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Effect of a Novel Edible Composite Coating Based on Gum Arabic and Chitosan on Biochemical and Physiological Responses of Banana Fruits during Cold Storage

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ABSTRACT: The composite effects of gum arabic (GA) (5, 10, 15, and 20%) and chitosan (CH) (1.0%) on the biochemical and physiological characteristics of banana fruits stored at 13 ± 1 °C and 80 ± 3% relative humidity (RH) for 28 days and afterward for 5 days at simulated marketing conditions (25 °C, 60% RH) were investigated. Significant ($P \leq 0.05$) differences were observed for the entire GA plus CH treatments as compared to the control. However, the results showed that after 33 days of storage, the weight loss and soluble solids concentration of fruits treated with 10% GA plus 1.0% CH composite coating were 24 and 54% lower, whereas fruit firmness, total carbohydrates, and reducing sugars were 31, 59, and 40% higher than the control, respectively. Furthermore, the composite edible coating of 10% GA plus 1.0% CH delayed color development and reduced the rate of respiration and ethylene evolution during storage as compared to the control. Similarly, sensory evaluation results also proved the effectiveness of 10% GA plus 1.0% CH composite coating by maintaining the overall quality of banana fruits. Consequently, the results of scanning electron microscopy also confirmed that the fruits coated with 10% GA plus 1.0% CH composite edible coating had very fewer cracks and showed a smooth surface. These findings suggest that 10% GA plus 1.0% CH as an edible composite coating can be used commercially for extending the storage life of banana fruits for up to 33 days.

KEYWORDS: banana, chitosan, gum arabic, respiration, scanning electron microscopy, shelf life, sensory characteristics

INTRODUCTION

Banana (*Musa acuminata* L.) is one of the most important fruits grown in the tropical and subtropical regions of the world. Being a climacteric fruit, banana has a relatively short postharvest life because many processes affecting quality loss take place after harvest.[1] The storage life of banana is limited by several factors including transpiration, postharvest diseases and disorders, increased ripening process, and senescence. However, the main factor coupled with banana shelf life, particularly in tropical regions where the temperature is high, is increased rate of respiration, which results in rapid fruit ripening and early deterioration of fruit quality.[2]

Thus, research has focused on minimizing postharvest losses and extension of shelf life. Low-temperature storage is commonly used for retention of freshness as it reduces the rate of respiration and thermal decomposition,[1] but prolonged storage at low temperature may cause chilling injury and damage the fruit physiologically.[3] The shelf life of banana can be increased by using controlled atmosphere and hypobaric storage, but these techniques are capital intensive and expensive to run.[2] Therefore, there is a need for alternative methods that can prolong the postharvest storage life of banana at less expense.

Recently, increased efforts have been made to discover new preservative compounds obtained from natural sources (e.g., beeswax, paraffin, carnauba, shellac, gums, and chitosan), having no known hazardous effects on human health.[4] It is also believed that coating fruit with preservative compounds generates a modified atmosphere by creating a semipermeable barrier against oxygen, carbon dioxide, moisture, and solute movement, thereby retarding ripening and senescence.[5] There have been many compounds obtained from a variety of agricultural commodities and/or wastes of the food production industry used as edible coatings, and their major constituents are proteins, lipids, or polysaccharides.[6] Edible coatings based on polysaccharides have been used widely to extend the shelf life of fruits and vegetables.[7]

Gum arabic (GA) is a neutral or slightly acidic salt of a complex polysaccharide containing calcium, magnesium, and potassium ions,[8] obtained from the stems or branches of *Acacia* species, and is commonly used in the industrial sector as a food additive.[9] It is considered the least viscous and the most soluble among all of the hydrocolloids,[7] and, therefore, extensively used in the industrial sector as an emulsifier.[9] The gum derived from *Acacia senegal* is the main gum used for commercial purposes because it has better emulsification properties as compared to the gum obtained from *Acacia seyal*.[10] More than 50% of the world's production of GA is used in confectionary to delay sugar crystallization and for thickening of candies, jellies, glazes, and chewing gums.[11] It has also been approved as a safe compound by the joint FAO/WHO Expert Committee on Food Additives.[12]

Chitosan (CH) is also a polysaccharide, having a chemical structure close to that of cellulose, and has long been known to

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protect perishable foods from deterioration by reducing dehydration and respiration, maintaining the textural quality.[13] Many edible films and coatings based on chitosan alone and blended with gelatin and alcohol have been developed for the preservation of fresh fruits and vegetables such as mango, papaya, strawberry, and tomato.[14−19] In fact, chitosan is often considered to be the ideal preservative coating for fresh fruits and vegetables because of its excellent film-forming and biochemical properties.[13] Moreover, chitosan has been approved as a food additive in Korea and Japan since 1995 and 1983, respectively.[20,21] However, approval from the U.S. Food and Drug Administration (U.S. FDA) is still pending.[22]

In a recent study by our group, an edible composite coating based on GA and CH was developed, and it was found that 10% GA incorporated with 1.0% CH showed promising results in terms of controlling postharvest anthracnose of banana caused by *Colletotrichum musae* during cold storage.[23] During this study, some preliminary results were also obtained regarding quality parameters after 33 days of storage, but a comprehensive study is needed to understand the complete mechanism of edible composite coating for maintaining postharvest quality and shelf life.

Therefore, the present study was designed to evaluate the effect of composite coating on the extension of postharvest shelf life and maintaining the quality of banana fruit and also to investigate the influence of different concentrations of GA plus CH coatings on the gaseous exchange characteristics and sensory attributes of banana fruit during cold storage.

MATERIALS AND METHODS

Materials. Bananas (AAA group, cv. Pisang Berangan) were obtained at two different intervals of time from the same commercial orchard located at Beranang, Semenyih, Darul Ehsan Selangor, Malaysia. The fruits were visually selected for uniformity in size, color, and absence of blemishes and fungal infection and transported to the laboratory within 1 h.

