

The Applications of 'Active Packaging and Chlorine Dioxide' for Extended Shelf Life of Fresh Strawberries

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Fresh strawberries are highly perishable because of their high respiration rates. Three alternative packaging approaches were investigated to maintain the high quality and to extend the shelf life of strawberries. These were active packaging using chlorine dioxide (ClO₂) and ethylene-moisture sachets. The quality properties of four groups of samples were measured over 3 weeks at 4°C. The groups were: control, active packaging without ClO₂ treatment, active packaging with low-dose (5 ppm) ClO₂ treatment and active packaging with high-dose (10 ppm) ClO₂ treatment. Measured properties were weight loss, gas concentration, pH, titratable acidity (TA), soluble solids content, texture profile and colour. Active packaging with low-dose (5 ppm) ClO₂ treatment was found to be the most effective for TA retention and for maintaining (*L*) brightness values. The control group showed the largest total soluble solids reduction from 7.60 to 6.57. Active packaging without ClO₂ treatment showed the lowest weight loss (0.33%), while the control group showed the highest (1.86%) at the end of the storage.

Active packaging with high-dose ClO₂ treatment showed the highest preference value in global appearance, colour and firmness properties. The low- and high-dose active packaging groups had greater firmness, gumminess and chewiness than that of all other treatments. The results from this study showed that active packaging treatment with ClO₂ and the ethylene-moisture sachets had a beneficial effect on the quality of strawberries and could be used commercially. Copyright © 2010 John Wiley & Sons, Ltd.

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INTRODUCTION

Fresh strawberries are highly perishable fruits that have a fast ripening stage due to their high respiration rates.¹ Strawberries undergo a sequence of considerable physiological and biochemical changes. These limit their shelf life, storage time and ease of transportation without damage.² The shelf life and quality properties of these fresh fruits could potentially be maintained by applying modified-atmosphere packaging (MAP) and active packaging technologies such as ethylene and moisture absorbers, and different types of sanitizers. Thus, an investigation of the current and developing novel alternative practices² is necessary for preserving the quality of post-harvested fresh fruits.

MAP of fresh products refers to the technique that prolongs the shelf life by modification to the atmosphere within the package. This can be done by controlling the respiration of the product and the gas permeability of the packaging material (passive MAP) or by changing the gas composition within the package by gas flushing or gas-scavenging systems (active MAP).³ MAP can be carried out by sealing fresh products in polymeric film packages that modify O₂ and CO₂ levels within the package

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atmosphere.² Preserving fresh produce through packaging has been the subject of a great deal of research over the last decades.

Effective control of deterioration factors can be obtained by washing fresh fruits and vegetables with a ClO₂ sanitizing agent,⁴ and by combining this treatment with MAP and an ethylene-moisture sachet.

ClO₂ is a strong oxidizing and sanitizing agent. It could be used in gaseous or aqueous forms for washing fresh fruit and vegetables to keep them safe from bacterial contamination.^{4,5} Application of this sanitizing agent has recently received attention after the United States Food and Drug Administration (USFDA) allowed washing fruits and vegetables before consumption.^{6,7} Aside from its strong antimicrobial power, it has some detrimental effects on fruit and vegetables, including whitening and deterioration of the sensory characteristics.⁸ These limit the use of ClO₂ for preserving the quality and improving the shelf life of fruits.

The use of low O₂ concentrations of 1–5% and high CO₂ concentrations of 5–10% with a cold storage environment have been used to extend the shelf life of fruits and vegetables.⁹ Under these conditions, the product's tolerance to high levels of CO₂ has to be carefully considered. High CO₂ levels may cause physiological disorders, off flavours and decay susceptibilities.¹⁰ Under normal concentrations, however, CO₂ reduces the respiration rates and prevents deterioration of fruits and vegetables. This extension in shelf life results in longer distribution channels and improved product value.¹¹

Ethylene is a plant hormone responsible for the ripening of fruit. During storage; ascending concentration of ethylene could result in significant quality loss. This tends to accelerate the ripening and senescence processes in plants.¹² It also decreases the fruit's susceptibility to pathogens with a net reduction in post-harvest life.¹³ Therefore, ethylene inhibition or its removal should be used to maintain post-harvest quality. One tool for ethylene removal is the absorber sachet, which contains a zeolite compound. Zeolites are volcanic aluminosilicate crystalline materials. They have been used in many applications' areas because of their cation exchange properties and open-porous structures.¹⁴ Various researchers have reported that ethylene absorbers can extend the shelf life by decreasing the ripening of various items of produce.^{15,16}

Strawberries are known to be sensitive to humidity. During storage, they can lose water, which can be trapped within the headspace of the package and favours microbial growth and undesirable textural changes.¹⁷ The use of moisture-absorbing sachet containing silica gel can be used to control this problem. Silica gel is an absorber having an amorphous structure. It is allowed for use as a desiccant within food packaging under European Union regulation.¹⁸ Several studies have supported the use of desiccants in certain food packaging/products as a moisture absorber.^{19–21}

The literature also supports the use of other types of moisture absorbers as direct additives to food products. As examples, Ben-Yehoshua *et al.*²² used 5 g of calcium chloride (CaCl₂) crystals in high-density polyethylene bag containing bell pepper. This caused a reduction in the humidity but also caused weight loss, softening and an increase in membrane leakage of the peppers.

Shirazi and Cameron²¹ also studied the effect of 10 g sorbitol, xylitol, sodium chloride (NaCl), potassium chloride (KCl) and CaCl₂ on mature green tomato fruit at 20°C. They found that a NaCl-containing pouch extended the storage life of the tomato by 15–17 days and retarded the growth of surface moulds.

