhances this effect by supporting antioxidant defense systems [29]. The maintenance of vitamin C levels at 36.90 mg/100 g on day 15 of the Put + MAP application demonstrates that this combination not only slows respiration but also effectively suppresses

oxidative stress. Similarly, the superior effect of MAP and polyamine combinations on vitamin C preservation has previously been reported in different fruit types such as plums, figs, and pomegranates [32, 33, 47].

Specific phenolic compounds

During storage, a statistically significant decrease occurred in all individual phenolic compounds examined in strawberry tree fruits, including gallic acid, catechin, quercetin, rutin, chlorogenic acid, ferulic acid, protocatechic acid, syringic acid, p-coumaric acid, and florizin ($p \leq 0.001$). According to average values, phenolic compounds, which were at high levels at harvest, decreased significantly on the 5th day of storage; this loss was observed to increase further on the 10th and 15th days. When the applications were compared, it was determined that the fastest decrease in phenolic compounds occurred in the control group; Put 1 mM and MAP applications partially limited this loss; and the highest phenolic preservation was achieved in the Put + MAP combination throughout the entire storage period. Specifically, the fact that gallic acid, catechin, rutin, and chlorogenic acid content was preserved at significantly higher levels on days 10 and 15 in the Put + MAP treatment compared to other treatments indicates that the combination has a strong effect on phenolic stability. The fact that gallic acid content remained at higher levels in the Put + MAP treatment group on day 15 of storage, despite a significant decrease in the control group, supports this

Table 2 Influence of putrescine and MAP applications on the phenolic compounds of strawberry tree fruit during storage (mg/100 g)

Storage time		Gallic	Quercetin	Catechin	Rutin	Ferulic
Harvest		7.68±0.11a	1.58±0.05a	4.86±0.07a	1.39±0.03a	0.92±0.02a
Day 5		5.87±0.19b	1.08±0.07b	4.07±0.10b	1.06±0.03b	0.72±0.04a
Day 10		5.33±0.34b	0.76±0.05c	3.29±0.07c	0.78±0.04c	0.49±0.04b
Day 15		4.16±0.33c	0.61±0.05c	2.94±0.08d	0.50±0.04d	0.36±0.05b
Putrescine and Storage time interaction						
Harvest		7.68±0.11a	1.58±0.05a	4.86±0.07a	1.39±0.03a	0.92±0.02a
Day 5	Control	5.25±0.13d	0.84±0.04d	3.75±0.04e	0.95±0.03de	0.59±0.04cde
	Put 1mM	5.62±0.17 cd	0.99±0.04c	3.94±0.05d	1.02±0.03 cd	0.66±0.03c
	MAP	6.22±0.23b	1.20±0.04b	4.19±0.03c	1.10±0.02bc	0.76±0.04b
	Put + MAP	6.41±0.17b	1.30±0.04b	4.43±0.04b	1.18±0.05b	0.87±0.04a
Day 10	Control	3.91±0.36f	0.61±0.03ef	3.06±0.05hi	0.64±0.04i	0.36±0.03 fg
	Put 1mM	5.36±0.13d	0.69±0.03e	3.22±0.06gh	0.75±0.03gh	0.42±0.02f
	MAP	5.91±0.11bc	0.82±0.03d	3.36±0.03 fg	0.82±0.02 fg	0.54±0.03e
	Put + MAP	6.13±0.12b	0.93±0.03 cd	3.51±0.04f	0.92±0.03ef	0.64±0.03 cd
Day 15	Control	3.14±0.12 g	0.45±0.03 g	2.67±0.06j	0.41±0.03j	0.19±0.04 h
	Put 1mM	3.57±0.08 fg	0.53±0.03 fg	2.81±0.05j	0.44±0.03j	0.30±0.02 g
	MAP	4.63±0.14e	0.63±0.03ef	3.05±0.05i	0.50±0.05j	0.42±0.03f
	Put + MAP	5.30±0.05d	0.82±0.06d	3.22±0.07 g	0.67±0.04hi	0.55±0.04de
ANOVA						
F (Storage time)		12.52***	26.13***	56.81***	56.17***	17.1***
F (Put × Storage time)		58.57***	77.14***	152***	78.24***	44.11***

Different letters in the same column indicates statistical differences at $p \leq 0.05$. *** indicates $p \leq 0.001$

