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Sustainable Bamboo-Based Packaging and Passive Modified Atmosphere: A Strategy to Preserve Strawberry Quality During Cold Storage

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Abstract

This study investigates the potential of bamboo-based sustainable packaging in combination with passive modified atmosphere (MA) and cold storage to enhance the shelf life of strawberries while preserving their physico-chemical properties, bioactive compounds, and antioxidant enzyme activity. The study monitored key parameters such as fruit weight loss, firmness, color, and the content of bioactive compounds as well as phenolics and flavonoids. Additionally, antioxidant enzyme activity, including catalase, ascorbate peroxidase, and superoxide dismutase, was assessed to evaluate oxidative stress during 9 days at 4 °C. The results show that strawberries packaged with bamboo materials in a passive MA retained their physico-chemical traits, exhibiting slower changes in firmness, color, and bioactive compound content compared to those in unpackaged samples. Furthermore, the antioxidant enzyme activity remained significantly higher, suggesting a lower oxidative stress in packaged fruit. This combination of bamboo-based packaging with passive MA is a valid, effective, and sustainable approach to prolonging the qualitative traits of strawberries during cold storage, offering both environmental and nutritional benefits.

Keywords: bamboo-based packaging; sustainability; shelf life; strawberry; qualitative traits



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1. Introduction

The strawberry is a widely cultivated berry in different countries around the world with global production at 8.9 million tons, led by China with 38% of the total [1]. The fruit is consumed due to its flavor, aroma, delicious taste, and nutritional value, being rich in sugars, organic acids, vitamins, and mineral elements. Furthermore, this red berry is a dietary source of bioactive compounds such as polyphenols, flavonoids, and anthocyanins with health-promoting effects and represents an important component of human diets [2–5]. In addition, fresh strawberries can be consumed in their processed forms such as wine, strawberry juice, jellies, canned fruit, and jam [6].

The strawberry is a non-climacteric fruit, but its high water content, softening, and respiration rate cause postharvest losses and waste throughout the supply chain due to

physical injuries, fungal spoilage, and off-flavor development, which can be more than 30% before reaching consumer tables [4,7].

The important attributes for fruit selection, such as freshness, firmness, size, color, and flavor, act as promoters of purchase and consumption intentions [8]. Furthermore, several studies have demonstrated that other factors as well as price, availability, packaging, convenience, and brand affect consumer food choices [9,10].

An important support for the delivery of highly perishable fruit is the cold chain combined with other postharvest strategies, which play positive roles in the preservation of food from field to table [11]. Additionally, packaging makes it possible to improve transfer along the supply chain to the consumer while ensuring fruit with a high-quality shelf life [12]. In recent years, some efforts have also been made to produce biodegradable packaging to decrease the environmental burden of the material's production and after-use disposal [13].

Converting agro-waste into sustainable packaging materials not only reduces its environmental impact but also supports the circular economy [14].

Several studies have focused on developing plant-based biodegradable packaging materials by utilizing natural waste to extract fibers, starch, and cellulose for the creation of environmentally friendly packaging solutions [14,15].

Bamboo is a rapidly renewable resource with a 3–4 year growth cycle, making it an attractive reinforcement for polymer composites. Its composition, primarily cellulose, hemicellulose, and lignin, accounts for over 95% of its mass, along with minor components like resins and waxes. Chemically similar to wood, bamboo contains higher levels of these minor compounds. However, most current research focuses on composites reinforced with short bamboo fibers; meanwhile, studies on the use of bamboo waste remain limited [16].

Regarding strawberry fruits, several studies on the development of environmentally sustainable and consumer-friendly postharvest treatments, such as salicylic acid treatment combined with blue light [6], chitosan-based coatings alone [17,18] or with the incorporation of functional compounds such as turmeric and green tea extracts [19], ascorbic acid [20] and cellulose plus oregano essential oil [21], and composite film packaging [22], have demonstrated that they can be used to maintain the fruit's quality during cold storage, minimizing the postharvest losses and extending the shelf-life of this fruit.

Modified atmosphere packaging (MAP) is a useful and cost-effective technology that can avoid anaerobiosis activities and prolong the shelf life of several commodities [23]. Several aspects such as food respiration and transpiration rates, environmental conditions (humidity and temperature), and package permeability influence the successful use of MAP systems [24]. The gas concentration inside MAP can be due to the product's physiological traits and film permeability (passive) or the previous injection of pre-set gas mixtures into the package (active) [25].

Several studies have demonstrated that modified atmosphere packaging (passive and active MAP) represents a valuable strategy that can reduce the respiration rate, slow down softening and color changes, maintain nutraceutical features, and extend the postharvest quality of strawberry fruit [26–28].

Few studies have evaluated the effectiveness of modified atmosphere packaging (MAP) combined with biodegradable trays for the preservation of whole or fresh-cut fruit.

The aim of this study was to assess the potential applications of bamboo-based sustainable packaging, combined with a passive modified atmosphere and cold storage, for the extension of the shelf life of strawberry fruit. Notably, this work presents, for the first time, the development and use of trays produced from bamboo processing waste, offering an innovative approach to biodegradable packaging. The study investigated the effects of this novel packaging system on the physico-chemical and nutraceutical properties of straw-

berries throughout storage. Furthermore, the impact on the fruit's antioxidant enzymatic system and the extent of oxidative damage during storage were also analyzed.

2. Materials and Methods

2.1. Fruit Sample and Experimental Design

Strawberry fruits (cv. Melissa) were randomly harvested during the commercial ripening stage and selected on the basis of the absence of physical defects and qualitative decay.

The trays were produced from waste generated during the processing of bamboo stems, which were dried, ground, and mixed with cellulose (23% *w/w*) and starch (2% *w/w*).