Villaescusa and Gil²³ used sorbitol (10, 15 and 20 g) and silica gel (3, 5, 7 and 15 g) to extend the shelf life of mushrooms. They found that sorbitol stimulated tissue leakage. Silica gel reduced condensation and provided a clear view through the package. These moisture absorbers did not affect the gas composition inside the package.

Mahajan *et al.*¹⁷ used silica gel, xylitol, CaCl₂, sorbitol, KCl, calcium oxide (CaO) and bentonite to develop a moisture absorber for mushrooms. They tested the mixtures of two to three desiccants in different proportions. Results showed that 5 g of the desiccant decreased the browning index and made appearance scores better.

To our knowledge, however, no studies have been published about using desiccants to control strawberries. Thus, the main objective of this research was to evaluate the potential effects of liquid ClO₂, zeolite and silica gel sachet systems combined with active packaging treatments in preserving the quality of fresh strawberries during storage at 4°C.

MATERIALS AND METHODS

Materials

Fresh daily 'Camarosa' strawberries were purchased from Lezzetli Gıda Tic. and San. Ltd. Sti. (Istanbul, Turkey), and transported to the laboratory. Fruits with uniform size and colour, free of external blemishes or damaged were then selected. Polyvinyl chloride-polyethylene trays (20 cm × 30 cm) were filled with 200 g of fresh strawberry fruits and heat-sealed with the polyethylene terephthalate/adhesive/cast polypropylene combination lid films by ReePack ReeTray 25TC MAP APACK (Istanbul, Turkey). Oxygen (O₂) and carbon dioxide (CO₂) permeability of film were 97.74 cc/m²/day (24°C) and 502.40 cc/m²/day (24°C). Film thickness was 52.50 μm. Gas tanks were obtained from Birlesik Oksijen Sanayi Tic and San Ltd. Sti. (Istanbul, Turkey). The samples were packaged with 8%O₂ + 15%CO₂ + 77%N₂ and stored at 4°C.

Zeolite (ethylene absorber)

Sachets containing chabazite zeolite (2 g per sachet) were used as ethylene absorber. Sachets adsorb ethylene at 1.35 ml/g. The material used for forming the sachet was sterile grade 1059B Tyvek (DuPont E.I. du Pont de Nemours & Co., Wilmington, Del., U.S.A.) and porosity rate was 35 s/gurley. Zeolite was obtained from Me-Mak Madencilik Ltd. Şti. (Ankara, Turkey).

Silica gel (moisture absorber)

Sachets containing silica gel (2 g per sachet) were used as moisture absorber. The amount of 2 g desiccant was chosen according to our preliminary trials. Sachets adsorb moisture at 0.4 g/1 g. Silica gel was obtained from Delta Endüstriyel Ürünler ve Dış Tic. San. Ltd. Sti. (Istanbul, Turkey).

Chlorine dioxide

Liquid solutions were prepared with a chlorine dioxide generator (ALLDOS, Oxiper D164-005) Alldos Eichler GmbH (a Grundfos company), Pfingstal, Germany. The generator mixes sodium chlorate (NaClO₂, 7.5%, w/w) and hydrochloric acid (HCl, 9%, w/w) solutions in a small batch reactor where ClO₂ was produced in a gaseous form according to the following equation:



The gas was then contacted with by-pass water to dissolve ClO₂. Liquid chlorine dioxide was collected in dark glass bottles, which were sealed and stored at 4°C.²⁴ ClO₂ solution was prepared daily and its concentration was determined by DPD (the N,N-diethyl-p-phenylenediamine) method using a DR/2800 spectrophotometer (HACH, Co., Loveland, CO, USA).

Treatments

Strawberries were randomly distributed into four groups. One group was chosen as the untreated (control) group. Treatments were:

1. Washed strawberries with water + MAP (8%O₂ + 15%CO₂ + 77%N₂) (Control) (F1).
2. Washed strawberries with water + MAP (8%O₂ + 15%CO₂ + 77%N₂) + Silica gel absorber + Zeolite absorber (F2).
3. Washed strawberries with 5 ppm chlorine dioxide + MAP (8%O₂ + 15%CO₂ + 77%N₂) + Silica gel absorber + Zeolite absorber (F3).
4. Washed strawberries with 10 ppm chlorine dioxide + MAP (8%O₂ + 15%CO₂ + 77%N₂) + Silica gel absorber + Zeolite absorber (F4).

These formulations were named as F1, F2, F3 and F4, respectively. Sachets were adhered to the wall of the packages just before the sealing of the trays. In all experiments, three replicates per treatment were used. Gas concentration in trays, pH, titratable acidity (TA), total soluble solids (TSS), weight loss, surface colour, texture profile analysis (TPA) and sensory evaluation were periodically determined during storage.

pH measurement

For each replicate, three strawberries were squeezed. The pH values were determined for the squeezed strawberry juice²⁵ and measured using a pH meter (Sartorius PP-50, Goettingen, Germany). Each measurement was replicated six times.

TA

TA was measured on the 2 ml of pressed strawberry juice, which was diluted to 50 ml with distilled water was titrated with 0.1 N sodium hydroxide to a pH of 8.1 with pH meter (Sartorius PP-50, Goettingen, Germany). Titratable acidity was expressed as a percentage citric acid.²⁶

TSS

TSS content of the squeezed strawberry juice was measured with an Atago Pal-1 pocket refractometer (Atago Co. Ltd, Tokyo, Japan). Results were expressed in °Brix.²⁷

Weight loss

The weights of individual package were measured on day 0, and after 3, 5, 7, 14 and 21 days of storage, package weights were recorded. At each sampling time, the weight was measured twice. Weight loss was expressed as the percentage loss of the initial total weight.^{28–30}

Surface colour

Colour values of the fruit surface were measured directly with Minolta CR-400 Chromometer (Konica Minolta Sensing, Osaka, Japan), using the CIE colour space *L*, *a*, *b* values. It was calibrated with a white plate before use. Twelve strawberries were analysed and there were two determinations for each strawberry. Results were expressed as *L–a–b* values as *L* (lightness), *a* (green to red; higher positive *a* values indicate red colour) and *b* (blue to yellow; higher positive *b* values indicate a more yellow skin colour) values were recorded.²⁷

Composition of atmosphere inside the packages

Concentration of gas (O₂ and CO₂) inside each package (trays) was analysed before measurements were taken, using an OxyBaby (HTK, Hamburg, Germany) gas analyser as a v/v percentage. Analyses were performed by inserting the probe through a rubber seal²⁸ attached to the outside of the packaging, and each package was used only for a single determination of the headspace gas composition. The instrument was calibrated with air.