Gum arabic powder, KB-120 food grade, was supplied by Jumbo Trading Co., Ltd. Bangkok, Thailand, and locally prepared shrimp shell chitosan (M_w = 500 kDa and 95% deacetylated) was obtained from Chitin-Chitosan Research Center of Universiti Kebangsaan Malaysia (UKM), Malaysia. All other chemicals were purchased from Sigma Chemical Co. (St. Louis, MO) and were of analytical grade.

Preparation and Application of GA and CH Coating Treatments. To prepare GA coating solutions at 5, 10, 15, and 20% (w/v), 5, 10, 15, and 20 g of powder was dissolved in 100 mL of purified water. The solutions were stirred with low heat (40 °C) for 60 min on a hot plate magnetic stirrer (model LMS-HTS-1003; Bunkyo-Ku, Tokyo, Japan) and then filtered to remove any undissolved impurities using a four layers cheesecloth. CH coating solution was prepared by dissolving 1.0 g of CH in 100 mL of purified water containing 0.5 mL (v/v) of glacial acetic acid. The solution was agitated constantly using an overhead stirrer (model IKA RW 14 basic; Fisher Scientific Sdn Bhd., Malaysia) for 60 min. The pH of both solutions was adjusted individually to 5.6 by adding 1 N NaOH using a pH-meter (model CyberScan pH 510; Eutech Instruments Pte Ltd., Singapore). The coating treatments were selected according to the previous study in banana.[23]

Before treatment application, banana fruits were washed with a solution of sodium hypochlorite (0.01%) for 3 min. The fruits were allowed to air-dry at room temperature (25 °C), after which they were randomly divided into five different treatments. Each treatment was conducted with four replicates. Followed by drying, the banana fruits were immersed into each concentration of GA (5, 10, 15, and 20%) incorporated with 1.0% CH coating solution for 2−3 min; it was assured that the coating solution was applied uniformly on the whole surface. Control fruits were dipped in purified water. GA plus CH composite coating solutions prepared were also used to measure the viscosity using a Viscometer (model LVDV-I Prime; Brookfield, USA) at a constant speed of 100 rpm and spindle number 64. The average values of each treatment were as follows: 5% GA + 1.0% CH, 27.2 ± 2.31 cpi; 10% GA + 1.0% CH, 56.4 ± 4.51 cpi; 15% GA + 1.0% CH, 409.1 ± 7.12 cpi; 20% GA + 1.0% CH, 1002.1 ± 12.31 cpi. After treatment, fruits were air-dried, packed in cardboard corrugated boxes, and stored (13 ± 1 °C and 80 ± 3% relative humidity (RH)) for 28 days and then for 5 days at simulated marketing conditions (25 °C and 60% RH). The data were recorded at 7 day internals for 28 days during cold storage and then for 5 days at simulated marketing conditions.

Determination of Physical Quality. *Weight Loss.* A total of 80 fruits from each treatment were weighed using a digital balance (model GF-6100, A&D Co. Ltd., Japan) at day 0 and at the end of each storage interval. The difference between initial and final fruit weights was considered as total weight loss during that storage interval and calculated as a percentage on fresh weight basis.

Fruit Firmness. Fruit firmness was determined by measuring the amount of force (N) to puncture a hole in the fruit on each sampling day, using an Instron Universal Testing Machine with an 8.00 mm plunger tip, single-column model (Instron 2519-104, Norwood, MA) interfaced with a computer. The machine was set for maximum compression with a speed of 20 mm/min. Measurements were taken for 12 fruits on each sampling day in each treatment at the stem end, midregion, and blossom end of each fruit using the probe, and then the average of three readings was recorded as the fruit firmness.

Color. Peel color was measured using the Hunter Lab System, Miniscan XE Plus colorimeter model (model 45/0-5; Reston, VA). The meter was equipped with a measuring head that had an 8 mm diameter measuring area and calibrated with standard black and white tiles. Values were recorded as L^* [white (100) to black (0)], $C^* = (a^{*2} + b^{*2})^{1/2}$, which represented the hypotenuse of a right triangle with values ranging from 0 = least intense to 60 = most intense, and hue angle ($h°$) was the angle of tangent^{-1} b^*/a^* ($h°$ represents red-purple at an angle of 0°, yellow at 90°, bluish green at 180°, and blue at 270°). The mean values of L^*, C^*, and $h°$ were obtained for 80 fruit sin each treatment from two different points along the banana circumference. Before readings were taken during each sampling day, the Miniscan XE Plus colorimeter was calibrated using calibration black and white tiles with values of X = 79.0, Y = 83.9, and Z = 87.9.

Determination of Chemical Quality. *Soluble Solids Concentration (SSC) and Titratable Acidity (TA).* SSC of banana pulp was determined using a Palettle Digital Refractometer (model PR-32α; Atago Co, Ltd. Japan). Briefly, banana fruit pulp (10 g) from a mixture of 12 fruits in each treatment was homogenized using a kitchen blender with 40 mL of purified water. The mixture was centrifuged at 5000*g* for 5 min and then filtered through cotton wool. A drop of the filtrate was then placed on the prism glass of the refractometer to obtain the %SSC reading. Before measurements were made, the refractometer was calibrated with purified water to give a 0% reading. The readings were multiplied by dilution factor to obtain an original %SSC of the banana pulp. The readings were also corrected to a standard temperature of 27 °C by adding 0.28% to obtain %SSC at 20 °C.

The remainder of the filtrate from SSC determination was used to measure TA, and TA was measured using the titration method.[24] Briefly, the filtrate (5 mL) with 2−3 drops of 0.1% phenolphthalein solution as an indicator was titrated using 0.1 N NaOH to an end point pink (pH 8.1). The results were expressed as the percentage of malic acid per 100 g of fresh weight.