Afterward, the fruit were placed inside the trays made from bamboo waste (30 × 10 × 3 cm) and wrapped in a semipermeable film (SP) (Cryovac, Elmwood Park, NJ, USA) (polyolefines; 15 µm thickness; CO₂ transmission rate 41,000 cm³ m^{−2} day^{−1}; O₂ transmission rate 10,000 cm³ m^{−2} day^{−1} at 23 °C and 0% RH; moisture transmission vapor 25 g m^{−2} day^{−1} at 38 °C and 100% RH) (B-PMA) (Figure S1). Control (CTRL) samples were placed inside plastic containers (polyethylene terephthalate) without a semipermeable film. Three biological replicates containing eight fruits were realized per sampling date and stored for 9 days at 4 ± 1 °C and a 95 ± 0.5% relative humidity. Every three days, all analyses were performed in three technical replicates.

All reagents were analytical grade and purchased from Merck, Milan, Italy.

2.2. Physico-Chemical Traits

Fruit firmness was assessed with a digital penetrometer (TR-Turoni, Bologna, Italy) using a 5 mm diameter probe, applying measurements on two opposite sides of ten fruits. The results were recorded in Newtons (N). The total soluble solids (TSSs) and total acidity (TA) were analyzed from the extracted juice. TSS was determined with a digital refractometer (Sinergica Soluzioni, DBR35, Pescara, Italy), while TA was measured through acid–base titration, following the methodology described by Petriccione et al. [14]. The values were expressed in Brix for TSS and g of citric acid per liter of juice for TA, respectively. Fruit color was analyzed with a Minolta colorimeter (CR5, Minolta Camera Co., Tokyo, Japan), measuring chromaticity coordinates—L* (lightness), a* (green to red), and b* (blue to yellow)—on two opposite sides of 15 fruits for each packaging condition. The hue angle (H*) was derived from the a* and b* values, following the method reported by Adiletta et al. [29].

Weight loss was monitored at each sampling point and calculated as a percentage relative to the initial fruit weight.

2.3. Bioactive Compounds

Strawberry samples (1:5 *w/v*) were extracted using an 80% (*v/v*) methanol solution, following the approach outlined by Adiletta et al. [30]. The supernatant, obtained through centrifugation at 12,000 × *g* for 15 min at 4 °C, was collected for further analysis. The total phenolic content (TPC) in the strawberry extract was assessed using the Folin–Ciocalteu method, as described by Singleton & Rossi [31]. The results are reported as milligrams of gallic acid equivalents (GAEs) per 100 g of fresh weight (FW).

To determine the total monomeric anthocyanins (TACs) and total flavonoid content (TFC), the pH differential method and the aluminum chloride colorimetric method were applied, respectively, as described by Giusti & Wrolstad [32]. The findings are expressed in terms of cyanidin-3-glucoside equivalents (CGEs) per 100 g of FW and milligrams of catechin equivalents (CEs) per 100 g of FW.

The total antioxidant activity (AA) of the strawberry extracts was evaluated using the 1,1-diphenyl-2-picrylhydrazyl (DPPH) assay, following the procedure detailed

by Petriccione et al. [33]. The percentage reduction in DPPH concentration was recorded after 15 min of incubation. The results are expressed as μmol Trolox equivalents (TEs) per gram of FW, based on a standard curve.

2.4. Enzymatic Activity

Total soluble proteins were extracted from frozen fruit tissue powder in extraction buffer (1:5 *w/v*) as described by Petriccione et al. [17]. The resulting supernatant was used to determine the enzymatic activities of catalase, ascorbate peroxidase, and guaiacol peroxidase. The Bradford assay was used to assess the protein content in all samples [34]. Catalase (EC 1.11.1.6) (CAT) activity was evaluated according to Adiletta et al. [30]. The assay mixture (1.5 mL) contained potassium phosphate buffer 500 mM (pH 7.0), H_2O_2 88 mM, and 400 μL of crude enzyme extract. The specific activity was expressed as $\mu\text{mol H}_2\text{O}_2 \text{ g}^{-1}$ fresh weight (FW). Superoxide dismutase (EC 1.15.1.1) (SOD) activity was determined spectrophotometrically by measuring the inhibition of nitro blue tetrazolium (NBT) photoreduction using riboflavin. The reaction mixture included 50 mM potassium phosphate buffer (pH 7.8), 0.1 mM EDTA, 13 mM methionine, 75 mM NBT, 2 mM riboflavin, and 200 μL of crude enzyme extract. Samples were incubated at room temperature under continuous light, and absorbance was read at 560 nm. One unit of SOD activity corresponded to a 50% inhibition of NBT reduction. The results are expressed as units per gram of fresh weight (FW) [35]. Ascorbate peroxidase (EC 1.11.1.11) (APX) activity was evaluated at 290 nm as suggested by Pasquariello et al. [35]. The reaction mixture (1.5 mL final volume) contained potassium phosphate buffer 500 mM (pH 7.0), ascorbic acid 5 mM, H_2O_2 88 mM, sodium EDTA 10 mM (pH 7.0), and 50 μL of crude enzyme extract. The specific activity was expressed as $\mu\text{mol ascorbate g}^{-1}$ FW. Guaiacol peroxidase (EC 1.11.1.7) (GPX) activity was assayed according to Pasquariello et al. [35]. The reaction mixture contained potassium phosphate buffer 500 mM (pH 7.0), sodium-EDTA 10 mM (pH 7.0), H_2O_2 88 mM, guaiacol 32 mM, and 350 μL of crude enzyme extract in a final volume of 1.0 mL. The specific enzyme activity was expressed as $\mu\text{mol tetraguaiacol g}^{-1}$ FW.