TPA

TPA were performed with a TA-XT2i texture analyser (Stable Micro Systems Ltd, Godalming, Surrey, England) with the following parameters: pre-test speed 5.0 mm/s, test speed 1.0 mm/s and post-test speed 8.0 mm/s; penetration distance was 4 mm, with a rest period of 5 s between two cycles; and a trigger force of 1.0 N. The 10 mm diameter cylinder plunger SMS-P/10 CYL Delrin (Stable Micro Systems, Godalming, Surrey, England) probe always returned to the trigger point before beginning the second cycle.³¹ After the second cycle, the probe returned to its initial position. To obtain a good

estimation of overall TPA of strawberries, measurements were made on 10 strawberries per gas concentration of MAP and sampling day. Properties such as firmness, springiness, cohesiveness, adhesiveness, gumminess, resilience and chewiness were automatically calculated by the computer software.³²

Sensory evaluation of strawberries

A panel of nine trained judges evaluated the sensory profile of the strawberries. The analyses were carried out on day 5. The attributes analysed were global appearance, colour, firmness, flavour and general acceptability. The samples were coded with three-digit numbers to verify objectivity. The judges drunk water between the samples group. Ratings were based on a 9-point hedonic scale, where 9 = excellent, freshly cut; 7 = very good; 5 = good, limit of marketability; 3 = fair, limit of usability; and 1 = poor, unusable.³³

Decay incidence of strawberries

Strawberries were examined for visible mould incidence on days 0, 7 and 21. A strawberry was assumed infected when a visible surface lesion was observed.³⁴

Statistical analysis

All data were tested by bi-factorial model analysis of variance (ANOVA, time of storage \times kind of treatment) with SAS computer program except sensory evaluations.³⁵

Bi-factorial model:

$$Y_{ijk} = \mu + \alpha_i + \beta_j + (\alpha\beta)_{ij} + e_{ijk} \quad (1)$$

- Y_{ijk} : Random variable giving the response for observation t of the treatment at level i of α and level j of β .
- μ : General population mean.
- α_i : Effect of storage periods ($i = 1, 2$).
- β_j : Effect of treatments ($j = 1, 2, 3, 4$).
- $(\alpha\beta)_{ij}$: Effect of storage by treatments interaction.
- e_{ijk} : Independent random variables.

One-way ANOVA was used for the evaluation of sensorial value. When interactions were found to be not significant, overall value and comparisons were used. In order to determine significant differences between means, Tukey post-hoc comparison test was used ($p < 0.05$). Mean and standard deviation of the results are reported.

RESULTS AND DISCUSSION

Changes in pH levels

A significant increase in pH was observed after day 3 for all treatments (Table 1). The results are in concordance with previous reports that the decrease of acidity during storage showed the senescence.^{28,36,37} The values remained at around 3.65 except for control at the end of storage. F2 and F3 treatments slowed the changes on pH compared with control. The lowest pH values were 3.65 and 3.66 obtained for F3 and F4 groups, respectively. This decrease in pH is probably due to the oxidation of carbohydrates to carboxylic acid⁸ by dissolved ClO_2 in strawberry tissue. However, in the package of F1 and F2 treatments, CO_2 level increases naturally due to high respiration of the fruit. By the solubilization of CO_2 in strawberry, HCO_3^- is produced and the raising of HCO_3^- in cells leads to an

Table 1. pH changes during storage.

pH		Treatments			
		F1	F2	F3	F4
DAY	0	3.44 ± 0.03 ^{A,a}	3.44 ± 0.03 ^{A,a}	3.44 ± 0.03 ^{A,a}	3.44 ± 0.03 ^{A,a}
	3	3.49 ± 0.09 ^{B,a}	3.49 ± 0.11 ^{A,a}	3.50 ± 0.02 ^{B,a}	3.51 ± 0.26 ^{B,a}
	5	3.57 ± 0.02 ^{C,b}	3.54 ± 0.08 ^{B,a,b}	3.51 ± 0.04 ^{B,a}	3.54 ± 0.03 ^{B,a,b}
	7	3.63 ± 0.06 ^{D,b}	3.62 ± 0.02 ^{C,b}	3.58 ± 0.08 ^{C,a}	3.59 ± 0.05 ^{C,a}
	14	3.69 ± 0.05 ^{E,b}	3.67 ± 0.09 ^{D,c}	3.63 ± 0.04 ^{D,a}	3.63 ± 0.03 ^{D,a}
	21	3.72 ± 0.03 ^{E,b}	3.67 ± 0.02 ^{D,a}	3.65 ± 0.04 ^{D,a}	3.66 ± 0.05 ^{E,a}

^{a-b} Mean in the same row with different letters are significantly different ($p \leq 0.05$).

^{A-D} Mean in the same column with different letters are significantly different ($p \leq 0.05$).

^E F1-DAY 14, F1-DAY 21 and F4-DAY 21.

Table 2. Titratable acidity changes during storage.