Table 3 Continuation of Table 3 (mg/100 g)

Storage time		Chlorogenic	Protocatechuic	Syringic	<i>p</i> -Coumaric	Phloridzin
Harvest		3.08 ± 0.10a	1.83 ± 0.05a	0.95 ± 0.03a	0.81 ± 0.05a	0.70 ± 0.02a
Day 5		2.49 ± 0.04b	1.36 ± 0.05b	0.71 ± 0.03b	0.60 ± 0.03b	0.46 ± 0.03b
Day 10		2.03 ± 0.06c	0.99 ± 0.06c	0.37 ± 0.04c	0.31 ± 0.03c	0.36 ± 0.02c
Day 15		1.57 ± 0.06d	0.68 ± 0.09d	0.28 ± 0.04c	0.23 ± 0.03c	0.33 ± 0.03c
Putrescine and Storage time interaction						
Harvest		3.08 ± 0.10a	1.83 ± 0.05a	0.95 ± 0.03a	0.81 ± 0.05a	0.70 ± 0.02a
Day 5	Control	2.36 ± 0.08d	1.18 ± 0.05de	0.63 ± 0.04c	0.54 ± 0.04d	0.37 ± 0.03efg
	Put 1mM	2.43 ± 0.03 cd	1.30 ± 0.05c	0.65 ± 0.03c	0.55 ± 0.03 cd	0.40 ± 0.01de
	MAP	2.54 ± 0.04bc	1.46 ± 0.03b	0.75 ± 0.03b	0.63 ± 0.02bc	0.51 ± 0.02c
	Put + MAP	2.63 ± 0.04b	1.49 ± 0.02b	0.83 ± 0.03b	0.68 ± 0.05b	0.58 ± 0.01b
Day 10	Control	1.83 ± 0.05f	0.78 ± 0.04 fg	0.24 ± 0.03 fg	0.21 ± 0.04hij	0.31 ± 0.02ij
	Put 1mM	1.95 ± 0.03ef	0.89 ± 0.04f	0.30 ± 0.03f	0.27 ± 0.01gh	0.34 ± 0.01hi
	MAP	2.05 ± 0.05e	1.08 ± 0.04de	0.40 ± 0.02e	0.34 ± 0.02 fg	0.36 ± 0.03fgh
	Put + MAP	2.27 ± 0.06d	1.20 ± 0.03 cd	0.52 ± 0.03d	0.43 ± 0.03e	0.43 ± 0.01d
Day 15	Control	1.40 ± 0.05 g	0.44 ± 0.04 h	0.15 ± 0.02 h	0.15 ± 0.01j	0.30 ± 0.02j
	Put 1mM	1.51 ± 0.02 g	0.53 ± 0.03 h	0.20 ± 0.02gh	0.17 ± 0.02ij	0.30 ± 0.02j
	MAP	1.55 ± 0.05 g	0.68 ± 0.04 g	0.31 ± 0.03f	0.25 ± 0.01hi	0.34 ± 0.04ghi
	Put + MAP	1.83 ± 0.06f	1.06 ± 0.05e	0.45 ± 0.04de	0.36 ± 0.02ef	0.38 ± 0.01ef
ANOVA						
F (Storage time)		68.83***	27.37***	35.7***	43.63***	23.2***
F (Put × Storage time)		82.24***	99.66***	80.95***	54.12***	117.10***

Different letters in the same column indicates statistical differences at $p \leq 0.05$. *** indicates $p \leq 0.001$

finding (Tables 2 and 3). The observed decrease in phenolic compounds during storage is related to the acceleration of oxidative reactions and enzymatic degradation of phenolics in the post-harvest period. In particular, the increase in the activity of oxidative enzymes such as polyphenol oxidase (PPO) and peroxidase (POD) is known to accelerate the oxidation of phenolic compounds, leading to a decrease in the individual phenolic acid and flavonoid contents. This mechanism is consistent with findings previously reported in strawberry tree and other phenolic-rich soft fruits [8, 46]. The faster decrease in phenolic compounds in the control group can be explained by the higher respiration rate and oxidative stress levels in these fruits. The literature emphasizes that an increase in respiration rate promotes the formation of ROS, which in turn accelerates the oxidative degradation of phenolic compounds [44]. In this study, the higher respiration rate and phenolic loss in control fruits indicate that this mechanism also applies to strawberry tree. The effectiveness of MAP in protecting phenolic compounds is related to the fact that atmospheric conditions with low O_2 and high CO_2 suppress oxidative enzyme activities and reduce the rate of phenolic oxidation. The restriction of oxygen under MAP conditions reduces PPO activity, ensuring that phenolic compounds remain stable for longer periods. This effect has also been clearly demonstrated in studies conducted on different fruit types such as apples, pears, and strawberries [16, 43, 45]. The protective effect of putrescine application on phenolic compounds is explained by the stabilization of the cell