2.5. Polyphenoloxidase and Lipoxxygenase Activity and MDA Content

Polyphenoloxidase activity (PPO) was determined following the extraction and assay described by Pasquariello et al. [35] and the absorbance of the reaction mixture was monitored at 398 nm. The specific activity is expressed as $\mu\text{mol catechol g}^{-1}$ FW. Lipoxxygenase (LOX) activity was quantified according to the method and the assay described by Pasquariello et al. [35]. LOX activity was monitored at 234 nm and the results are expressed as $\text{nmol hydroperoxides g}^{-1}$ FW.

The malondialdehyde (MDA) content was evaluated according to the extraction and the assay as suggested by Pasquariello et al. [35] using three wavelengths (432, 532, and 600 nm) for spectrophotometric determination. The MDA content was calculated according to Bao et al. [36] and is expressed as $\mu\text{mol 100 g}^{-1}$ FW.

2.6. Statistical Analyses

All experimental data are reported as the mean $\pm$ standard deviation. The significant differences ($p < 0.05$) between packaged and unpackaged strawberry fruit, were evaluated by one-way ANOVA and Tukey test for mean comparisons ($p < 0.05$). Principal component analysis (PCA) was applied to simplify complex data by transforming it into a set of principal components that describe the relationship between the physico-chemical, nutraceutical, and enzymatic traits. SPSS v. 20.0 software (IBM Corporation, Armonk, NY, USA) was used to carry out the statistical analyses.

3. Results

3.1. Effect of Packaging and MAP on Strawberry Physicochemical Features

The physico-chemical traits evaluated in the CTRL and B_PMA strawberry samples during 9 d of cold storage are reported in Table 1. Weight loss showed a significant increase throughout the storage period with significantly lower values in the B_PMA samples, reaching at the 9th day a loss of 4.16% and 37.26% in the B_PMA and CTRL strawberries, respectively (Figure 1). The packaging system preserved the moisture and firmness of the fruit compared to the unpackaged sample. A firmness and moisture reduction of 39.1% and 19.3%, respectively, was recorded after 9 d of storage for the CTRL strawberries.

The TSS increased during storage in the CTRL samples, while no statistical differences in sampling days in the B-PMA samples were registered. The TA content decreased during storage in the CTRL samples, whereas it remained stable in the B-PMA strawberries.

The L^* and hue angle in the CTRL strawberries showed a rapid decrease from 30.94 ± 2.33 to 24.00 ± 1.24 and from 33.78 ± 0.29 to 26.09 ± 2.30 at the end of the storage period, respectively. In contrast, the B-PMA strawberries retained their initial colorimetric parameters.

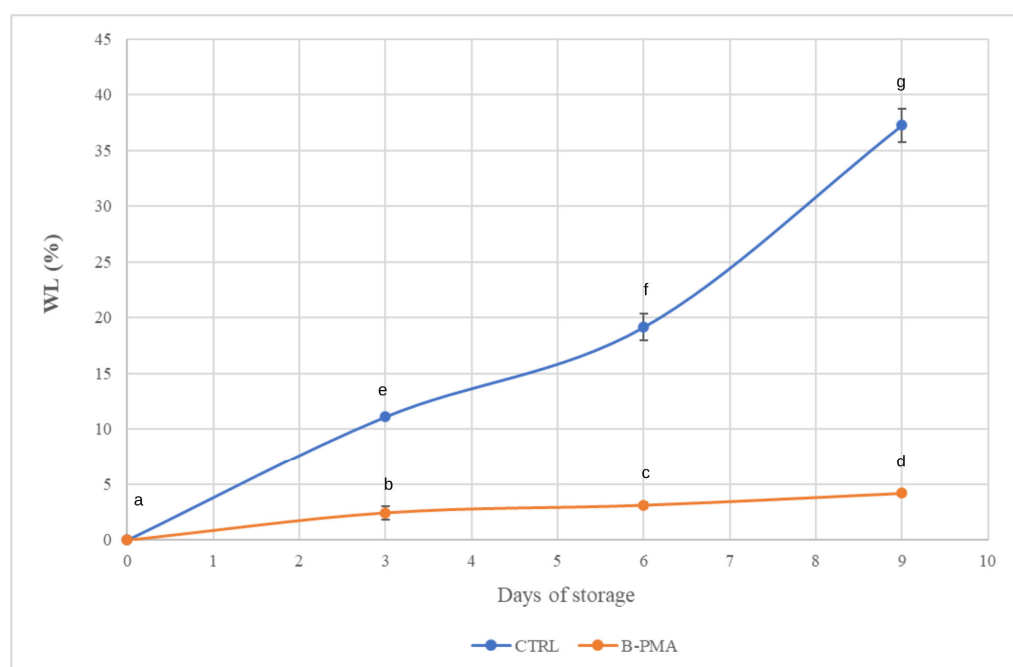


Figure 1. Weight loss (WL) (%) in packaged (B-PMA) and unpackaged (CTRL) strawberries after 9 days of cold storage at 4 °C. The data are expressed as mean $\pm$ sd and different letters indicate significant differences between samples (Tukey test; $p < 0.05$).

Table 1. Physico-chemical traits (firmness (N), total soluble solids (TSS; ° Brix), titratable acidity (TA; g citric acid per juice liter), lightness (L*), and hue angle (H)) evaluated in the CTRL and B-PMA strawberry samples during 9 d of cold storage. The data are expressed as mean ± sd and values followed by different letters in the same column are significantly different from each other (Tukey test; $p < 0.05$).