Tit. acidity		Treatments				OVERALL
		F1	F2	F3	F4	
Day	0	0.54 ± 0.01 ^{A,a}	0.51 ± 0.02 ^{A,a}	0.51 ± 0.01 ^{A,a}	0.51 ± 0.01 ^{A,a}	0.52 ± 0.02 ^A
	3	0.50 ± 0.01 ^{A,B,a}	0.50 ± 0.02 ^{A,B,a}	0.49 ± 0.01 ^{A,a}	0.49 ± 0.01 ^{A,a}	0.50 ± 0.01 ^{A,B}
	5	0.48 ± 0.01 ^{A,B,a}	0.49 ± 0.04 ^{A,B,a}	0.49 ± 0.02 ^{A,a}	0.48 ± 0.04 ^{A,a}	0.48 ± 0.03 ^B
	7	0.48 ± 0.08 ^{A,B,a}	0.50 ± 0.07 ^{A,B,a}	0.49 ± 0.03 ^{A,a}	0.48 ± 0.01 ^{A,a}	0.49 ± 0.04 ^B
	14	0.44 ± 0.02 ^{B,a}	0.45 ± 0.03 ^{A,B,a}	0.47 ± 0.01 ^{A,a}	0.42 ± 0.01 ^{A,B,a}	0.45 ± 0.02 ^C
	21	0.42 ± 0.02 ^{B,a}	0.45 ± 0.01 ^{B,a}	0.46 ± 0.01 ^{A,b}	0.39 ± 0.09 ^{B,a}	0.43 ± 0.03 ^C
Overall		0.48 ± 0.05 ^{a,b}	0.48 ± 0.03 ^{a,b}	0.49 ± 0.02 ^a	0.47 ± 0.04 ^b	

^{a-b} Mean in the same row with different letters are significantly different ($p \leq 0.05$).

^{A-C} Mean in the same column with different letters are significantly different ($p \leq 0.05$).

increase in the pH.³⁸⁻⁴⁰ These results agreed with those reported by Ke *et al.*⁴¹ and Holcroft and Kader⁴² who found that high CO₂ level inside the package increases the pH values of strawberry.

Changes in TA levels

TA has an important role in cell pH regulation and fruit flavour. Citric acid is a major organic acid found in strawberry.^{43,44} Acidity loss has been related with quality loss and affects the consumer acceptability.⁴⁵ It was found that initial values of this acid (0.51 mg/100 ml) significantly decreased through storage for all treatments (Table 2), with the exception of F2 on day 7. The decrease in TA showed ripening and was associated with quality loss during storage.¹³ The F3 treatments were found to be effective in the retention of TA compared with the other treatments. Changes in TA were clearly related to the treatment, especially in F4 groups. This result contrasts with the result of pH values. However, there is no direct relationship between TA and pH, because pH depends on the free hydrogen ions in the solution, whereas TA related with all of the available hydrogen ions and those bound to undissociated weak acids such as citric and malic acids.⁴⁶ According to our measurements, higher ClO₂ concentration results in higher acidity depletion.

Probably, because of this reduction, citric acids could not regulate the cellular pH, and this influenced the anthocyanin stability.⁴⁷ Thereby, F4 group showed the lowest *a* value at the end of the storage. High respiration rate, as with regard to high CO₂ levels inside the F1 group, would result in the use of more citric acid as a substrate for the process, and therefore, F1 group has the lower TA value.⁴⁸ This results agreed with the paper of Du *et al.*⁴ who observed that the TA value of ClO₂-treated green bell peppers were higher than control.

Only at the end of storage were there significant differences between treatments in the TA value. For an acceptable flavour, maximum 8% TA have been recommended for strawberries. All groups have the recommended TA values at the end of the storage.⁴⁹

Changes in TSS content

Soluble solid content is a quality criterion for strawberries and it represents an indirect measurement of the hardness.⁵⁰ TSS content is significantly decreased with storage time for all treatment groups (Table 3).

The reduction of TSS during storage have been attributed to hydrolysis and the utilization of the reducing sugars and acids, which are the main substrates in the fruit respiration.^{2,43} Only in F3 groups were there no significant changes with time. The F1 group showed the highest decrease in TSS. There were significant differences between treatments only at the end of storage. During storage, the F3 group had the highest value compared with other treatments. At the end of storage, TSS of the control group decreased by 6.57°Brix, while other treatment groups ranged between 6.90 and 7.15°Brix.

Higher TSS reduction from packages without active packaging (F1 group) from harmony with their higher CO₂ levels have been associated with sugar content and respiration rate.⁴³ Lower TSS reduction was noticed in ClO₂ treatments. This was probably because ClO₂ treatment reduces the respiration rate and TSS depletion by maintaining physiological activity using least sugar content during respiration.⁴³

Similar results were reported by Zheng *et al.*² and Almenar *et al.*⁴³ for MAP or active packaging in strawberries.

Changes on weight loss levels

Weight loss is related to respiration and moisture evaporation on the fruit's surface.³⁷ When the moisture sachets reached the saturation point of capacity, the weight loss from the strawberry is caused by loss of water from the package to the surrounding atmosphere; therefore, we can use weight loss parameter to determine the fruit dehydration.

Weight loss was observed throughout storage for all treatment groups (Table 4). After treatment, the F3 group showed a 1.16% weight loss with respect to the initial weight. F2 treatment restricted water

Table 3. Total soluble solids changes during storage.

