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Sustainable Edible Coatings for Reducing Oxidative Deterioration in Fresh Fruits

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ABSTRACT—Oxidative deterioration is a major cause of quality loss and postharvest waste in fresh fruits. This study evaluated four biopolymer-based edible coatings for limiting oxidative damage in strawberries (*Fragaria* × *ananassa* Duch.) stored at 4 °C and 90% relative humidity for 12 days. Treatments were an uncoated control, chitosan (CH), sodium alginate (AL), chitosan with gum arabic (CH-GA), and chitosan with gum arabic enriched with rosemary extract (CH-GA-RE). A completely randomized design with three replicates of 60 fruit per treatment (900 fruit in total) was used. Weight loss, firmness, decay incidence, soluble solids, titratable acidity, malondialdehyde (MDA), total phenolics, DPPH radical scavenging capacity and superoxide dismutase (SOD) activity were measured at 0, 3, 6, 9 and 12 days. After 12 days, CH-GA-RE fruit showed 54.1% lower weight loss, 77.1% lower decay and 41.7% lower MDA than the control. They also retained 72.3% of initial firmness and 98.1% of initial total phenolics, compared with 39.7% and 72.1% in the control. MDA was strongly and negatively correlated with firmness (r = −0.94) and phenolic content (r = −0.91). Multi-component coatings with natural antioxidants therefore offer a sustainable, biodegradable way to preserve strawberry quality by suppressing lipid peroxidation and sustaining endogenous antioxidant defences.

KEYWORDS—edible coatings; chitosan; gum arabic; oxidative stress; lipid peroxidation; postharvest quality; strawberry

INTRODUCTION

Fresh fruits are highly perishable. Substantial quantities are lost between harvest and consumption because of water loss, softening, microbial spoilage and oxidative reactions. Strawberries are especially vulnerable because they have a thin epidermis, a high respiration rate and no climacteric ripening pattern that would allow harvest before full maturity. Even under refrigeration, their shelf life is generally limited to a few days (Gol et al., 2013).

Oxidative deterioration is central to this loss of quality. During postharvest storage, senescence and stress cause reactive oxygen species (ROS) such as superoxide, hydrogen peroxide and hydroxyl radicals to accumulate faster than the antioxidant system can remove them (Apel & Hirt, 2004). The excess ROS peroxidize membrane lipids, increase electrolyte leakage, degrade phenolic compounds and pigments, and reduce the activity of protective enzymes such as SOD. Malondialdehyde, a secondary product of lipid peroxidation, is widely used as an indicator of the resulting membrane damage. In consumer terms, these changes appear as softening, off-flavours, browning and greater susceptibility to decay.

Edible coatings are thin layers of food-grade material applied directly to the fruit surface. They act as semi-permeable barriers to moisture, oxygen and carbon dioxide, which modifies the internal atmosphere and slows metabolism (Baldwin et al., 1995; Dhall, 2013). Coatings made from polysaccharides, proteins and lipids are renewable and biodegradable, and they can be consumed with the fruit. This makes them attractive alternatives to petroleum-based packaging and synthetic postharvest chemicals (Hassan et al., 2018). They can also carry natural antioxidants and antimicrobials directly to the fruit surface (Rojas-Graü et al., 2009).

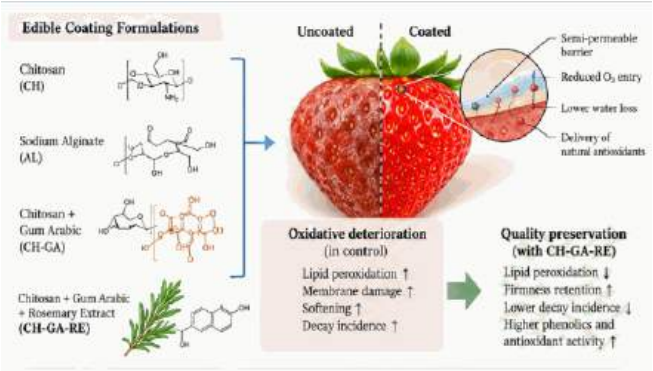
Most earlier work has focused on single-polymer coatings and on weight loss or decay. Fewer studies have compared single and composite coatings for their effects on oxidative stress markers and endogenous antioxidant systems under the same conditions. This study therefore had three objectives:

- to compare chitosan, alginate and chitosan–gum arabic coatings for their effects on physical quality and decay of strawberries;
- to determine whether adding rosemary extract improves control of lipid peroxidation and preserves antioxidant capacity;
- to quantify the relationship between oxidative damage and quality attributes during cold storage.