Samples	Days	Firmness (N)	TSS (° Brix)	TA (G Citric Acid per Juice Liter)	L*	H
CTRL	0	5.14 ± 0.61 ^c	7.03 ± 0.21 ^a	5.56 ± 0.02 ^c	30.94 ± 2.33 ^c	33.78 ± 0.29 ^d
	3	4.65 ± 0.09 ^{bc}	7.47 ± 0.15 ^a	4.63 ± 0.05 ^b	25.14 ± 1.66 ^{ab}	30.19 ± 2.62 ^{bc}
	6	3.65 ± 0.14 ^{ab}	8.10 ± 0.20 ^b	4.45 ± 0.18 ^{ab}	26.12 ± 1.64 ^{ab}	29.60 ± 2.07 ^b
	9	3.13 ± 0.10 ^a	11.77 ± 0.20 ^c	4.36 ± 0.05 ^a	24.00 ± 1.24 ^a	26.09 ± 2.30 ^a
B-PMA	0	5.14 ± 0.61 ^c	7.03 ± 0.21 ^a	5.56 ± 0.02 ^c	30.94 ± 2.33	33.78 ± 0.29 ^d
	3	5.24 ± 0.39 ^c	7.07 ± 0.11 ^a	5.54 ± 0.02 ^c	31.53 ± 1.50 ^c	33.96 ± 1.97 ^d
	6	5.56 ± 0.53 ^c	7.10 ± 0.10 ^a	5.60 ± 0.04 ^c	30.73 ± 2.27 ^c	32.18 ± 1.99 ^{bcd}
	9	5.33 ± 1.11 ^c	7.13 ± 0.15 ^a	5.51 ± 0.13 ^c	28.56 ± 2.36 ^{bc}	33.19 ± 1.92 ^{cd}

3.2. Influence of Packaging and MAP on Strawberry Bioactive Compounds

Bioactive compounds such as polyphenols, flavonoids, and anthocyanins, and antioxidant activity were measured in the strawberries to evaluate the influence of the packaging conditions. The current results reveal that bamboo-based sustainable packaging combined with MAP significantly increased polyphenol (Figure 2A), flavonoid (Figure 2B), and anthocyanin (Figure 2C) content in the strawberries during storage. The bioactive compounds of the strawberries were strongly affected by the packaging systems and storage time. An increment in polyphenol and flavonoid content was found until 6 d of storage followed by a slight decrease at the end of the experiment. Comparing both storage conditions, B-PMA showed a higher content of these bioactive compounds for all storage durations (Figure 2A,B). No significant differences in anthocyanin content were observed in the B-PMA samples, whereas a significant decrease in the CTRL samples was registered from the first to the last day of storage (Figure 2C). Antioxidant activity displayed a similar behavior to polyphenol content; after 9 days of storage, the antioxidant activity of the CTRL strawberries was the lowest (2.86), compared to B-PMA ($p < 0.05$) (Figure 2D).

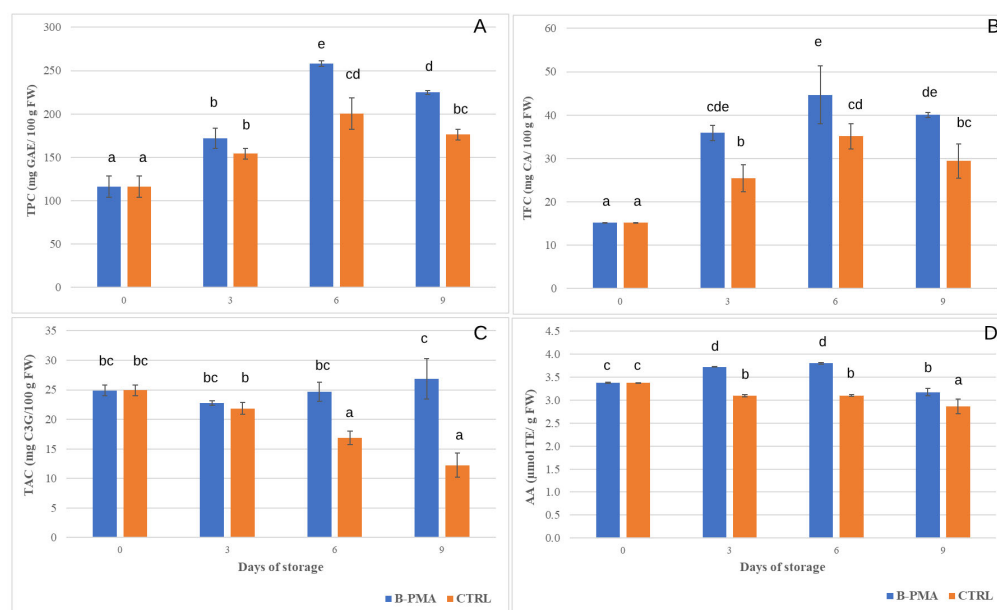


Figure 2. Total phenol content (TPC) ((A), mg GAE 100 g^{−1} FW), total flavonoid content (TFC) ((B), mg CE 100 g^{−1} FW), total anthocyanins content (TAC) ((C), mg C3G 100 g^{−1} FW), antioxidant activity (AA) ((D), μmol TE/g FW) in packaged (B-PMA) and unpackaged (CTRL) strawberries after 9 days of cold storage at 4 °C. The data are expressed as mean ± sd and different letters indicate significant differences between samples (Tukey test; $p < 0.05$).

3.3. Influence of Packaging and MAP on Antioxidant Enzymes and Membrane Damage

The activities of antioxidant enzymes, such as superoxide dismutase (SOD), catalase (CAT), and ascorbate peroxidase (APX), evaluated during storage in packaged and unpackaged strawberries, are shown in Table 2. SOD activity in both storage conditions showed an upward trend, with higher activity in the B-PMA fruit compared with the CTRL samples at each sampling (Table 2). CAT activity significantly decreased during storage, while an opposite trend in APX activity was observed. The B-PMA samples displayed higher CAT and APX activity with respect to the CTRL samples during the 9 days of cold storage (Table 2).