membrane by polyamines, the support of intracellular redox balance, and the indirect suppression of the activity of oxidative enzymes. Polyamines have been reported to be closely related to phenolic metabolism and to slow down the oxidative degradation of phenolics in different fruit types. However, the fact that putrescine alone does not show as strong an effect as MAP reveals the decisive role of oxygen presence in phenolic degradation. The fact that the highest phenolic protection is obtained with the Put + MAP combination clearly demonstrates that the two applications have a complementary and synergistic effect. While MAP application suppresses oxygen-based oxidative processes, Putrescine supports intracellular defense mechanisms and redox balance, ensuring the protection of phenolic compounds in a more stable environment. This synergistic effect has become particularly pronounced in compounds that make significant contributions to antioxidant capacity, such as gallic acid, catechin, and rutin.

Multivariate evaluation of fruit quality and biochemical responses to postharvest treatments

The multivariate analyses presented in Figs. 2, 3, 4 and 5 provide a holistic assessment of how Put, MAP, and combinations of these two applications regulate fruit quality, organic acid metabolism, and phenolic stability in strawberry tree fruits during storage. When these analyses are considered together, it is clearly demonstrated that post-harvest quality maintenance does not depend on a single

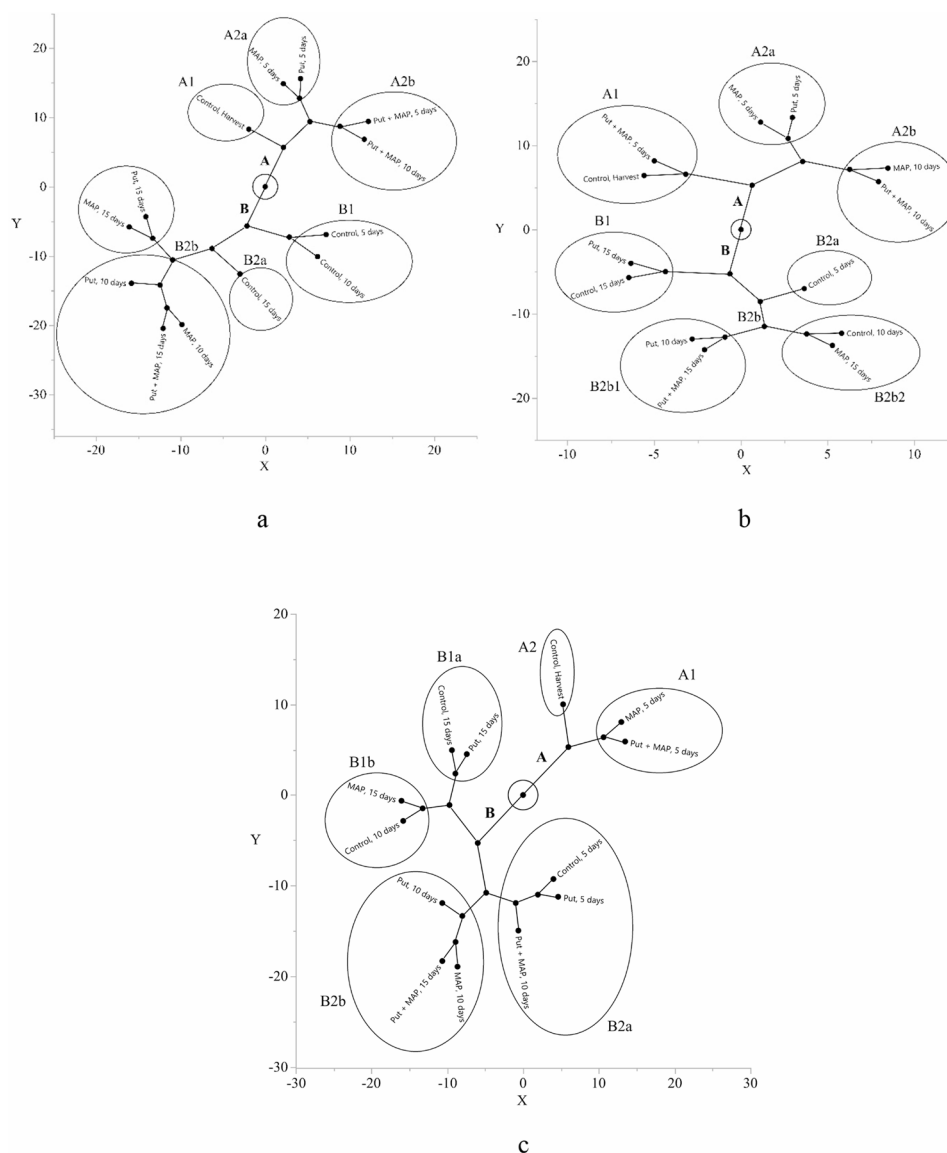


Fig. 2 Classification of applications in terms of fruit quality characteristics (a), organic acid content (b) and phenolic compound content (c)

parameter; rather, it is achieved through the coordinated regulation of physiological and biochemical processes.