LITERATURE REVIEW

Early work established that edible coatings can function as selective barriers on fresh produce. Baldwin et al. (1995) described how coatings on lightly processed fruits and vegetables reduce moisture and solute migration and restrict gas exchange. Olivas and Barbosa-Cánovas (2005) later reviewed the use of coatings on fresh-cut fruits and highlighted the importance of matching coating composition to the physiology of each commodity. Dhall (2013) summarized advances in coating materials and application

methods. Hassan et al. (2018) compared polysaccharide-, protein- and lipid-based coatings and found that polysaccharides give good gas barrier properties but relatively weak moisture barriers, which motivates the use of composite formulations.



Chitosan, a deacetylated derivative of chitin, is among the most studied coating polymers. It forms cohesive, semi-permeable films and has intrinsic antimicrobial and elicitor activity (Elsabee & Abdou, 2013). Romanazzi et al. (2017) reviewed chitosan treatments for fruits and vegetables and concluded that they reduce decay and extend shelf life across many commodities, partly by inducing host defence responses. Jiang and Li (2001) found that chitosan coating delayed quality deterioration and pericarp browning in longan, and Ali et al. (2011) reported that chitosan coatings slowed ripening and reduced weight loss in papaya during cold storage.

Evidence that coatings influence oxidative metabolism comes mainly from studies on strawberries. Wang and Gao (2013) reported that a chitosan-based coating maintained higher levels of antioxidants and enhanced antioxidant enzyme activity in strawberries, which improved postharvest quality. Gol et al. (2013) showed that coatings enriched with chitosan improved quality and extended the shelf life of strawberries. In bananas, a composite of gum arabic and chitosan delayed ripening-related biochemical and physiological changes during cold storage (Maqbool et al., 2011). This suggests that combining polysaccharides can produce more effective barriers than either polymer alone.

A second line of research concerns functional additives. Rojas-Graü et al. (2009) reviewed incorporation of active ingredients, including antioxidants, antimicrobials and nutraceuticals, into edible coatings for fresh-cut fruits and noted that the matrix influences how efficiently these compounds are retained on the surface. Valencia-Chamorro et al. (2011) reviewed antimicrobial films and coatings and showed that essential oils, plant extracts and organic acids can strengthen the protective effect against spoilage organisms. Because plant phenolics are effective free radical scavengers, adding such extracts to a polysaccharide matrix could in principle lower oxidative load directly while the polymer slows metabolism.

Despite this progress, three gaps remain. Many studies report only weight loss, colour or decay, with limited biochemical evidence of oxidative stress. Direct comparisons of single and composite coatings under the same storage regime are scarce. Quantitative links between lipid peroxidation and textural or compositional quality are rarely reported. This study addresses these gaps.

Materials and Methods

Plant Material and Experimental Design

Strawberries (*Fragaria* × *ananassa* Duch.) were hand-harvested at commercial maturity (approximately 75% red surface colour) from a single commercial planting and transported to the laboratory within 2 hours. Fruit of uniform size, free of visible defects and infection, were selected and randomly allocated to five treatments. The experiment followed a completely randomized design with three replicates per treatment. Each replicate comprised 60 fruit, giving 900 fruit in total. Of these, 30 fruit per replicate were reserved for weight loss and decay tracking over the full storage period. The other 30 (six per sampling day) were used for destructive analyses.