Total soluble solids	TREATMENTS			
	F1	F2	F3	F4
0	7.60 ± 0.32 ^{A,a}	7.60 ± 0.32 ^{A,a}	7.60 ± 0.32 ^{A,a}	7.60 ± 0.32 ^{A,a}
3	7.47 ± 0.17 ^{A,B,a}	7.55 ± 0.12 ^{A,a}	7.55 ± 0.12 ^{A,a}	7.50 ± 0.18 ^{A,B,a}
5	7.20 ± 0.08 ^{A,B,C,a}	7.28 ± 0.13 ^{A,B,a}	7.40 ± 0.08 ^{A,a}	7.36 ± 0.17 ^{A,B,a}
7	7.15 ± 0.16 ^{B,C,a}	7.24 ± 0.18 ^{A,B,a}	7.35 ± 0.14 ^{A,a}	7.31 ± 0.16 ^{A,B,a}
14	6.88 ± 0.17 ^{C,D,a}	7.02 ± 0.13 ^{B,a}	7.26 ± 0.16 ^{A,a}	7.16 ± 0.16 ^{A,B,a}
21	6.57 ± 0.15 ^{D,a}	6.90 ± 0.10 ^{B,a,b}	7.15 ± 0.12 ^{A,b}	7.02 ± 0.17 ^{B,a,b}

^{a-b} Mean in the same row with different letters are significantly different ($p \leq 0.05$).

^{A-D} Mean in the same column with different letters are significantly different ($p \leq 0.05$).

Table 4. Weight loss changes during storage.

Weight loss (%)	Treatments				OVERALL
	F1	F2	F3	F4	
3	0.25 ± 0.16 ^{A,a}	0.15 ± 0.20 ^{A,a}	0.21 ± 0.26 ^{A,a}	0.33 ± 0.33 ^{A,a}	0.24 ± 0.25 ^A
5	0.30 ± 0.17 ^{A,a}	0.18 ± 0.21 ^{A,a}	0.32 ± 0.29 ^{A,a}	0.44 ± 0.35 ^{A,a}	0.32 ± 0.27 ^A
7	0.32 ± 0.08 ^{A,a}	0.17 ± 0.12 ^{A,a}	0.48 ± 0.35 ^{A,a}	0.55 ± 0.42 ^{A,a}	0.39 ± 0.30 ^A
14	0.37 ± 0.08 ^{A,a}	0.21 ± 0.09 ^{A,a}	0.59 ± 0.41 ^{A,a}	0.84 ± 0.43 ^{A,a}	0.53 ± 0.37 ^A
21	1.86 ± 2.31 ^{B,a}	0.33 ± 0.02 ^{A,a}	1.16 ± 0.03 ^{A,a}	1.35 ± 0.03 ^{A,a}	1.41 ± 1.59 ^B
Overall	0.45 ± 0.77 ^a	0.18 ± 0.17 ^b	0.38 ± 0.35 ^{a,b}	0.51 ± 0.41 ^a	

^{a-b} Mean in the same row with different letters are significantly different ($p \leq 0.05$).

^{A-B} Mean in the same column with different letters are significantly different ($p \leq 0.05$).

transfer and delayed dehydration statistically over the whole storage period. The control group (F1), compared with the treatment groups, showed significantly higher weight loss (1.86%) at the end of storage.

In spite of the same permeability film used among all groups, the highest weight loss of the F1 group was purely related to the non-containing absorber and the relative humidity inside packaging. Thus, the result showed the increasing diffusivity of water vapour through film among the other treatments.

The F4 group showed 0.33% weight loss on day 3, whereas the F2 group had the same loss on day 19. Comparing all treatments, F2 treatment had a significant effect on weight loss, presenting as the group having the lowest values in each day. It is possible that the F2 group regulated the moisture in packaging and prevented the loss of moisture throughout packaging film. On the contrary, our result is in disagreement with the previous studies by Mahajan *et al.*¹⁷ and Villaescusa and Gil²³ who found that absorbers increased the weight loss of mushroom. Over the whole storage period, the F4 group showed the biggest weight loss (0.51%) due to the negative effect of high ClO₂ concentration on the fruit cell wall. It may be explained that ClO₂, which is a powerful oxidant, oxidized the amino acids or disulfide bonds that exist in the cell wall.⁵¹ It was reported that weight loss, approximately 6% before marketability, is impaired.⁴³ All our treatments did not reach this value at the end of storage, even including the control group.

Changes on external colour

Colour is an important attribute for consumer acceptance and perception of strawberry quality. Loss of colour in fresh strawberries is most likely related to degradation of pigments. Changes in the external colour of strawberries were analysed by measuring lightness (*L*, lightness/darkness) and 'a' (redness) values during storage. In all treatment groups, *L* value was decreased significantly (Table 5). Compared with the treated groups, *L* values of the control group (F1) were the lowest. After the 19th day, F3 groups had the highest *L* value (30.55) among the other groups and the control group (data not shown). All treatments significantly slowed down the *L*-value changes on day 19 compared with control. By the end of the storage period, the control group had the lowest *L* value (25.87) and the F3 group had the highest value (28.08). Therefore, F3 treatment was the most effective. It can represent oxidation of different oligosaccharides such as cellulose and hemicelluloses with 5 ppm ClO₂ and maybe preventing the phenolic compounds in strawberry.^{2,52}

Redness of strawberries was evaluated by measuring *a* values. In general, *a* value decreased significantly in F4 and control groups. The value 'a' decreased during storage due to the degradation of anthocyanins which are pigments contributing to red colour and increasing respiration rate-enzymatic processes.^{36,53} After the seventh day of storage, all treatments showed 'a' values of around 25 ± 1 (data not shown) (Table 6). Until the 13th day of storage, treatments were not different significantly. At the end of storage, the F4 group had the lowest *a* value (21.21) and the F3 group had the highest (25.11). The highest value of 'a' in the F3 group is probably due to decreasing respiration rate and retarding the enzymatic reaction. However, in the F4 group, the highest ClO₂ concentration may have a negative effect on anthocyanin stability.

Table 5. Changes in 'L' value during storage.