Table 2. Superoxide dismutase (SOD; U g^{−1} FW), catalase (CAT; μmol g^{−1} FW), and ascorbate peroxidase (APX; μmol g^{−1} FW) in packaged (B-PMA) and unpackaged (CTRL) strawberries after 9 days of cold storage at 4 °C. The data are expressed as mean ± sd and values followed by different letters in the same column are significantly different from each other (Tukey test; $p < 0.05$).

Samples	Days	SOD	CAT	APX
CTRL	0	0.45 ± 0.01 ^a	2.61 ± 0.06 ^e	0.18 ± 0.01 ^a
	3	0.46 ± 0.02 ^a	1.80 ± 0.07 ^c	0.22 ± 0.01 ^a
	6	0.57 ± 0.01 ^b	1.53 ± 0.04 ^b	0.23 ± 0.01 ^a
	9	0.66 ± 0.02 ^c	1.14 ± 0.10 ^a	0.25 ± 0.02 ^a
B-PMA	0	0.45 ± 0.01 ^a	2.61 ± 0.06 ^e	0.18 ± 0.01 ^a
	3	0.56 ± 0.02 ^b	2.47 ± 0.07 ^e	0.24 ± 0.02 ^a
	6	0.66 ± 0.02 ^c	2.23 ± 0.04 ^d	0.34 ± 0.02 ^b
	9	0.72 ± 0.01 ^d	2.06 ± 0.07 ^d	0.48 ± 0.01 ^c

In this study we observed a gradual increase in enzymatic browning and membrane damage until day 9 of cold storage. The packaging condition inhibited the increase in PPO and GPX activity compared to the CTRL samples, which showed an upward trend throughout cold storage (Figure 3).

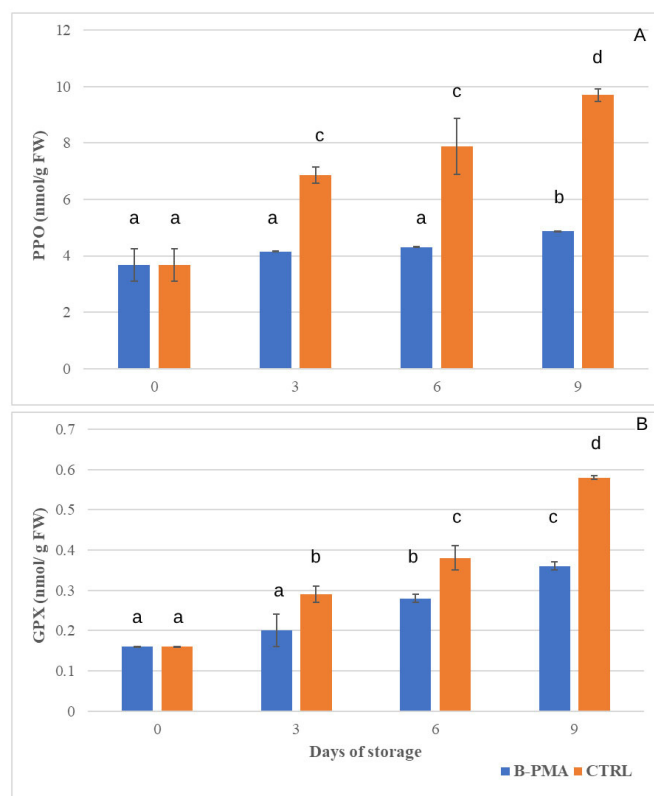


Figure 3. Polyphenol oxidase (PPO) ((A), $\text{nmol g}^{-1} \text{FW}$) and guaiacol peroxidase (GPX) ((B), $\text{nmol g}^{-1} \text{FW}$) activity in packaged (B-PMA) and unpackaged (CTRL) strawberries after 9 days of cold storage at 4 °C. The data are expressed as mean $\pm$ sd and different letters indicate significant differences between samples (Tukey test; $p < 0.05$).

Bamboo-based sustainable packaging combined with MAP significantly reduced membrane damage in strawberry fruit with a lower LOX activity (26.6%) and MDA content (35.8%) than in the CTRL samples at the end of storage (Figure 4A,B).