Coating Preparation and Application

The treatments were as follows:

Table 1. Composition of coating treatments

Treatment	Code	Coating composition
Control	C	Dipped in distilled water
Chitosan	CH	1.0% (w/v) chitosan, 0.5% (v/v) glycerol
Alginate	AL	1.5% (w/v) sodium alginate, 0.75% (v/v) glycerol, followed by 1% (w/v) $CaCl_2$ dip
Chitosan–gum arabic	CH-GA	1.0% (w/v) chitosan, 2.0% (w/v) gum arabic, 0.5% (v/v) glycerol
Chitosan–gum arabic–rosemary	CH-GA-RE	CH-GA formulation plus 0.5% (w/v) rosemary leaf extract

Chitosan (medium molecular weight) was dissolved in 1% (v/v) acetic acid with stirring for 4 hours, and the pH was adjusted to 5.5 with NaOH. Gum arabic, alginate and glycerol were added according to the formulations in Table 1. The rosemary extract was prepared by ethanolic extraction of dried leaves, evaporated and redissolved in the coating solution. Fruit were dipped for 2 minutes, drained and air-dried at 20 °C for 1 hour. Alginate-coated fruit were additionally immersed in the $CaCl_2$ solution for 1 minute. All fruit were then placed in ventilated polypropylene clamshells and stored at 4 ± 1 °C and 90 ± 3% relative humidity for 12 days. Samples were taken at 0, 3, 6, 9 and 12 days.

Physical and Chemical Quality Measurements

Weight loss was calculated for tracked fruit as the percentage difference between initial and sampling-day mass. Firmness was measured on the equatorial region of six fruit per replicate with a texture analyser equipped with a 2 mm cylindrical probe (10 mm penetration depth) and expressed in newtons (N). Decay incidence was recorded as the percentage of the 90 tracked fruit per treatment showing visible fungal growth. Total soluble solids (TSS, °Brix) were measured on filtered juice with a digital refractometer. Titratable acidity (TA) was determined by titration with 0.1 N NaOH to pH 8.2 and expressed as percent citric acid.

Oxidative Stress and Antioxidant Assays

Lipid peroxidation was estimated as malondialdehyde content using the thiobarbituric acid reaction according to Heath and Packer (1968) and expressed in nmol g^{-1} fresh weight (FW). Total phenolics were determined with the Folin–Ciocalteu reagent following Singleton and Rossi (1965) and expressed as mg gallic acid equivalents (GAE) per 100 g FW. DPPH radical scavenging capacity was measured by the method of Brand-Williams et al. (1995) and reported as percent inhibition. Superoxide dismutase activity was assayed by inhibition of nitroblue tetrazolium photoreduction (Beauchamp & Fridovich, 1971), with protein determined by the Bradford (1976) method. SOD activity was expressed as units per mg protein.

Statistical Analysis

Data are presented as mean ± standard deviation (SD) of three replicates. Two-way analysis of variance (ANOVA) tested the effects of treatment, storage time and their interaction. One-way ANOVA with Tukey's honestly significant difference (HSD) test compared treatments at each sampling day at $p < 0.05$. Pearson correlation coefficients were calculated using replicate-level data at day 12 ($n = 15$) to evaluate relationships between MDA and quality attributes.