'L' value	Treatments			
	F1	F2	F3	F4
0	29.14 ± 1.55 ^{A,a}	29.19 ± 1.11 ^{A,C,a}	29.26 ± 1.24 ^{A,B,a}	29.08 ± 1.31 ^{A,B,a}
3	29.11 ± 1.51 ^{A,B,a}	29.61 ± 1.13 ^{A,a}	29.18 ± 1.55 ^{A,B,a}	29.66 ± 1.45 ^{A,a}
5	28.42 ± 1.06 ^{A,B,a}	27.79 ± 0.99 ^{C,a}	28.83 ± 1.16 ^{A,B,a}	28.55 ± 0.62 ^{A,B,a}
7	29.73 ± 1.21 ^{A,a}	28.31 ± 1.84 ^{A,C,a}	29.49 ± 0.99 ^{A,B,a}	29.59 ± 0.96 ^{A,B,a}
14	26.80 ± 0.65 ^{B,C,a}	28.10 ± 0.57 ^{A,C,a,b}	30.55 ± 1.30 ^{A,b}	29.21 ± 1.20 ^{A,B,a,b}
21	25.87 ± 1.83 ^{C,a}	26.90 ± 0.70 ^{B,C,a}	28.08 ± 0.82 ^{B,a}	27.06 ± 1.70 ^{B,a}

^{a-b} Mean in the same row with different letters are significantly different ($p \leq 0.05$).

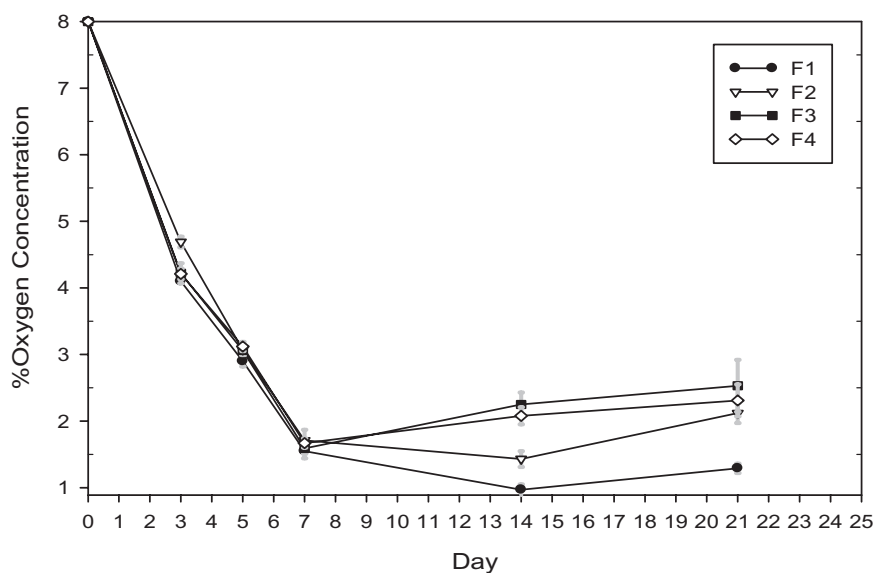
^{A-C} Mean in the same column with different letters are significantly different ($p \leq 0.05$).

Table 6. Changes in 'a' value during storage.

'a' value	TREATMENTS			
	F1	F2	F3	F4
0	27.74 ± 1.58 ^{A,a}	26.72 ± 2.15 ^{A,a}	27.92 ± 2.02 ^{A,a}	27.29 ± 1.59 ^{A,a}
3	26.06 ± 1.52 ^{A,B,a}	26.64 ± 2.51 ^{A,a}	27.16 ± 1.86 ^{A,a}	25.17 ± 1.10 ^{A,B,a}
5	25.96 ± 0.77 ^{A,B,a}	26.00 ± 1.28 ^{A,a}	26.92 ± 1.63 ^{A,a}	24.70 ± 2.05 ^{A,B,a}
7	24.82 ± 2.57 ^{B,a}	25.58 ± 2.55 ^{A,a}	26.29 ± 2.23 ^{A,a}	23.18 ± 2.51 ^{B,C,a}
14	24.34 ± 2.10 ^{A,B,a,b}	25.40 ± 2.01 ^{A,a,b}	26.20 ± 1.88 ^{A,a}	21.97 ± 1.66 ^{B,C,b}
21	24.16 ± 1.36 ^{B,a,b}	24.38 ± 1.21 ^{A,a,b}	25.11 ± 2.19 ^{A,a}	21.21 ± 0.79 ^{C,b}

^{a-b} Mean in the same row with different letters are significantly different ($p \leq 0.05$).

^{A-C} Mean in the same column with different letters are significantly different ($p \leq 0.05$).

Figure 1. O₂ composition in packaging during storage.

Headspace gas concentration

The effect of the active packaging systems on the composition of MAP inside each package was also analysed during storage. Strawberry respiration caused modification of packaging gases during the storage (Figures 1 and 2). Because of respiration, O₂ content of packages were decreased to 2% levels. By day 21, the F1 group had the lowest O₂ and highest CO₂ concentration (0.96 and 30.14). These conditions result in the starting of fermentation off odours and off flavours.⁵⁴ CO₂ concentration in the package depends on film transmission rate and product characteristics,⁵⁵ and according to CO₂ levels inside the package, we can say this material provided too much barrier. After 3 days of storage, CO₂ dissolves in the aqueous phase of the product and this results in the decreasing of the CO₂ concentration in all treatments.⁵⁶ Until day 21, there were no statistical differences in O₂ concentration inside packaging between treatments. After day 7, CO₂ content showed an increase to a higher-than-initial-concentration level in all treatments. At the end of the storage, F4 treatments had significantly high O₂ levels than the other treatments. The results indicated that high ClO₂ concentration may have caused a lower respiration rate during the storage.