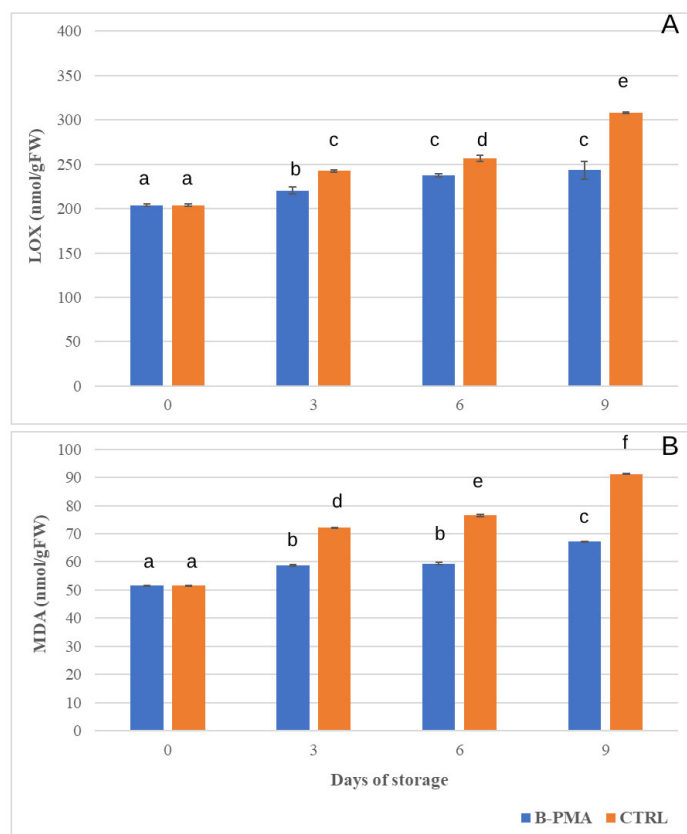


Figure 4. Lipoxigenase activity (LOX) ((A), $\text{nmol g}^{-1} \text{FW}$) and malondialdehyde content (MDA) ((B), $\text{nmol g}^{-1} \text{FW}$) in packaged (B-PMA) and unpackaged (CTRL) strawberries after 9 days of cold storage at 4 °C. The data are expressed as mean $\pm$ sd and different letters indicate significant differences between samples (Tukey test; $p < 0.05$).

3.4. Principal Component Analysis

All datasets obtained in this study underwent multivariate analysis to evaluate the effectiveness of the packaging conditions combined with MAP compared to unpacked samples of strawberries during 9 d of cold storage. PCA explained 81.99% of the total variance in the first two PCs (PC1 56.58% and PC2 25.41%). PC1 was positively correlated with L^* ($R^2 = 0.751$), hue angle ($R^2 = 0.778$), firmness ($R^2 = 0.903$), CAT ($R^2 = 0.980$), anthocyanin ($R^2 = 0.868$), and antioxidant activity ($R^2 = 0.798$), TA ($R^2 = 0.902$), while it was negatively correlated with TSS ($R^2 = -0.896$), GPX ($R^2 = -0.928$), PPO ($R^2 = -0.974$), LOX ($R^2 = -0.885$), and MDA ($R^2 = -0.987$). PC2 was positively correlated with weight loss ($R^2 = 0.866$), SOD ($R^2 = 0.884$), APX ($R^2 = 0.934$), POL ($R^2 = 0.903$), and FLAV ($R^2 = 0.851$). PCA showed significant variation in strawberries with different packaging systems. B-MPA induced significant differences during cold storage compared to the control samples in terms of physico-chemical, nutraceutical, and enzymatic traits (Figure 5). The packaged samples were characterized by different features with a shift along positive PC2 compared to the unpackaged ones, which showed a shift along negative PC1 during cold storage, highlighting the different effects on strawberries of the packaging conditions and the storage times.

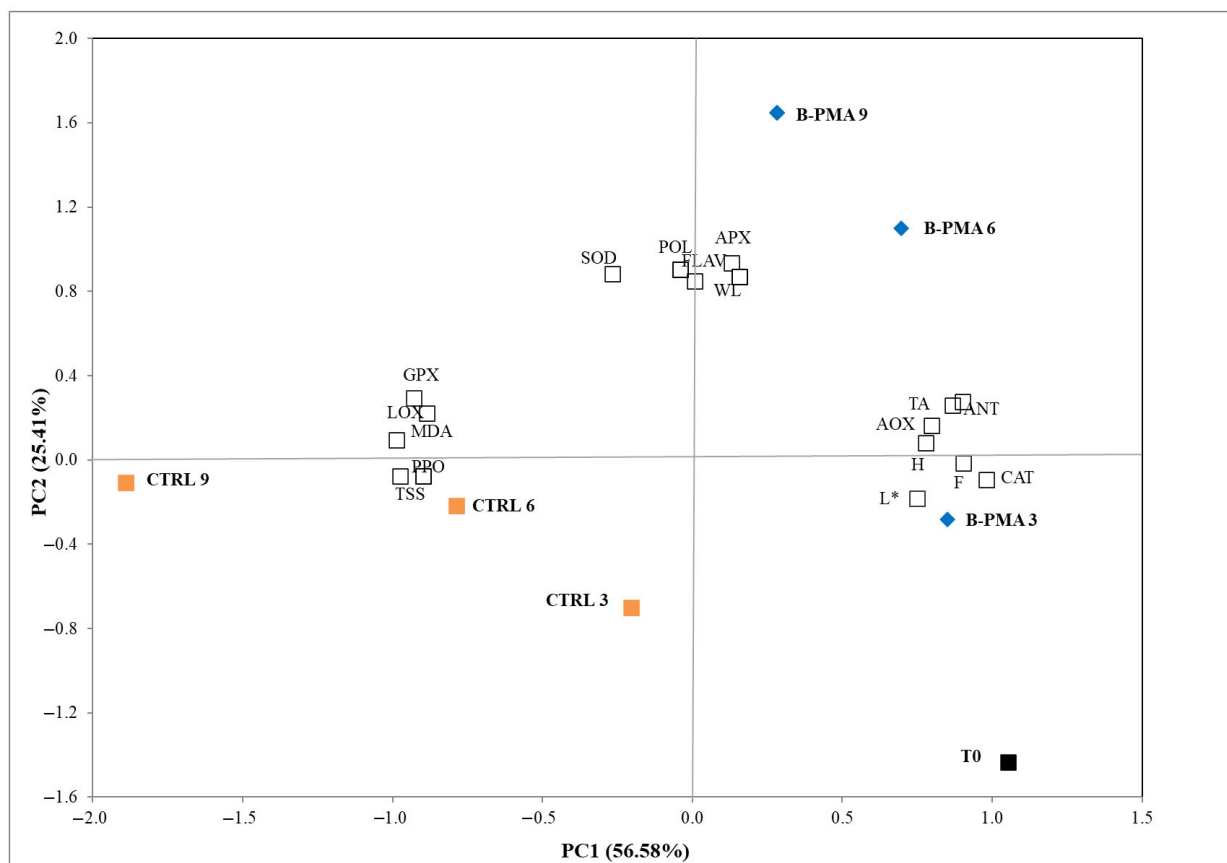


Figure 5. Principal component analysis of physico-chemical, qualitative, and enzymatic traits in packaged samples (B-PMA) and unpackaged (CTRL) strawberries after 0 (T0), 3 (3), 6 (6), and 9 (9) days of cold storage at $4^{\circ}\text{C} \pm 0.5$. Abbreviations: total soluble solids (TSSs), titratable acidity (TA); firmness (F), lightness (L), hue angle (H), weight loss (WL), total phenols (POLs); flavonoids (FLAVs); anthocyanin (ANT); antioxidant activity (AOX); superoxide dismutase (SOD); catalase (CAT); ascorbate peroxidase (APX); guaiacol peroxidase (GPX); polyphenoloxidase (PPO); malondialdehyde (MDA).