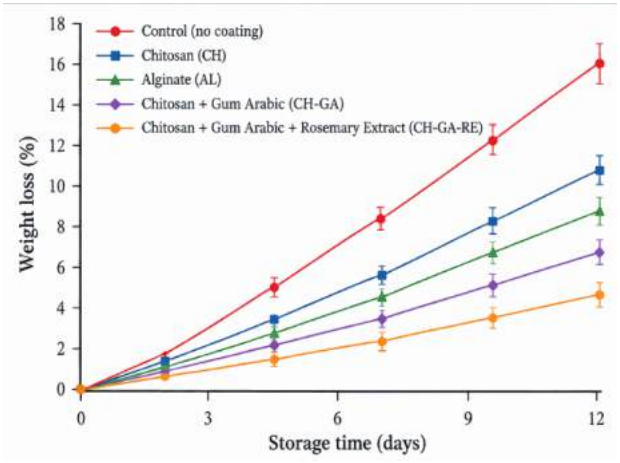
Results

Weight Loss, Firmness, Decay and Basic Composition

Two-way ANOVA showed significant effects of treatment ($F(4,50) = 186.3$, $p < 0.001$), storage time ($F(4,50) = 412.7$, $p < 0.001$) and their interaction ($F(16,50) = 14.8$, $p < 0.001$) on MDA content. All coatings significantly reduced weight loss and decay compared with the control (Table 2). After 12 days, uncoated fruit lost 9.84% of their initial weight, whereas CH-GA-RE fruit lost 4.52%, a 54.1% reduction. Firmness declined from an initial 5.82 ± 0.21 N to 2.31 N in the control but only to 4.21 N in CH-GA-RE fruit, which therefore retained 72.3% of initial firmness against 39.7% in the control. Decay incidence reached 38.9% in the control and 8.9% in CH-GA-RE fruit, a 77.1% reduction.

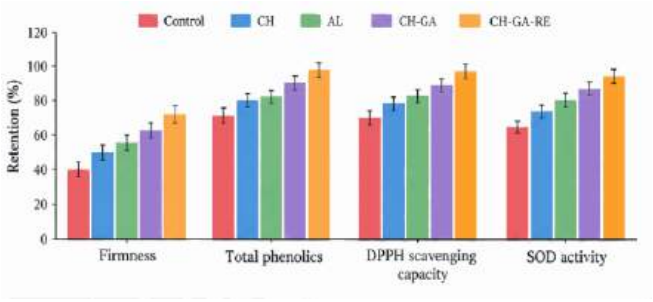
Table 2. Physical and compositional quality of strawberries after 12 days of storage at 4 °C (mean ± SD, n = 3)

Treatment	Weight loss (%)	Firmness (N)	Decay incidence (%)	TSS (°Brix)	TA (% citric acid)
Day 0 (initial)	—	5.82 ± 0.21	0.0	7.6 ± 0.2	0.92 ± 0.04
C	9.84 ± 0.52 a	2.31 ± 0.18 e	38.9 ± 4.8 a	8.9 ± 0.3 a	0.58 ± 0.03 d
CH	6.21 ± 0.38 c	3.42 ± 0.20 c	17.8 ± 3.9 c	8.3 ± 0.2 bc	0.71 ± 0.03 bc
AL	6.87 ± 0.41 b	3.18 ± 0.19 d	22.2 ± 4.2 b	8.5 ± 0.3 b	0.68 ± 0.04 c
CH-GA	4.96 ± 0.33 d	3.96 ± 0.22 b	11.1 ± 3.3 d	8.1 ± 0.2 cd	0.76 ± 0.03 ab
CH-GA-RE	4.52 ± 0.30 e	4.21 ± 0.21 a	8.9 ± 2.9 d	8.0 ± 0.2 d	0.79 ± 0.03 a



Different lowercase letters within a column indicate significant differences among treatments (Tukey HSD, $p < 0.05$).

TSS increased and TA decreased in all fruit during storage, consistent with ongoing ripening and respiration. The changes were smallest in coated fruit, particularly in CH-GA and CH-GA-RE, which kept TSS 0.9–0.8 °Brix below the control and TA 0.18–0.21 percentage points above it.



Lipid Peroxidation

MDA content rose in all treatments but at markedly different rates (Table 3). Initial MDA was 14.2 ± 0.9 nmol g^{-1} FW. In control fruit it reached 41.7 nmol g^{-1} by day 12, almost three times the initial value. Coated fruit accumulated less MDA, with the lowest content in CH-GA-RE (24.3 nmol g^{-1}), 41.7% below the control. Treatments differed significantly from the control from day 3 onward, and CH-GA-RE was significantly lower than CH and AL from day 6 ($p < 0.05$).