Total Carbohydrates (TC) and Reducing Sugars (RS). The phenol−sulfuric acid method was used to estimate TC.[25] Briefly, banana pulp (2 g) from a mixture of 12 fruits in each treatment was taken into a boiling tube and hydrolyzed by keeping it in a boiling water bath for 3 h with 5 mL of 2.5 N HCl and cooled to room temperature (25 °C). Then the solution was neutralized with solid sodium carbonate (Na_2CO_3) until the effervescence ceases. The volume was made up to 100 mL and centrifuged at 12000*g* for 15 min. Sample solution (0.1 mL) was pipetted out in a test tube and the volume made to 1 mL with purified water. Purified water was used as a blank. Phenol solution (5%, 1 mL) and sulfuric acid (96%, 5 mL) were added to each test tube and mixed nicely. After 10 min, the mixture was placed in a water bath at 25−30 °C for 20 min. Readings were taken at 490 nm using a spectrophotometer (model Biochrom Libra S12; Biochrom Ltd., Cambridge, U.K.). Glucose was used as a working standard, and the amount of TC present in the sample solution was calculated using the standard graph

$$\text{absorbance corresponds to 0.1 mL of the test} = X\text{mg of glucose}$$

$$\text{100 mL of the sample solution contains} = \frac{X}{0.1} \times 100 \text{ mg of glucose} = \text{\% of total carbohydrate present}$$

To estimate the RS in juice of each treated sample, the method of Lane−Eynon[26] as described by Horwitz[27] was used.

Gaseous Exchange Analysis. *Respiration and Ethylene Evolution.* The rates of respiration and ethylene evolution were measured according to the method by Ali,[24] with slight modification. Respiration rate as indicated by CO_2 production was measured by placing two banana fruits in a 1 L plastic container for 1 h, and 1 mL of gas sample was withdrawn from the headspace with a gastight hypodermic syringe and analyzed with a gas chromatograph (GC) (Claru-500, Perkin-Elmer, USA) equipped with a stainless steel column (Porapak R 80/100). Helium served as the carrier gas at a flow rate of 20 mL min^{-1}. Temperatures were 60, 100, and 200 °C for the oven, injector, and thermal conductivity detector (TCD), respectively. One milliliter of CO_2 gas (1.0%) (Scotty Gases, Bellefonte, PA) was used as the external standard for calibration. The amount of CO_2 production was expressed in milliliters per kilogram per hour.

Ethylene evolution was measured by taking a 1 mL sample from each jar using a hypodermic syringe and injecting it into a GC. The GC was equipped with a stainless steel column (Porapak T, 100/120) and a flame ionization detector (FID). Nitrogen, hydrogen, and air flow rates were 20 mL min^{-1}. Nitrogen served as a carrier gas. Temperatures were 150, 200, and 200 °C for the oven, injector, and FID, respectively. One milliliter of ethylene gas (10 μL mL^{-1}) (Scotty Gases) used as external gas standard was injected for calibration. The amount of ethylene was expressed in microliters per kilogram per hour.

Scanning Electron Microscopy (SEM). Four fruits from each treatment were used to see the images under a scanning electron microscope (Philips XL30). Samples of 1.5 mm^3 of banana were taken from the midregion of each fruit. The samples were mounted on aluminum stubs and viewed and photographed under a scanning electron microscope.

Sensory Evaluation. Sensory evaluation of the fruit for taste, pulp color, texture, flavor, and overall acceptability for all of the samples was performed at the end of the storage period using the method of ref 6. For sensory evaluation a sample of 60 fruits in each treatment was stored separately and used at the end of storage period. Panelists were asked to score the difference among the samples by allotting numbers from 0 to 9, where 0−2 represented extreme dislike; 3−5, fair; 6−8, good; and 9, excellent for taste, pulp color, texture, flavor, and overall acceptability.

Statistical Analysis. The experiment was conducted in a completely randomized design (CRD) with four replications. Analysis of variance (ANOVA) was used to measure the treatment effect using computer software MSTAT-C, and means were separated using the least significant difference (LSD) test at ($P \leq 0.05$). The entire experiment was repeated twice, and data were pooled before analysis.

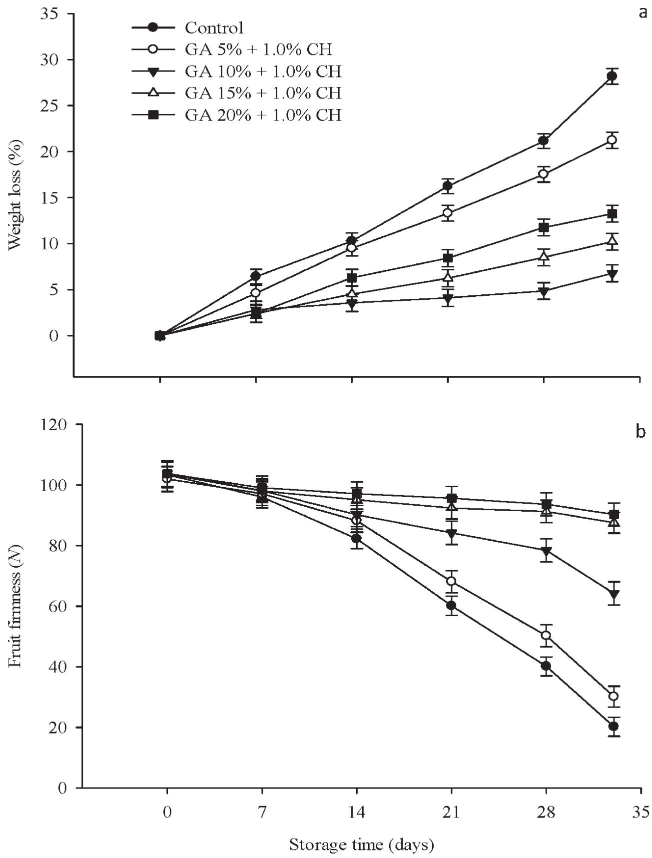

Figure 1. Effect of various concentrations of gum arabic incorporated with chitosan on (a) weight loss and (b) fruit firmness of banana fruits during storage (13 °C, 80% RH) for 28 days and afterward 5 days at simulated marketing conditions (25 °C, 60% RH). The vertical bars represent the standard error of means for four replicates.