The hierarchical classification given in Fig. 2 shows that the total effects of the treatments on fruit quality, organic acids, and phenolic compounds are distinctly differentiated. In terms of fruit quality characteristics (Fig. 2a), the control samples form a separate cluster characterized by high weight loss, increased respiration rate, and elevated decay rate. This clustering pattern indicates that metabolic activity accelerated and physiological aging progressed significantly in control fruits during storage. In contrast, while PUT and MAP applications were effective in limiting quality losses, they formed partially separated intermediate clusters, suggesting that both applications acted on quality improvement through different regulatory mechanisms. Remarkably, the Put + MAP

application demonstrated superior performance in simultaneously suppressing weight loss, respiration, and decay by forming the most compact and isolated cluster. This clear separation reveals the synergistic effect of MAP and the stabilization provided by putrescine at the cellular level. Classification of the treatments according to their organic acid content (Fig. 2b) further reinforced this interpretation. The clustering of control fruits in the region associated with the lowest levels of citric, malic, succinic, and oxalic acids indicates rapid depletion of respiratory substrates and intensification of tricarboxylic acid cycle activity. Put and MAP applications were associated with intermediate levels of organic acid content, but the Put + MAP combination was positioned near the highest organic acid values. This finding suggests that the combination application most effectively limits organic

