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The Effect of Chitosan-Based Edible Coating and Salicylic Acid with the Addition of Green Tea Extract on Extending the Shelf Life of Banana Fruit (*Musa paradisiaca* L.)

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ABSTRACT

Banana (Musa paradisiaca L.) ripens rapidly after harvest, resulting in short shelf life and high postharvest losses. Thus, delaying ripening is essential to maintain quality. This study aimed to evaluate the effects of salicylic acid (SA) and green tea extract (GTE) combinations on the postharvest quality of banana cv. Raja. The experiment used a factorial Completely Randomized Design with SA (3, 4, and 5 g) and GTE (30 and 35 mL), plus a control. Fruits were coated with chitosan-based solutions, stored at room temperature, and evaluated for weight retention, color change (ΔE), firmness, total soluble solids (TSS), and ethylene production. Data were analyzed using ANOVA and MANOVA. Results showed significant effects ($p < 0.05$) of SA and GTE on all parameters. The control exhibited higher weight retention (80.29%) and moderate color change (ΔE = 7.94). The sample A3B2 with combination of SA 5 g and GTE 35 mL gave the highest weight retention (85.13%) and TSS (26.5%) but faster softening and color change. In contrast, SA 5 g + GTE 30 mL (A3B1) better maintained firmness (3.0 kg/cm²) and suppressed ethylene production. In conclusion, A3B1 was identified as the most effective treatment for extending the shelf life and maintaining the postharvest quality of banana cv. Raja.

1. INTRODUCTION

Bananas (*Musa paradisiaca* L.) are widely consumed across tropical and subtropical regions, where they play an important role in food security, nutrition, and rural livelihoods. Their high nutritional value, low cost, and year-round availability have made them staple foods in many developing countries. However, bananas present a significant postharvest challenges. They are climacteric fruits that ripen quickly after harvesting. This accelerated ripening is driven by a rise in respiration and ethylene production and is accompanied by a series of visible and structural changes. The peel gradually loses its green color, cell walls begin to weaken, starch is converted into sugars, and the flesh softens. Together, these processes result in a short shelf life (Gidado, 2024). When proper storage conditions are lacking—particularly in regions without cold storage infrastructure where bananas are typically kept at room temperature—these changes progress quickly and lead to substantial postharvest losses (Sugianti *et al*., 2022). Therefore, the development of efficient postharvest technologies to delay ethylene-induced ripening while preserving fruit quality under ambient conditions remains a challenge.

Salicylic acid (SA) is a phenolic signalling molecule involved in plant defence and stress responses and has emerged as a promising postharvest regulator for climacteric fruits. Previous studies have demonstrated that exogenous SA application improves antioxidant defences and membrane integrity and delays senescence by inhibiting ethylene biosynthesis through suppression of ACC synthase and ACC oxidase activities (Srivastava & Dwivedi, 2000). Recent studies have linked SA-mediated ethylene regulation with delayed peel color change, firmness retention, reduced cell wall degradation, and oxidative damage during storage (Changwal *et al*., 2021; Kumar *et al*., 2021), preserving appearance and texture. In parallel, green tea extract (GTE) has gained attention as an additive in postharvest preservation. GTE is rich in polyphenols, especially epigallocatechin gallate (EGCG) which exerts antioxidant activity by scavenging reactive oxygen species and decreasing oxidative stress, thus accelerating chlorophyll breakdown, lipid peroxidation and cell wall degradation during ripening (Xing *et al*., 2019). However, most studies have focused on non-climacteric fruits or storage at refrigeration temperatures, limiting their relevance for bananas in countries at ambient temperatures (Jayamali *et al*., 2022; Ulfa *et al*., 2024).

In addition to biochemical regulation, edible coatings are a strategy for preservation postharvest quality. Chitosan based coatings have film forming properties, biodegradability and nontoxicity. They form a semipermeable barrier that reduces transpiration, oxygen influx, and ethylene diffusion, thereby lowering respiration and slowing ripening (Shah *et al*., 2020). In bananas, chitosan coatings reduce weight retention, delay peel color changes, and maintain firmness at room temperature (Aziz *et al*., 2021; Gidagiri *et al*., 2025). Chitosan carries bioactive compounds, enabling release and enhancing stability in systems (Shiekh *et al*., 2022).