RESULTS AND DISCUSSION

Physical Quality Changes of Banana Fruit. *Weight Loss.* The weight loss is considered to be the major determinant of storage life and postharvest quality of banana fruit. Figure 1a indicates that fruit coated with composite edible coatings showed significantly ($P \leq 0.05$) lower weight loss as compared to the control as the weight loss increased gradually during the storage period. However, the minimum weight loss was observed in 10% GA plus 1.0% CH treatment.

It is commonly believed that the weight loss from fresh fruits and vegetables is through the peel by vapor pressure,[28] which can cause flesh softening, fruit ripening, and senescence by metabolic reactions.[6] However, the respiration process also causes a weight reduction because a carbon atom is lost from the fruit in each cycle. In the present study, the reduction in weight loss was probably due to the effects of the composite coating, which served as a semipermeable barrier against oxygen, carbon dioxide, and moisture, thus reducing respiration, water loss, and oxidation reactions.[29,30] The results are supported by the findings of Banks,[31] who found that sucrose ester-based coatings on banana fruits extended their storage life through a reduction in water loss and a modification of the internal atmosphere. In this study, it was observed that 5 and 20% GA plus 1.0% CH treatments showed significantly higher weight loss as compared to 10 and 15% GA incorporated with 1.0% CH, which could be explained

Table 1. Development of L^*, C^*, and $h°$ of Peel in Banana Fruits Coated with Various Concentrations of Gum Arabic (GA) and Chitosan (CH) during Storage[a]

treatment	storage time					
	0 days	7 days	14 days	21 days	28 days	33 days
			L^* Value			
control	48.14 cd	57.04 c	62.07 b	70.12 a	69.02 ab	nd
5% GA + 1.0% CH	49.04 cd	56.43 c	65.43 b	71.64 a	67.37 ab	nd
10% GA + 1.0% CH	47.52 cd	48.12 cd	50.16 c	54.27 c	62.27 b	70.44 a
15% GA + 1.0% CH	47.98 cd	48.09 cd	50.70 c	52.53 c	55.38 c	58.50 c
20% GA + 1.0% CH	48.47 cd	49.78 cd	50.58 c	50.79 c	51.03 c	51.98 c
			C^* Value			
control	46.23 cd	50.39 b	53.52 ab	55.16 a	53.05 ab	nd
5% GA + 1.0% CH	45.95 d	49.85 c	53.05 ab	55.35 a	52.39 ab	nd
10% GA + 1.0% CH	44.92 d	48.60 c	52.57 ab	56.31 a	58.63 a	61.10 a
15% GA + 1.0% CH	46.21 cd	50.92 b	51.55 b	50.94 b	52.84 ab	54.52 b
20% GA + 1.0% CH	45.90 d	49.25 c	46.23 cd	45.17 d	46.36 cd	43.28 d
			$h°$ Value			
control	158.1 a	123.4 c	91.0 d	80.0 e	76.4 ef	nd
5% GA + 1.0% CH	160.0 a	127.8 c	110.0 d	99.0 d	90.3 d	nd
10% GA + 1.0% CH	159.4 a	156.2 a	152.4 a	136.1 c	120.0 c	110.0 d
15% GA + 1.0% CH	161.1 a	157.4 a	151.6 a	147.3 b	144.1 b	140.1 b
20% GA + 1.0% CH	159.8 a	156.8 a	151.4 a	150.2 b	148.7 b	145.3 b

[a] Means with different letters in a column are significantly different ($P \leq 0.05$) using LSD. Each value is the mean of four replicates. Data were recorded after 28 days at 13 °C, and 80% RH) and afterward 5 days at simulated marketing conditions (25 °C, 60% RH). nd, not detected due to rotting.

by the thickness of composite coatings. A coatig of 5% GA plus 1.0% CH was not so thick that it can provide enough barriers against water loss, whereas a 20% GA plus 1.0% CH composite coating was so thick that it completely covered the surface of the fruit and blocked the lenticels. Similar results were obtained in a recent study by our group when 10% GA was used alone as an edible coating on tomato.[32] Park et al.[33] also reported similar results for tomato coated with an edible corn-zein film. During their study they observed that corn-zien film coated too thickly showed too-low oxygen and too-high carbon dioxide concentrations and also produced ethanol. The primary reason for increased weight loss of thickly coated banana fruits might be the generation of heat and production of end products from anaerobic fermentation. Clearly, a relatively lower weight loss in the banana fruits that were coated with 10% GA incorporated with 1.0% CH composite coating contributed to extending shelf life and maintaining better fruit quality during storage.

Fruit Firmness. Firmness is the most important parameter that determines the postharvest shelf life and quality of fruit. Figure 1b shows that fruit coated with composite edible coatings presented significantly ($P \leq 0.05$) higher firmness as compared to the control at the end of storage period and that firmness decreased as the coating concentrations decreased. There was no significant (($P \leq 0.05$) difference in all treatments, up until day 14 of cold storage, but at the end of the storage period, fruit treated with 5% GA plus 1.0% CH and control clearly showed the lowest firmness values. The maximum firmness was retained by the 20% GA plus 1.0% CH followed by 15% GA plus 1.0% CH treated banana fruit.