Table 3. Malondialdehyde content (nmol g^{-1} FW) during storage at 4 °C (mean ± SD, n = 3)

Treatment	Day 0	Day 3	Day 6	Day 9	Day 12
C	14.2 ± 0.9	18.6 ± 1.0 a	25.4 ± 1.3 a	33.1 ± 1.6 a	41.7 ± 1.9 a
CH	14.2 ± 0.9	16.9 ± 0.9 b	21.3 ± 1.1 b	26.2 ± 1.3 c	31.5 ± 1.5 c
AL	14.2 ± 0.9	17.4 ± 0.9 b	22.5 ± 1.2 b	28.0 ± 1.4 b	33.9 ± 1.6 b
CH-GA	14.2 ± 0.9	16.2 ± 0.8 bc	19.8 ± 1.0 c	23.1 ± 1.1 d	27.0 ± 1.3 d
CH-GA-RE	14.2 ± 0.9	15.8 ± 0.8 c	18.7 ± 0.9 c	21.4 ± 1.0 e	24.3 ± 1.1 e

Different lowercase letters within a column indicate significant differences among treatments within each sampling day (Tukey HSD, $p < 0.05$). One-way ANOVA at day 12: $F(4,10) = 118.4$, $p < 0.001$.

Phenolics, Antioxidant Capacity and SOD Activity

Endogenous antioxidants declined during storage in all fruit, but coatings slowed the decline (Table 4). Total phenolic content fell from 262 ± 9 mg GAE 100 g^{-1} FW to 189 mg in the control, a retention of 72.1%. In CH-GA-RE fruit, phenolics remained at 257 mg, or 98.1% of the initial level. DPPH scavenging capacity decreased from 78.4% to 52.6% in the control and to 73.2% in CH-GA-RE fruit (retentions of 67.1% and 93.4%). SOD activity declined from 42.1 to 24.8 U mg^{-1} protein in the control (58.9% retention) but remained at 38.2 U mg^{-1} protein in CH-GA-RE fruit (90.7% retention).

Table 4. Antioxidant attributes of strawberries after 12 days of storage at 4 °C (mean ± SD, n = 3)

Treatment	Total phenolics (mg GAE 100 g^{-1} FW)	DPPH scavenging (%)	SOD activity (U mg^{-1} protein)
Day 0 (initial)	262 ± 9	78.4 ± 1.9	42.1 ± 1.6
C	189 ± 8 e	52.6 ± 2.4 e	24.8 ± 1.4 e
CH	224 ± 9 c	63.8 ± 2.1 c	31.6 ± 1.5 c
AL	215 ± 10 d	60.9 ± 2.3 d	29.7 ± 1.4 d
CH-GA	238 ± 9 b	68.7 ± 2.0 b	35.4 ± 1.5 b
CH-GA-RE	257 ± 10 a	73.2 ± 1.9 a	38.2 ± 1.6 a

Different lowercase letters within a column indicate significant differences among treatments (Tukey HSD, $p < 0.05$).

Relationships Among Variables

Replicate-level data at day 12 (n = 15) showed that MDA was negatively correlated with firmness ($r = -0.94$), total phenolics ($r = -0.91$) and SOD activity ($r = -0.93$), and positively correlated with weight loss ($r = 0.89$) and decay incidence ($r = 0.92$) (Table 5). All coefficients were significant at $p < 0.001$.

Table 5. Pearson correlation coefficients between MDA content and quality attributes at day 12 (n = 15)

Variable	r with MDA	p-value
Firmness	−0.94	< 0.001
Total phenolics	−0.91	< 0.001
SOD activity	−0.93	< 0.001
Weight loss	0.89	< 0.001
Decay incidence	0.92	< 0.001

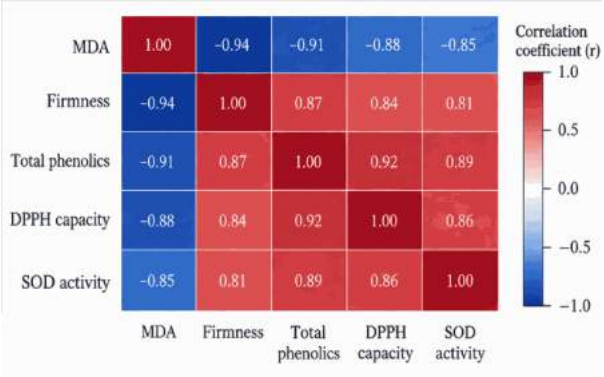
Discussion

All coatings improved the postharvest performance of strawberries, and the improvement increased as the formulation became more complex. The ranking of treatments (CH-GA-RE > CH-GA > CH > AL > control) was consistent across every variable measured, which supports the interpretation that physical barrier effects and antioxidant effects operate together.