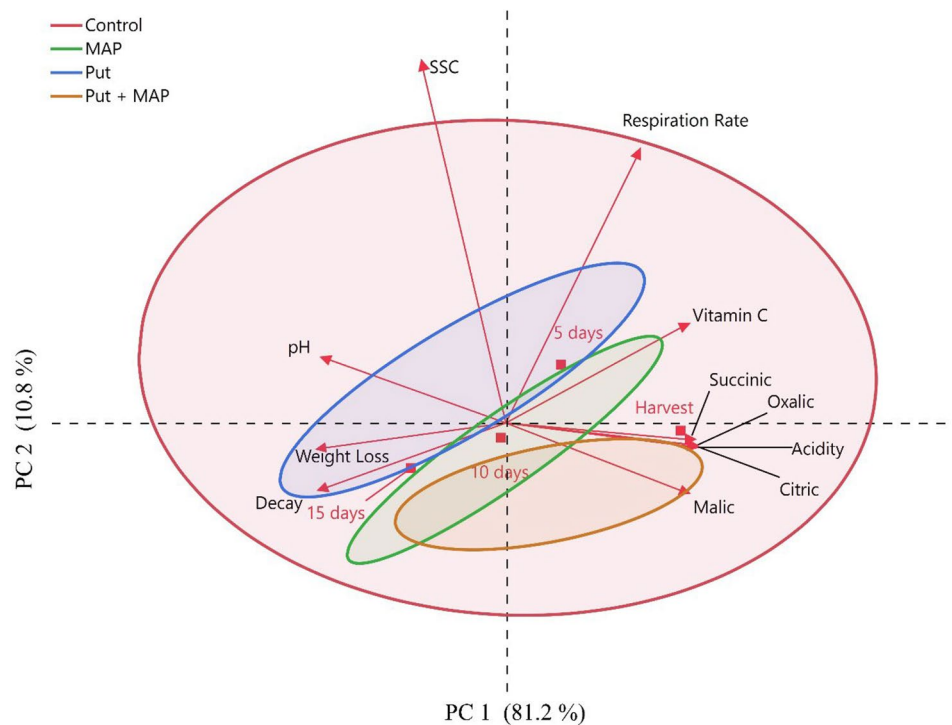


Fig. 3 Principal component analysis (PCA) of the response of organic acid and fruit quality characteristics to putrescine and MAP applications during storage

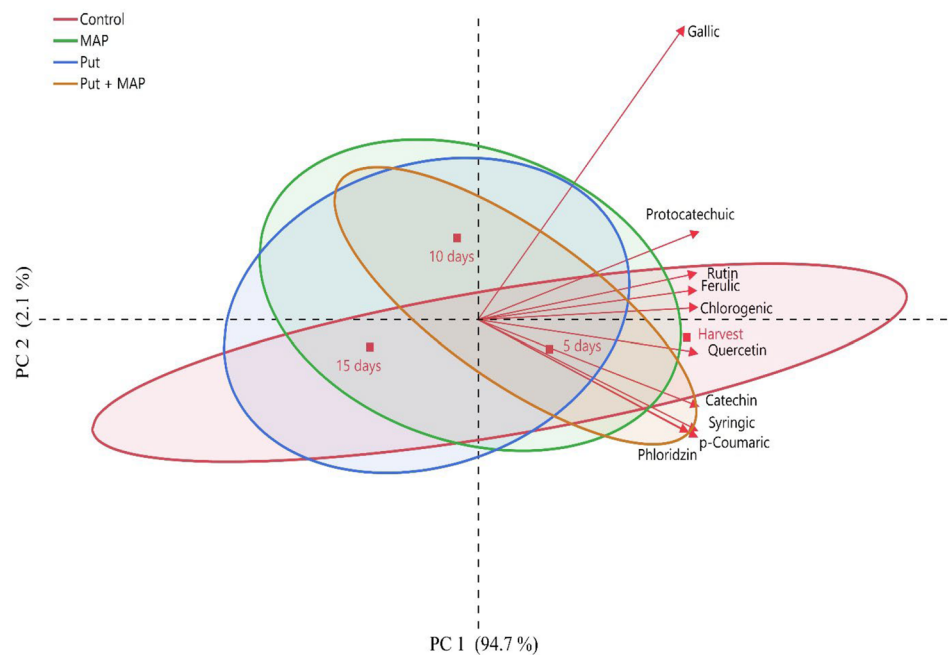


Fig. 4 Principal component analysis (PCA) of the response of phenolic compounds to putrescine and MAP applications during storage

acid catabolism and suppresses mitochondrial respiration more strongly compared to single applications.

Classification based on phenolic compounds (Fig. 2c) revealed the most significant difference in terms of biochemical stability. The weak association of control fruits

with phenolic compounds such as gallic acid, catechin, rutin, and chlorogenic acid indicates that oxidative degradation is more intense in this group. Put and MAP applications were in the intermediate position where phenolics were partially conserved, Put + MAP fruits