Fruit softening is normally attributed to the destruction of cell structure and the deterioration in cell wall composition and intracellular materials.[34] It is a biochemical process that involves the hydrolysis of pectin and starch by enzymes, for example, wall hydrolases.[34] The progression in fruit ripening leads to the depolymerization or shortening of the chain length of pectin substances, which increased the activities of pectinesterase and polygalacturonase.[28] Low levels of oxygen and high levels of carbon dioxide restrict the activities of these enzymes and allow retention of the fruit firmness during storage. In agreement with these findings, Baez-Sañudo et al.[35] reported that respiration and ethylene consumption of 1-methylcyclopropene and chitosan-based composite edible coating on banana were lower than those of noncoated banana fruits. The reduced rate of respiration in coated bananas could be responsible for delaying ripening, which resulted in retention of firmness during storage. The maintenance of fruit firmness in bananas coated with 10% GA plus 1.0% CH composite coating could be due to the higher antifungal activity[23] and covering of the cuticle and lenticels, thus reducing infection, respiration, and other ripening processes during storage.[14,5]

Color. Peel color of banana fruit is one of the major visual attributes. There was continuous color change in bananas from green to yellow over the storage period. Uncoated control fruit and fruits treated with 5% GA plus 1.0% CH showed a faster change in color compared to higher concentrations of GA plus CH coatings (Table 1). The control and 5% GA plus 1.0% CH treated fruits attained their maximum color after 21 days of storage and by the end of 28 days, the fruits were dark brown in color as a result of faster ripening and were unmarketable due to shrivelling, excessive softness, and an overgrowth of fungal mycelium. The fruits treated with 10% GA plus 1.0% CH underwent slower changes in their peel color as indicated by the slower increase in L^* and C^* values. However, there was almost no change in the peel color in 15 and 20% GA plus 1.0% CH

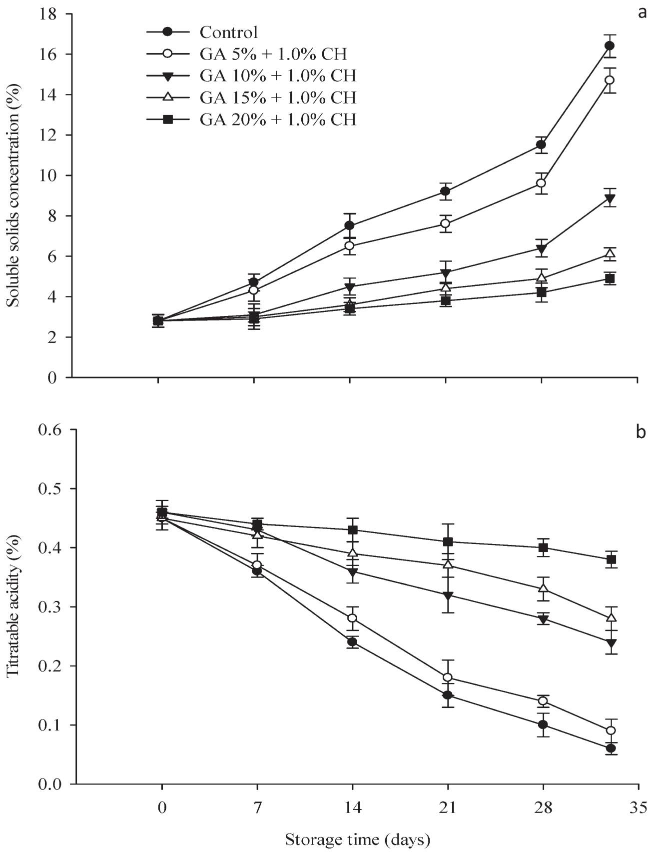

Figure 2. Effect of various concentrations of gum arabic incorporated with chitosan on (a) soluble solids concentration and (b) titratable acidity of banana fruits during storage (13 °C, 80% RH) for 28 days and afterward 5 days at simulated marketing conditions (25 °C, 60% RH). The vertical bars represent the standard error of means for four replicates.

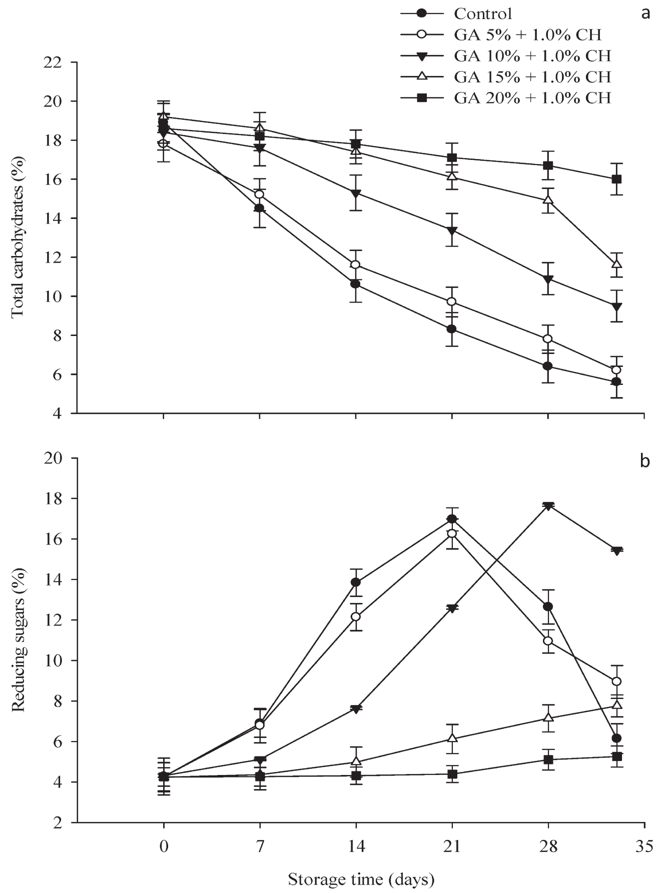

Figure 3. Effect of various concentrations of gum arabic incorporated with chitosan on (a) reducing sugars and (b) total carbohydrates of banana fruits during storage (13 °C, 80% RH) for 28 days and afterward 5 days at simulated marketing conditions (25 °C, 60% RH). The vertical bars represent the standard error of means for four replicates.

treated fruits until day 14, and after that there was a slight change in color by the end of the storage period.