TPA

Firmness, cohesiveness, gumminess and chewiness properties of strawberry were decreased and springiness, adhesiveness parameters were increased with storage time (Figure 3). Changes in fruit

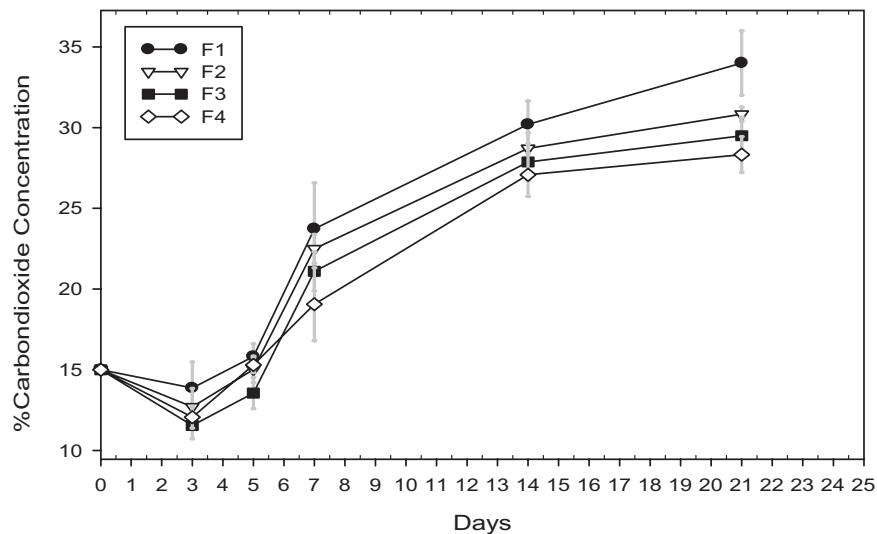


Figure 2. CO₂ composition in packaging during storage.

texture are related with consequence of disassembly of primary cell wall and middle lamella structure. Firmness loss is attributed to the degradation of the cell wall and loss of turgor pressure in the cells reduced by water loss.⁵⁷ At the end of the storage, firmness forces were 152, 122, 184 and 233 g.f for F1, F2, F3 and F4 groups, respectively. Measurements showed that F3 and F4 treatments prevented water loss and maintained hardness (Figure 3a). It can be concluded that ClO₂ may inhibit the pectin-degrading enzymes. The results for the F2 treatment can be explained by the fact that the sachet inhibited ethylene production until the seventh day, and after this day sachet saturated and conversion of protopectin to pectin increased.⁵⁸

Adhesiveness is a surface characteristic and is related with adhesive and cohesive forces.⁵⁹ In our work, adhesiveness (action necessary to pull the compression from strawberry) increased from 7.93 to 12.69, 10.38, 9.50 and 8.59 g.sec for F1, F2, F3 and F4, respectively (Figure 3b). Compared with F1 and F2 treatments, adhesiveness was maintained in the F3 and F4 groups.

Springiness values significantly increased throughout the storage (Figure 3c). However, there were no significant changes between treatments, but the F3 treatment showed the highest value (0.66) at the end of the storage.

Cohesiveness contributes to the comprehensive understanding of viscoelastic properties, including tensile strength.¹¹ Cohesiveness values decreased during the storage (Figure 3d). F3 treatment showed the minimum values during the storage compared with the other treatments. Tissue softening may be the resulting loss of cohesiveness values because of solubilization of pectinaceous material in the middle lamellae of adjacent cells.¹¹

Gumminess is a term of chewing energy to bite off the sample. Gumminess values decreased from 146 to 61.03, 29.53, 89.86 and 103.16 for F1, F2, F3 and F4, respectively (Figure 3e).

Chewiness is a parameter that related with products hardness, cohesiveness and elasticity.⁶⁰ Chewiness decreased from 105 to 32 during storage (Figure 3f). Decreasing chewiness values showed that strawberries became softer throughout the storage.⁶¹ The highest chewiness values were shown by the F3 group and lowest values were observed in the F2 group.

The general trend observed in Figure 2 was that F3 and F4 groups had greater firmness, gumminess and chewiness than the other treatments.

Sensory evaluation

Treatments did not reduce the sensory attributes, including global appearance and colour, statistically (Table 7). Panellist scores given to global appearance, colour, firmness and flavour attributes were similar between treatments except the F3 group. Whitening effect of ClO₂ was not observed by the