4. Discussion

Strawberries, with their delicate texture and vibrant flavor, are highly perishable fruits that require effective preservation technologies to maintain their quality from harvest to consumption [37,38]. Various innovative technologies have been developed to extend the shelf life, enhance the freshness, and preserve the nutritional attributes of strawberries [39]. Several studies have demonstrated that MAP involves modifying the composition of the air surrounding the strawberries to slow down the ripening process and inhibit microbial growth [26,40]. Packaging with controlled levels of oxygen and carbon dioxide helps maintain fruit color, firmness, and flavor in this fruit [39,41]. Passive MAP operates on the principle of gas permeability and selective barrier properties inherent in the packaging materials. These materials allow for a controlled exchange of gases between the internal and external environments, creating a modified atmosphere within the package [42].

The bamboo-based sustainable packaging combined with a passive modified atmosphere and cold storage as tested in this study made it possible to delay senescence and minimize physiological changes, offering a powerful tool in efforts to reduce food waste and meet consumer expectations for high-quality strawberries. In our study this method, which regulates the gaseous environment around the fruits, plays a pivotal role in minimizing weight loss and extending the shelf life of strawberries. Weight loss in stored strawberries is primarily attributed to the fruit's thin pellicle, which makes them more susceptible to rapid transpiration and respiration processes [40]. One of the key objectives

of MAP is to reduce the levels of oxygen around the fruits, slowing down respiration and the associated weight loss [43].

These findings are consistent with those reported by Korte et al. [44], who evaluated various bio-based and conventional packaging trays for their impact on quality loss in fresh cherry tomatoes. Their study highlighted that both the material and structural design of the packaging can significantly influence weight loss by regulating internal relative humidity.

Furthermore, various equilibrium-modified atmosphere packaging (EMAP) systems (cellulose trays with a cellulose film, polylactic acid (PLA) trays and film, and polyethylene terephthalate trays (PET) with a film of polypropylene (PP)) were effective at reducing weight loss in gooseberry fruit during storage [45].

Our results agreed with previous findings obtained by Afifi et al. [26], which highlighted that the MAP-based packaging of strawberries retained their weight compared to unpackaged samples, with a prominent reduction in weight loss. Lei et al. [46] observed a decrease in firmness in strawberries stored both in modified atmosphere packaging systems and without packaging. In our study, the weight loss was below the limit of marketability, which for soft fruit is 6% of the initial value of fresh weight, as reported by Paulsen et al. [41], underscoring the effectiveness of the packaging system in terms of mitigating weight loss during storage.

Consumer acceptance of fruit is often influenced by a combination of sensory attributes, including TSS and TA. These two parameters play significant roles in shaping the flavor profile of strawberries, and their balance is crucial for achieving a desirable taste that resonates with consumer preferences and gives the fruit its commercial value [38]. Total soluble solids (TSSs) refers to the sum of all sugars, organic acids, and other dissolved compounds in a solution that contribute to the taste and sensory attributes of the strawberry [47]. In our study, the smallest changes to TSS content were observed under passive MAP conditions, as reported by Pasha et al. [47].

The titratable acidity of fruits, a key parameter indicating the presence of organic acids, plays a crucial role in determining their flavor, freshness, and overall quality [41]. When integrated with MAP, a preservation technique that alters the gaseous environment around fruits, the management of titratable acidity becomes pivotal for maintaining optimal taste and extending shelf life. In our study the TA value of the modified atmosphere decreased significantly less than that of the control samples during cold storage, due to a slowdown in the respiration rate of the strawberries, as suggested by Paulsen et al. [41] and Pasha et al. [47].

Our results align with those of Baratter et al. [48], who reported a gradual decline in titratable acidity during strawberry storage, with higher acidity levels preserved in fruit stored in cassava starch-based biodegradable trays. This suggests that the packaging material may play a significant role in slowing metabolic changes associated with fruit senescence.

Firmness loss in fruits is often associated with increased respiration rates and ethylene production. MAP allows for the regulation of oxygen and carbon dioxide levels, slowing down respiration and mitigating the impact of ethylene on fruit softening [39]. Preserving fruit firmness is not only a technical consideration but also directly impacts consumer satisfaction. Firmness was negatively correlated with weight loss as reported by Pasha et al. [47], due to an increase in water transpiration. In addition, fruit softening is also caused by the degradation of cell wall polysaccharides during storage [11]. In this study firmness showed higher values in MAP-packaged strawberries than in the control samples, as has been reported in other studies [41,47], probably due to the packaged samples exhibiting the lowest weight loss under a modified atmosphere.

Firmness declined during storage, as also observed by Dladla et al. [49] in tomatoes stored in different packaging materials, including expandable polystyrene (EPS) and paper

trays covered with polyvinyl chloride (PVC) and flow wrap. They suggested that the type of packaging significantly influences texture changes over time.