The reduction in weight loss and the better firmness retention are consistent with the barrier function described for edible coatings (Baldwin et al., 1995; Dhall, 2013). Lower weight loss reflects reduced transpiration. The slower softening is likely related to lower respiratory activity and reduced cell wall degradation. The performance of chitosan-based coatings agrees with earlier work on strawberries (Gol et al., 2013) and with the broader literature on chitosan (Romanazzi et al., 2017). The advantage of CH-GA over CH alone is consistent with the idea that combining polysaccharides

yields a more compact film. This resembles the benefit seen when gum arabic was combined with chitosan on bananas (Maqbool et al., 2011). The lower decay incidence in chitosan-containing coatings is consistent with chitosan's antimicrobial activity and its ability to elicit host defence responses (Elsabee & Abdou, 2013; Romanazzi et al., 2017).

The biochemical results show that the coatings acted on oxidative metabolism and not only on water relations. MDA accumulation was substantially lower in coated fruit, indicating less membrane lipid peroxidation. The strong correlations between MDA and firmness, phenolics and decay (Table 5) suggest that membrane damage is closely tied to the loss of fruit quality. This does not by itself prove causation, because senescence drives both oxidative damage and softening. The retention of phenolics, DPPH scavenging capacity and SOD activity in coated fruit agrees with the maintenance of antioxidants and antioxidant enzymes reported for chitosan-coated strawberries by Wang and Gao (2013). A plausible mechanism is that the coating modifies the internal gas atmosphere, which lowers metabolic rate and ROS generation. As a result, endogenous antioxidants are consumed more slowly.



The additional benefit of rosemary extract was moderate but consistent. CH-GA-RE had significantly lower MDA than CH-GA from day 9 and retained about 19 mg more phenolics per 100 g FW at day 12. Part of the phenolic retention in this treatment may reflect phenolics supplied by the extract itself, and the assays used here cannot distinguish extract-derived from fruit-derived compounds. This is a limitation of the approach. It is consistent with the expectation that incorporating natural antioxidants into the matrix can enhance protection (Rojas-Graü et al., 2009; Valencia-Chamorro et al., 2011). Alginate gave the smallest improvement among the coatings. This may reflect its hydrophilic character, which gives a weaker moisture barrier than the chitosan-based films (Hassan et al., 2018).

From a sustainability perspective, the coatings were composed of renewable, biodegradable, food-grade materials. Chitosan is derived from crustacean-processing by-products, gum arabic is a natural exudate and the extract comes from a common culinary herb. These materials may help reduce reliance on synthetic fungicides and plastic packaging, although cost, consumer acceptance and regulatory approval of each formulation need to be assessed.

Several limitations should be noted. Only one cultivar and one storage temperature were examined, and storage was limited to 12 days. Sensory evaluation was not included, so possible effects of the coating on taste or appearance remain unknown. Future work should include sensory panels, gas permeability measurements, additional enzymes such as catalase and peroxidase, and trials at retail temperatures and across cultivars.

CONCLUSION

Chitosan, alginate and composite chitosan–gum arabic coatings all reduced weight loss, decay and oxidative deterioration of strawberries during 12 days of cold storage. The composite coating enriched with rosemary extract gave the best results. It reduced weight loss by 54.1%, decay by 77.1% and MDA content by 41.7% compared with uncoated fruit. It also preserved 72.3% of firmness and more than 90% of total phenolics, DPPH scavenging capacity and SOD activity. The strong association between lipid peroxidation and quality loss indicates that controlling oxidative stress is a key mechanism by which edible coatings extend shelf life. Multi-component, biodegradable coatings containing natural antioxidants are therefore a promising, sustainable option for postharvest preservation of delicate fruits.

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Conflict of Interest

The authors declare no conflict of interest.

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