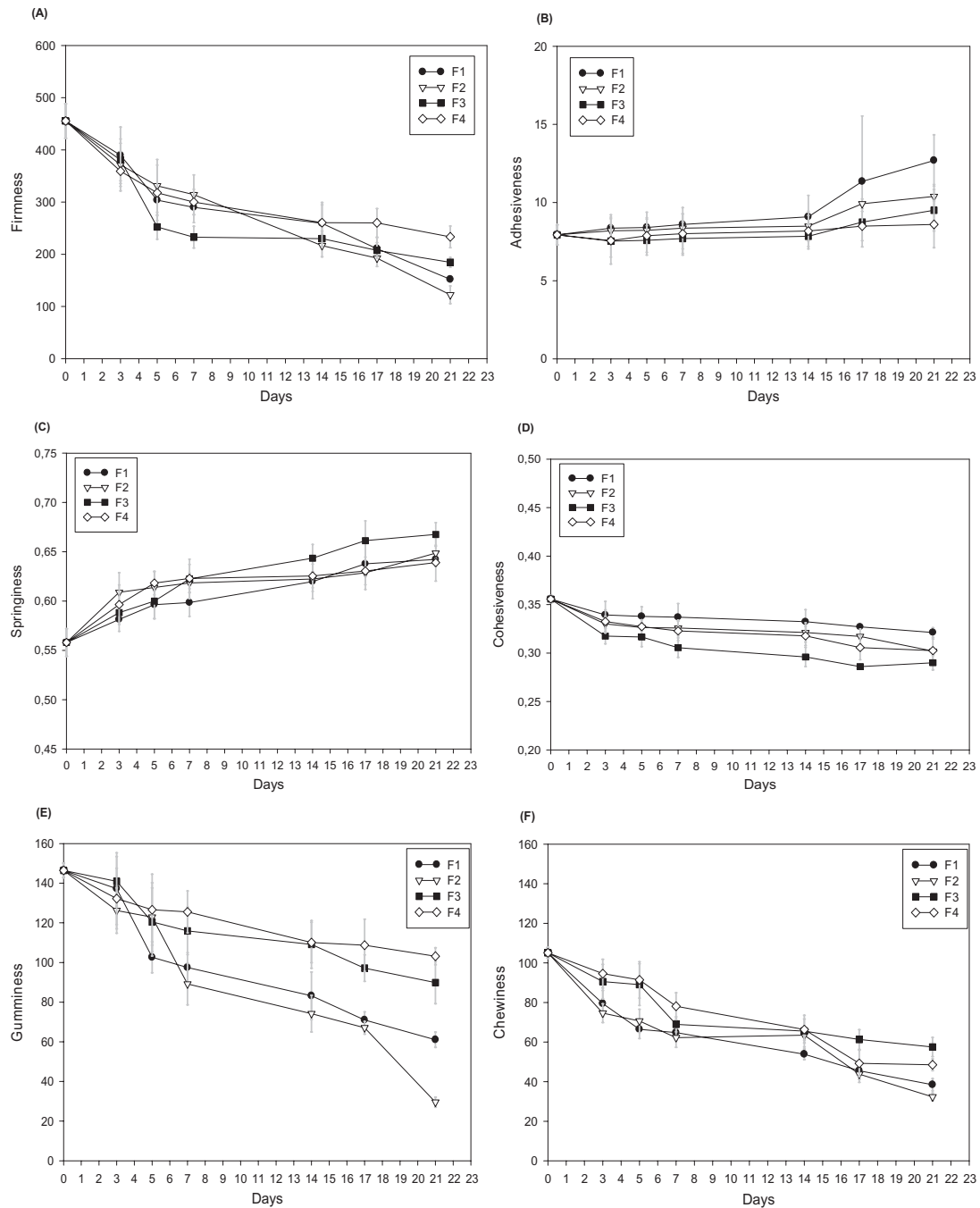


Figure 3. Effect of treatments on (a) firmness; (b) adhesiveness; (c) springiness; (d) cohesiveness; (e) gumminess; (f) chewiness of strawberries. The x-axis shows the days and the y-axis shows the TPA values.

panellist, statistically. This finding contrasts with the results reported in the literature.⁶² Colour, firmness and flavour of the F3 group were considered less intense than other groups in agreement with the instrumental analysis of the texture of which the F2 group had the lowest value. The F1 group had the lowest value (4.97) only in global appearance. The F4 group showed the highest preference value in global appearance, colour and firmness properties. It should be noted that, although lower scores were given for the F3 group from panellists, they did not see a significant difference in global

Table 7. Average scores for the evaluated sensory attributes for strawberries.

		Treatments			
		F1	F2	F3	F4
Sensory evaluation	Global appearance	4.97 ± 1.06 ^a	4.46 ± 1.23 ^a	4.98 ± 1.07 ^a	5.15 ± 1.13 ^a
	Colour	5.18 ± 1.08 ^a	4.69 ± 1.12 ^a	4.65 ± 1.35 ^a	5.47 ± 0.73 ^a
	Firmness	5.92 ± 1.20 ^a	5.43 ± 0.93 ^a	4.61 ± 0.56 ^b	6.08 ± 0.97 ^a
	Flavour	6.18 ± 0.88 ^a	5.53 ± 0.67 ^a	4.87 ± 0.68 ^b	5.78 ± 1.11 ^a
	General acceptability	7.22 ± 0.71 ^a	5.20 ± 0.92 ^c	4.55 ± 0.57 ^d	5.76 ± 0.60 ^b

^{a-d} Mean in the same row with different letters are significantly different ($p \leq 0.05$).

appearance and colour. F1 treatments were considered to maintain general acceptability when compared with other groups.

Visible mould growth

Visible mould growth was not detected until the seventh day of storage. The first visible mould development in F1 and F4 group appeared after 7 days. The levels of carbon dioxide inside the packaging of F4 were lowest in days 7, and therefore, CO₂ could not show the inhibiting effect on mould growth (see headspace gas concentration section).³⁴

Except for the F4 group, it is possible that active package – especially silica gel sachet – of the F2 and F3 group lower the relative humidity of the samples, resulting in low water activity that the moulds were not able to grow.³⁴

At the end of the storage, the control (F1) group of strawberries had the highest (11%) decay incidence (infected) by moulds (data not shown). After day 14, high CO₂ levels (>25%) may have inhibited the mould growth, but there were still mould trace on the strawberry surface, and therefore, we accepted these strawberries as an infected fruit. In this study, it was found that active package controlled mould growth better than the F1 group.

CONCLUSIONS

It is evident from this study that ClO₂ treatment and active packaging including ethylene-moisture sachets are complementary technologies that are capable of maintaining the quality of strawberries, especially after 14 days of storage. ClO₂ treatments had a beneficial effect on firmness, TSS and colour values. The minimum weight loss was obtained in strawberries with sachets treatments. Treatments retarded the senescence process with resulting minimum CO₂ levels at the end of the storage. Also, treatments did not diminish the sensory quality, including global appearance and colour.

In conclusion, we could recommend the application of these treatments in order to extend the shelf life of strawberries during transport and storage conditions. However, translating these treatments into practice, we should focus on the package barrier characteristics, concentration of sachets and exposure times of ClO₂.

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