The color of strawberries is a key quality attribute that reflects both ripeness and consumer appeal. BMAP effectively preserved the color of the strawberries throughout the storage period. These results are in agreement with Garavito et al. [45], who reported slower color changes in cape gooseberry fruits stored in different biodegradable equilibrium modified atmosphere packaging systems.

Strawberries are renowned not only for their sweet taste but also for their remarkable antioxidant activity [50]. Total phenolics, anthocyanins, and flavonoids are essential components of the plant's non-enzymatic antioxidant system, playing a crucial role in neutralizing free radicals as antioxidant molecules. [46]. Our findings on the trend in bioactive compound content are consistent with those of Lei et al. [46] in active equilibrium modified atmosphere-packaged strawberries. This significant increase in bioactive compound content may be attributed to the reduced oxidative stress due to MAP preservation [51]. Anthocyanin content was significantly higher in the B-MAP samples, which is consistent with findings by Esmaili et al. [52], who demonstrated similar results in strawberries packaged under modified atmosphere conditions using an *Aloe vera*-based coating and stored for 15 d at 4 °C. In this study, antioxidant activity followed a similar trend to polyphenol content, showing significant improvement in the B-MAP samples during cold storage. Antioxidant activity is closely linked to bioactive compound content and declined with changes in strawberry weight and quality [17,51].

MAP can influence the activity of antioxidant enzymes, which play a crucial role in protecting cells from oxidative stress. By altering oxygen and carbon dioxide levels, this technique can help preserve food quality, delay spoilage, and maintain enzymatic functionality [53,54]. Several antioxidant enzymes work synergistically to neutralize reactive oxygen species (ROS) and preserve cellular integrity in strawberry fruit. SOD is a pivotal enzyme that catalyzes the dismutation of superoxide radicals (O_2^-) into molecular oxygen (O_2) and hydrogen peroxide (H_2O_2), playing a crucial role in the first line of defense against oxidative stress in strawberries by eliminating superoxide radicals [55]. Catalase is responsible for breaking down hydrogen peroxide (H_2O_2) into water (H_2O) and molecular oxygen (O_2), preventing the accumulation of H_2O_2 , which can be harmful to cellular structures. APX is involved in the ascorbate–glutathione cycle, wherein it reduces hydrogen peroxide using ascorbate as the electron donor. This enzyme contributes to the detoxification of ROS, particularly within the chloroplasts and cytosol of strawberry cells [17]. MAP treatment efficiently maintained higher SOD, CAT, and APX activities, which play a crucial role in mitigating oxidative stress in strawberry fruits. Other studies have demonstrated that SOD, CAT, and APX activities were significantly higher in fruits stored under MAP conditions [30,56]

GPX utilizes reduced glutathione (GSH) to reduce hydrogen peroxide and lipid hydroperoxides, playing a key role in maintaining cellular redox balance in strawberries. Though not a direct antioxidant enzyme, PPO contributes to browning by oxidizing phenolic compounds, while POD catalyzes substrate oxidation using hydrogen peroxide [54]. In our study, GPX and PPO activities were significantly higher in the controls compared to MAP-stored strawberries, which is consistent with findings in litchi fruit as reported by Ali et al. [56]. The lower GPX and PPO enzyme activities may be attributed to the high CO_2 concentration within MAP films, which suppresses enzyme activity [57].

A lower level of LOX and MDA in MAP-stored samples displayed the maintenance of membrane integrity as demonstrated in strawberries stored with other postharvest treatments [17,58,59].

These results confirmed that the reduction in color changes is due to the preservation of cell compartmentalization and the separation of PPO and GPX enzymes from their phenolic substrates, as reported by Petriccione et al. [33].

Several studies have demonstrated that PCA is a valid multivariate data analysis tool that makes it possible to reduce large matrix data; analyze physico-chemical, qualitative, and enzymatic traits; and discriminate fruit crop samples under different postharvest conditions [60].

5. Conclusions

The integration of bamboo-based passive modified atmosphere packaging with cold storage effectively preserved strawberry quality, minimizing weight loss, maintaining firmness, and enhancing bioactive compounds and enzymatic antioxidant activity. This sustainable packaging system delayed senescence, reduced oxidative stress, and extended shelf life, offering an eco-friendly solution to improve postharvest storage while reducing food waste.

Bamboo-based sustainable packaging, when combined with a passive modified atmosphere (PMA) and cold storage at 4 °C, is a highly effective and eco-friendly solution for preserving the quality of strawberries over a 9-day period. This packaging system significantly reduced weight loss (4.16% vs. 37.26% in unpackaged fruit) and maintained higher firmness and moisture content, effectively delaying typical postharvest degradation processes. Strawberries stored under B-PMA conditions retained higher levels of polyphenols, flavonoids, anthocyanins, and overall antioxidant activity, highlighting the system's ability to preserve nutraceutical value. Enzymatic assays further confirmed that antioxidant enzymes (SOD, CAT, and APX) were significantly more active in the packaged samples, suggesting a more robust defense against oxidative stress. Moreover, the activities of browning-related enzymes such as PPO, GPX, and LOX, as well as the content of malondialdehyde (MDA), were significantly lower in the B-PMA samples, indicating reduced membrane damage and a delay in senescence-related processes.

The integration of bamboo-based biodegradable packaging and passive MAP not only extends the postharvest life of strawberries but also preserves their sensory, nutritional, and functional qualities. This strategy represents a promising sustainable alternative to conventional packaging, aligning with current consumer demand for eco-friendly solutions while enhancing fruit preservation and reducing food waste.

Supplementary Materials: The following supporting information can be downloaded at: <https://www.mdpi.com/article/10.3390/pr13072262/s1>, Figure S1: Development and use of biodegradable trays made from bamboo processing residues for strawberry packaging.

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