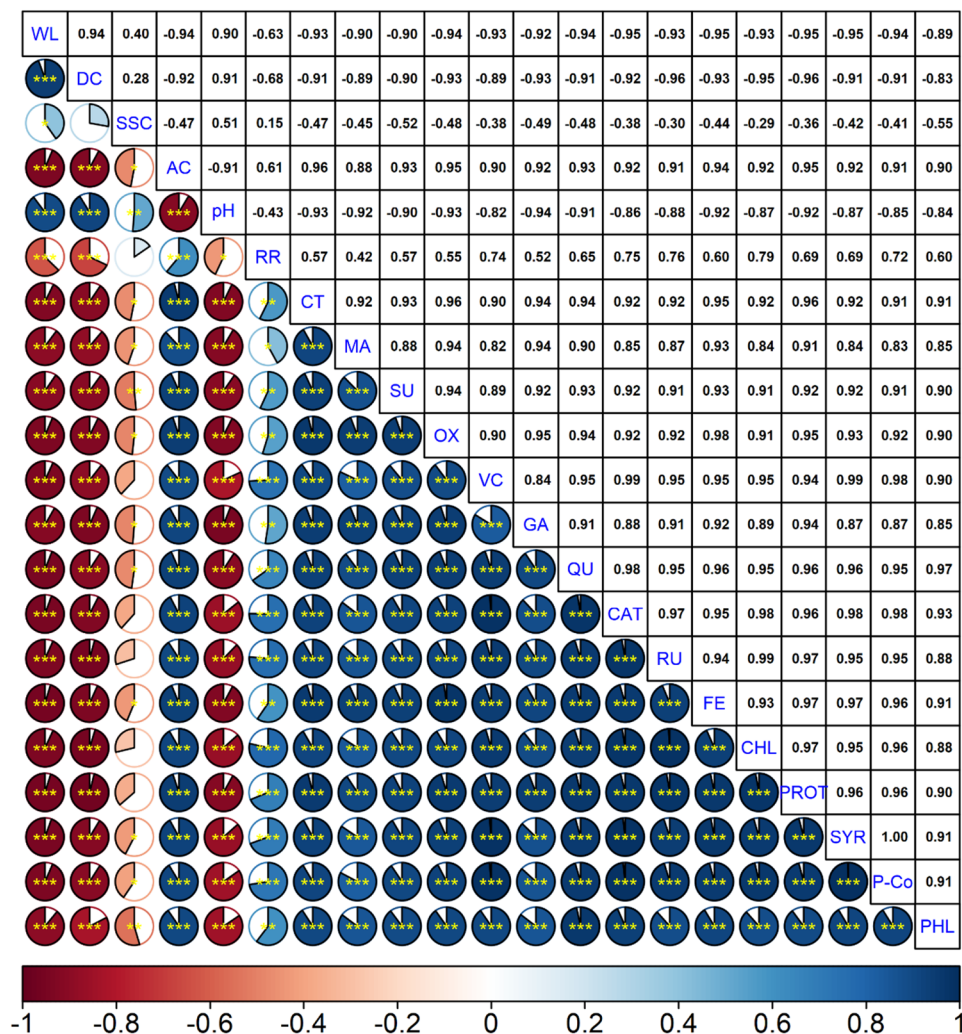


Fig. 5 The correlation between changes in fruit quality characteristics and biochemical properties depending on storage and treatment. The color scale that disappears from dark to light shows the correlation values between -1 and $+1$. *, **, and *** indicates significance at $p \leq 0.05$, $p \leq 0.01$, and $p \leq 0.001$, respectively. WL: weight loss, DC: decay, SSC: soluble solid content, AC: acidity, RR: respiration rate, CT: citric, MA: malic, SU: succinic, OX: oxalic, VC: vanillic, GA: gallic, QU: quercetin, CAT: catechin, RU: rutin, FE: ferulic, CHL: chlorogenic, PROT: protocatechuic, SYR: syringic, P-Co: p-Coumaric, PHL: phloridzin

clustered strongly in phenolic-rich regions. Considering the high susceptibility of phenolic compounds to oxidative enzymes such as polyphenol oxidase and peroxidase, this result suggests that the combination application significantly reduces oxidative stress and enzymatic degradation. PCA analysis (Fig. 3), which evaluates fruit quality characteristics together with organic acids, provides a mechanistic explanation for these results. The first principal component (PC1), which explains the majority of the variation, shows a strong positive correlation with organic acids and titratable acidity, representing a favorable biochemical-sensory profile. In contrast, the second principal component (PC2) is associated with indicators of quality loss such as weight loss, decay, and respiration rate. The concentration of control fruits along the PC2 axis confirms that these samples are characterized by increased metabolic activity and quality loss. Put and

MAP applications are located in intermediate positions, the strong overlap of Put+MAP application with PC1 indicates that the preservation of organic acids and the suppression of quality losses are achieved simultaneously. This balanced distribution reveals that the combination application provides the most effective coordination between metabolic slowing and quality preservation.