Peel color is an important criterion of postharvest quality and consumer acceptability, especially with respect to bananas.[35] In this study, a composite coating of 10% GA plus 1.0% CH showed the best results in delaying the color change throughout the storage period, which might be due to an increase in carbon dioxide and a decrease in oxygen levels. The peel color retardation in banana fruit treated with higher concentrations of GA plus CH could be attributed to the slower rate of respiration and reduced ethylene production, leading to the creation of a modified atmosphere around the fruits. This, in turn, delayed the ripening process and senescence of the fruits, ultimately resulting in reduced color change and fruit firmness. In a previous study, it has been shown that elevated carbon dioxide levels (>1%) retarded fruit ripening by inhibiting ethylene synthesis.[5] Therefore, the presence of carbon dioxide around the fruit might be sufficiently high to suppress the activity of ethylene and, thus, retarded the ripening process.[5] The results from this study are in agreement with those of El-Anany et al.,[36] where edible coatings based on gum, wax, and glycerol were used to preserve Anna apples during cold storage. They found that GA used alone showed better results in maintaining fruit color and visual quality as compared to control. Similarly, edible coatings based on 1-methylcyclopropene and chitosan also slowed skin color development in bananas when stored at 22 °C for 8 days.[35] Ali et al.[14] also found delayed color development in chitosan-coated papayas. The differences in hue and color intensity are possibly due to the different levels of various pigments, for example, lycopene and carotenoids, synthesized during ripening. Delayed color development in fruits is also reported by the slow rate of chlorophyll degradation of peel tissues.[37]

Chemical Quality Changes of Banana Fruit. *SSC.* In general, a gradual increase in SSC was observed during the complete storage period (Figure 2a). However, in control fruits the value of SSC was significantly higher ($P \leq 0.05$) as compared to GA plus CH-coated fruits, and the rate of reduction in SSC was directly proportional to the concentrations of the GA plus CH composite coatings, whereas the lowest levels of SSC were observed in the fruits coated with 15 and 20% GA plus 1.0% CH. The present results revealed that the composite coatings provided an excellent semipermeable barrier around the fruit, which modified the internal atmosphere by reducing oxygen and/or elevating carbon dioxide levels and suppressed ethylene evolution.

Chitosan has been known to have filmogeneic properties, which create a modified atmosphere around the fruit and suppress ethylene production.[14] It is also believed that a decreased rate of respiration slows the synthesis and the use of metabolites, resulting in lower SSC values.[28] Similar results were obtained in a previous study, when tomato fruits were coated with different concentrations of GA alone and stored for 20 days at 20 °C.[32] Furthermore, these results are also in agreement with the findings of Kittur et al.,[38] who recorded a slow rise in SSC in mango and banana fruits treated with chitosan alone.

TA. Malic acid is the major organic acid in ripe banana fruit. The values of TA in coated and uncoated banana fruits decreased gradually over storage time, with the most significant ($P \leq 0.05$) changes after 14 days (Figure 2b). However, the maximum decrease in TA was recorded in the control fruit followed by 5% GA plus 1.0% CH. On the other hand, a slight decrease in TA was observed in fruits coated with 20% GA plus 1.0% CH concentration. The low levels of TA in the control fruit as compared to the coated fruits suggest that the GA plus CH composite coating delayed the ripening process by providing a semipermeable film around the fruit. Organic acids, such as malic or citric acid, are considered to be the primary substrates for respiration process; therefore, a reduction in acidity is expected in high-respiring fruits.[36] It is also believed that edible coatings reduce the rate of respiration and may therefore delay the utilization of organic acids.[28] Previously, in many studies the retention of TA has been reported in various fruits and vegetables treated with edible coatings and films.[3,14,28] Han et al.[16] also reported that in chitosan-coated raspberries and strawberries, the changes in TA were slowed and effectively resulted in delayed fruit ripening.

Total Carbohydrates (TC) and Reducing Sugars (RS). The interaction of carbohydrates and sugars is considered to be one of the basic criteria to evaluate the fruit ripening. The amount of TC in coated and uncoated bananas decreased gradually over storage time, whereas the highest decrease in TC was recorded in the control fruit followed by 5% GA plus 1.0% CH. On the other hand, a slight decrease in TC was observed in bananas coated with 20% GA plus 1.0% CH (Figure 3a).

The amount of RS increased in control and 5% GA plus 1.0% CH fruits until day 21, but after that there was a sudden decrease, which continued until the end of the storage period (Figure 3b). Fruits treated with 10% GA plus 1.0% CH showed the highest amount of RS after 28 days of storage, and after that a sharp decrease was observed. On the other hand, a constant increase in RS was observed in 15 and 20% GA plus 1.0% CH coated fruits during the complete storage period.