PCA analysis focusing on phenolic compounds (Fig. 4) also clearly confirms the superiority of the Put+MAP application. PC1, representing the general variation of phenolic compounds, shows strong loadings with compounds that contribute highly to antioxidant capacity, such as gallic acid, catechin, rutin, and chlorogenic acid. The negative orientation of the control fruits along this axis indicates significant phenolic depletion during storage. Put and MAP applications showed a moderate correlation, and the strong and positive orientation of the

Put + MAP application on PC1 clearly demonstrates that phenolic integrity is most effectively preserved with this application. This suggests that the combination application reduces the accumulation of ROS and suppresses oxidative enzyme activity.

The correlation matrix presented in Fig. 5 integrates the findings by quantitatively revealing the relationships between quality parameters and biochemical components. The strong negative correlations identified between weight loss, decay, and respiration rate and both organic acids and phenolic compounds indicate that increased respiration and water loss accelerate biochemical degradation. In contrast, the strong positive correlations between TA and individual organic acids confirm that TA is a reliable indicator reflecting acidic status. The positive correlation of phenolic compounds with both organic acids and acidity reveals the close interaction between primary and secondary metabolism. The fact that many relationships were found to be statistically significant at the $p \leq 0.01$ and $p \leq 0.001$ levels confirms that the observed patterns are physiologically significant and consistent. Overall, integrated multivariate analyses clearly demonstrate that the Put + MAP combination provides comprehensive superiority in terms of suppressing respiration, limiting water loss and decay, preserving organic acids, and stabilizing phenolic compounds. This coordinated arrangement explains the superior quality preservation observed in fruits treated with Put + MAP and supports the idea that the use of putrescine in conjunction with modified atmosphere packaging is a powerful and synergistic strategy for extending the post-harvest shelf life of strawberry tree fruit.

Conclusion

The results of this study demonstrated that the combined application of putrescine and MAP was highly effective in maintaining post-harvest quality and preserving biochemical properties of strawberry tree fruits during storage. This study clearly demonstrated that post-harvest quality losses in strawberry tree fruits are not dependent on a single physiological parameter; rather, respiration, water loss, organic acid metabolism, and phenolic stability must be regulated together and in coordination. While the use of putrescine and MAP applications alone partially limited quality losses, the Put + MAP combination created significant synergy in these processes. The combination application reduced weight loss and decay, suppressed respiration rate, and preserved organic acids (as quality-related metabolites) and bioactive compounds such as phenolics and flavonoids, thus more effectively maintaining the physiological and biochemical integrity of the fruit during storage. Multivariate statistical analyses clearly demonstrated that the Put + MAP application created the most balanced and stable profile between

quality parameters and biochemical components. These findings support the idea that the stabilization provided by putrescine at the cellular level, combined with the environmental regulatory effect of MAP, results in a more robust preservation strategy.

However, this study has some limitations. The experiment was conducted under controlled storage conditions and over a relatively short storage period, which may not fully reflect commercial supply chain conditions. In addition, only a single concentration of putrescine and a passive MAP system were evaluated, limiting the ability to compare different application doses and packaging configurations.

Future research should focus on evaluating different concentrations of putrescine, active MAP systems with controlled gas compositions, and longer storage durations under commercial conditions. Moreover, integrating molecular and enzymatic analyses could provide deeper insights into the mechanisms underlying the observed effects. Expanding this approach to other highly perishable fruit species would also help to validate its broader applicability.

In conclusion, the Put + MAP combination can be considered a viable, environmentally friendly, and effective post-harvest preservation method for extending the shelf life and increasing the fresh consumption potential of strawberry tree fruits. This approach is also thought to offer a promising alternative for other soft fruit species with similar physiological characteristics.

Abbreviations

h	Hour
min	Minute
pH	Power of hydrogen
SSC	Soluble solids content
TA	Titrateable acidity
Put	Putrescine
MAP	Modified atmosphere packaging

Supplementary Information

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Supplementary Material 1.

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Authors' contributions

M.G., G.Y. and A.M.Ç.: Conceptualization, methodology, software, formal analysis, investigation visualization, data curation. E.A. and M.G.: Validation, resources, software, writing-original draft preparation. All authors reviewed the manuscript.

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Data availability

Data will be available on request to corresponding authors.

Declarations

Ethics approval and consent to participate

Not applicable.

Consent for publication

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Competing interests

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Clinical Trial

Not applicable.

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