The lowest amount of TC but the highest amount of RS in control as well as 5% GA plus 1.0% CH coated fruits suggests that the higher concentrations of GA plus CH composite coatings delayed ripening of banana fruits by providing a semipermeable film around the fruit. During ripening, the fruit texture is changed due to the alteration in cell wall structure, and the degradation of starch and resultantly bound carbohydrate fractions, especially pectic substances and hemicelluloses, is rapidly depolymerized by hydrolysis.[34] The starch contents in banana pulp are steadily decreased during the ripening process, which leads to the production of sugars,[39] but at later stages of ripening these sugars are used as substrates in respiration.[14] Thus, a sharp decrease in TC and a faster increase in RS contents of control and 5% GA plus 1.0% CH coated fruits suggest that those fruits were ripened more quickly as compared to 10, 15, and 20% GA plus 1.0% CH coated fruits. Similar results were also observed in a previous study by Jiang et al.,[3] who found that starch content in banana fruit decreased drastically during storage; however, 1-MCP treatment slightly retarded the decline in starch level of the fruit. Starch content in mango fruit was also decreased dramatically during storage, but the coating treatments, especially TP−chitosan,

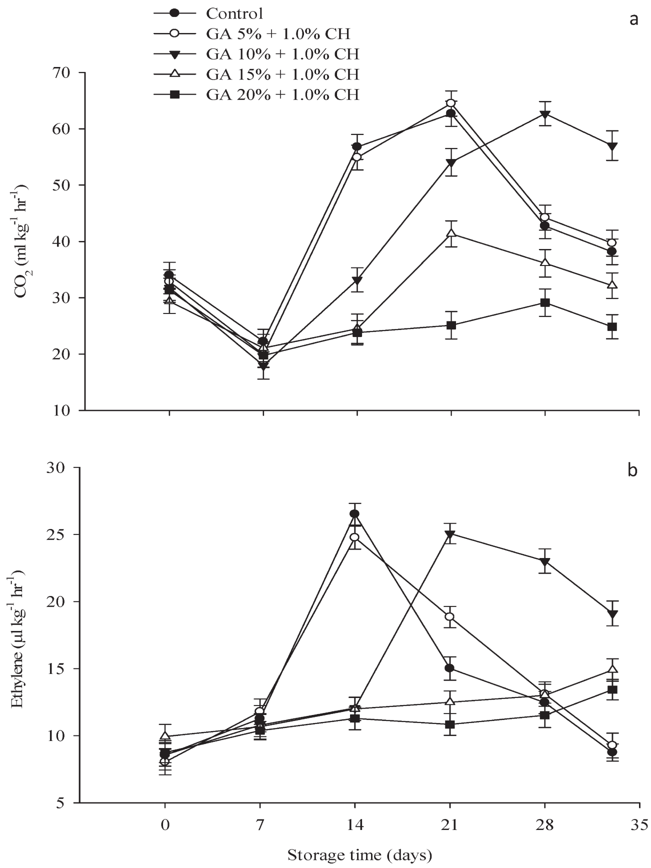

Figure 4. Effect of various concentrations of gum arabic incorporated with chitosan on (a) CO_2 and (b) ethylene evolution of banana during storage (13 °C, 80% RH) for 28 days and afterward 5 days at simulated marketing conditions (25 °C, 60% RH). The vertical bars represent the standard error of means for four replicates.

significantly delayed the decline of starch content in mangoes.[15] In another study, Kittur et al.[38] demonstrated that a lower rate of RS was found in banana coated with chitosan than in uncoated fruits. Tripathi et al.[40] also found an increase in reducing sugars of banana during ripening, and this increase in RS was correlated with the enzymatic conversion of starch to reducing sugar and also the conversion of some nonreducing sugars to reducing sugars through the process of inversion.

Respiration Rate and Ethylene Production. The rates of respiration and ethylene production in fresh fruits and vegetables are considered good indices for the determination of storage life. A decrease in respiration rate was observed initially in all treated and untreated banana fruits after 7 days of storage (Figure 4a). Thereafter, a sharp increase in untreated control and 5% GA plus 1.0% CH treated fruits was observed, which reached a peak value after 21 days, and after that, there was a continuous decrease until the end of the storage period. However, fruits treated with 10% GA plus 1.0% CH showed significantly delayed respiration rates and showed the same peak height after 28 days of storage, whereas in the case of 15 and 20% GA plus 1.0% CH coated fruits, a slight increase followed by a decrease in respiration rate was observed during the complete storage period.

Ethylene production in untreated control and 5% GA plus 1.0% CH increased rapidly, reached a peak after 14 days, and then decreased sharply (Figure 4b). However, 10% GA plus 1.0% CH

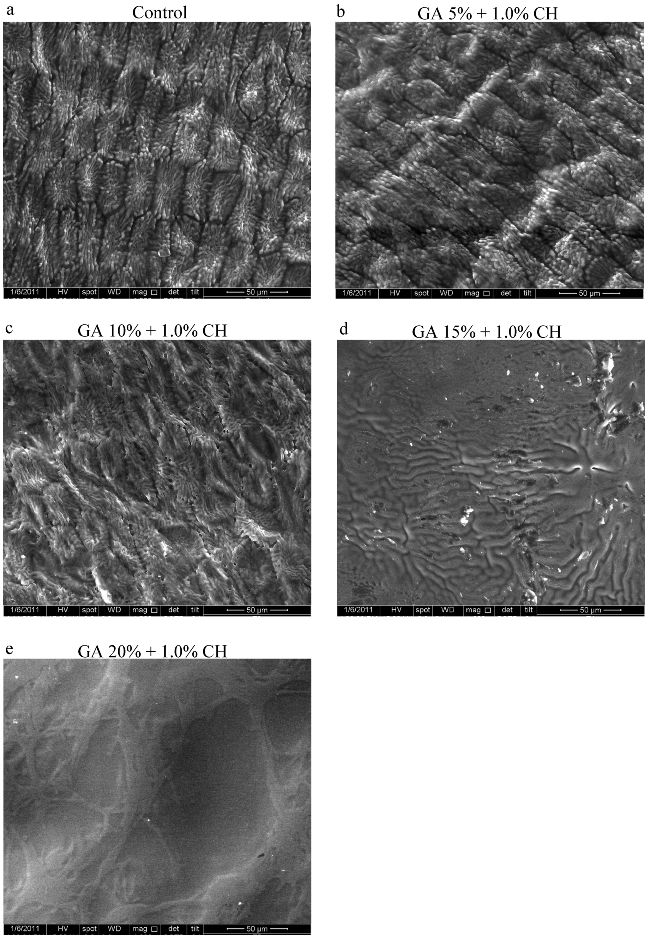

Figure 5. SEM photographs (50 μm) of coated and uncoated banana fruits surface.

treated bananas showed a maximum value of ethylene evolution after 21 days of storage and, thereafter, a slow decrease until the end of the storage period, whereas the fruits treated with 15 and 20% GA plus 1.0% CH showed a slight increase in ethylene production during the complete storage period.

The delayed increase in respiration rate and ethylene production of 10% GA plus 1.0% CH as compared to untreated control and 5% GA plus 1.0% CH coated fruits suggests that the composite coating exerted a barrier to the gaseous exchange. The reduced rate of respiration and ethylene production in banana fruits might be correlated with a delayed senescence and a reduced susceptibility to decay.[23] The pattern of respiration rate and ethylene production in this study was in agreement with the findings of Banks,[31] who reported that coating bananas with TAL-Prolong suppressed the rates of respiration and ethylene production by modifying the internal atmosphere of the fruits. Similar results were also observed by Ali,[24] who found that control fruits showed an early rise in respiration and ethylene evolution as compared to 1.5% CH coated papayas during 5 weeks of storage. A reduction in respiration rate and ethylene production as a result of coating with films has also been reported by many researchers in various fruits such as papaya, grape, mango, and strawberry.[14,19,38,41,]

SEM of Banana Pericarp. The uncoated control and fruits treated with 5% GA plus 1.0% CH had severe structure surface damages such as cracks on epidermal cells of the skin, some becoming big enough to be cleavage, whereas the pericarp surface of 10% GA plus 1.0% CH coated fruit had very fewer cracks and showed a smooth surface (Figure 5a−c). SEM results of the fruits coated with higher concentrations of GA plus CH showed that coatings completely covered the cuticles and blocked the pores on the fruit surface (Figure 5d,e).

The cracking and shrivelling of control as well as 5% GA plus 1.0% CH coated fruits suggest that the waxy cuticle surface on the fruits facilitated the water loss from the surface, the higher rate of respiration, and finally the fungus invasion. It is believed that application of surface coatings covers the cuticle and blocks the pores on the fruit surface.[42] Furthermore, coatings also increase the resistance between the internal and external atmospheres of the fruits, which augment oxygen, carbon dioxide, and water partial pressure difference and decrease partial transmission rate.[24] These effects are the means by which edible coatings can slow the deterioration of banana fruits by modifying the internal atmosphere, suppressing the respiration rate, and reducing transpiration losses.

Table 2. Sensory Evaluation of Banana Fruits Coated with Various Concentrations of Gum Arabic (GA) and Chitosan (CH) after Storage ([a])

treatment	taste	pulp color	texture	flavor	overall acceptability
control	0.0 c	0.0 c	0.0 c	0.0 d	0.0 c
5% GA + 1.0% CH	0.0 c	0.0 c	0.0 c	0.0 d	0.0 c
10% GA + 1.0% CH	7.5 a	7.0 a	6.5 a	6.5 a	7.0 a
15% GA + 1.0% CH	3.0 b	3.0 b	3.5 b	3.0 b	3.0 b
20% GA + 1.0% CH	2.5 b	3.0 b	2.5 b	2.0 c	2.5 b
LSD value	0.724	0.813	0.641	0.910	0.564

[a] Means with different letters in a column are significantly different at $P \leq 0.05$ using LSD. Storage conditions: 28 days at 13 °C, 80% RH and afterward 5 days at 25 °C, 60% RH (n = 60).

Sensory Evaluation. Sensory evaluation of coated and uncoated banana fruits at the end of the storage period revealed significant ($P \leq 0.05$) differences in taste, pulp color, texture, flavor, and overall acceptability (Table 2). Fruits treated with 10% GA plus 1.0% CH attained the highest scores by the panelists in all tested parameters. The control or those treated with 5% GA plus 1.0% CH ripened after 21 days of storage and, thereafter, started rotting. Therefore, those fruits were not presented to the panelists for sensory evaluation, whereas those coated with 15 and 20% GA plus 1.0% CH were unable to ripen properly even after 33 days of storage and developed poor pulp color and inferior texture and were off-flavored. The sensory attributes of bananas coated with 10% GA plus 1.0% CH concentration demonstrated the overall superiority after 33 days of storage. These results suggest that 10% GA plus 1.0% CH composite coating can be used successfully as an edible coating for prolonging the shelf life and improving banana fruit quality during storage. Similar results were observed in a previous study by Ali et al.[32] when tomato fruits were coated with GA alone and stored for 20 days at 20 °C. Ali et al.[14] also found superior results after 5 weeks of storage when they coated papaya fruits with 1.5% chitosan alone.

Conclusions. In conclusion, the present study indicates that GA plus CH, as a preservative material, could delay ripening by inhibiting the respiration rate in banana fruits for up to 33 days.

The results suggest that a composite coating based on 10% GA plus 1.0% CH has positive effects on banana fruits during storage as compared to other concentrations of GA plus CH and control. Furthermore, sensory evaluation results also confirmed the overall acceptability of bananas treated with a 10% GA plus 1.0% CH composite coating. Therefore, 10% GA plus 1.0% CH could be used in the future as a novel edible composite coating in commercial applications for prolonging the storage life of banana fruits.

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