Although salicylic acid, green tea extract, and chitosan coatings have each been independently reported to delay fruit ripening, their integrated application within a chitosan based edible coating for banana (*Musa paradisiaca* L.) cv. Raja under room temperature storage has not been systematically evaluated in terms of quality related ripening indicators across storage duration. Combined postharvest treatments have received increasing interest to extend fruit shelf life and maintain quality, but their effects on the temporal dynamics of ripening-related attributes are poorly understood. In particular, there is little information on the changes in peel color and fruit firmness during the storage period and the related physiological responses, such as weight loss, accumulation of total soluble solids and ethylene production, under ambient storage conditions that are representative of commercial distribution and household storage environments. This limitation is particularly true for banana cv. Raja, a regionally important cultivar whose postharvest physiological behaviour may differ from more widely studied cultivars such as Cavendish (Aziz *et al*., 2021; Hosseini *et al*., 2023).

Salicylic acid, green tea extract and chitosan coatings have been reported to delay fruit ripening. Nevertheless, the combined use of salicylic acid and green tea extract in a chitosan based edible coating has never been systematically evaluated in banana (*Musa paradisiaca* L.) cv. Raja. More specifically, there is only limited information on its effects on ripening-related quality attributes during ambient storage. Particularly, the time-dependent modulation of ripening behaviour by combined postharvest treatments including peel color development, firmness degradation, weight loss, total soluble solids accumulation and ethylene production under ambient storage conditions representative for real world supply chain and household environments remains poorly understood. Therefore, this study aimed to evaluate the effect of salicylic acid and green tea extract incorporated into a chitosan based edible coating on quality related ripening indicators of banana (*Musa paradisiaca* L.) cv. Raja during room temperature storage, with particular emphasis on peel color development, firmness retention, weight retention, total soluble solids, and ethylene production.

2. MATERIALS AND METHODS

2.1. Material

Banana (*Musa paradisiaca* L.) fruits at uniform physiological maturity, characterized by a fully green peel and absence of visible defects or disease symptoms, were obtained from the Agricultural Technology Assessment and Development Installation (IP2TP), Ungaran, Semarang. Salicylic acid (SA) and chitosan were purchased from Sigma-Aldrich (Jakarta, Indonesia). Green tea extract (GTE) for cosmetic grade was purchased from Kimia Jaya Abadi (Semarang, Indonesia). Demineralized (demin) water was used throughout the study.

2.2. Experimental Design

The experiment employed a factorial Completely Randomized Design (CRD) with two factors: SA concentration (3 g, 4 g, 5 g) and GTE volume (30 mL, 35 mL). A control (without SA and GTE) was included, resulting in seven treatments: Control, A1B1 (SA 3 g + GTE 30 mL), A1B2 (SA 3 g + GTE 35 mL), A2B1 (SA 4 g + GTE 30 mL), A2B2 (SA 4 g + GTE 35 mL), A3B1 (SA 5 g + GTE 30 mL), and A3B2 (SA 5 g + GTE 35 mL). All solutions contained 20 g/L chitosan as a coating base.

2.3. Preparation of Coating Solution and Fruit Treatment

The coating solutions were prepared by first dissolving salicylic acid (SA) into the chitosan solution, followed by the addition of green tea extract (GTE) according to the specified treatment volume. Banana fruits were immersed in the respective treatment solutions for approximately 5 min to ensure uniform coating coverage, then removed, allowed to drain, and air-dried at room temperature. After drying, the fruits were stored at ambient conditions (27–29 °C). Control fruits were maintained under the same storage conditions without any treatment application.

2.4. Analysis of Postharvest Parameters

2.4.1. Fruit remaining weight analysis

The remaining fruit weight was measured to evaluate moisture loss during storage and the effectiveness of the edible coating treatments in reducing transpiration and delaying postharvest deterioration. The banana fruits were individually weighed at the beginning of the storage (initial weight) and at 0, 5, 10, 15 and 20 days of storage. The same fruits were used throughout the storage period to maintain consistency in measurements.

Fruit weight retention was calculated as the percentage of weight loss relative to the initial weight (Equation 1). To express the proportion of weight retained by the fruit, the fruit remaining weight (%) was calculated using Equation 2.

$$Weight\ loss\ (\%) = \frac{W_0 - W_t}{W_0} \times 100\% \tag{1}$$

$$Remaining\ weight\ (\%) = 100 - Weight\ loss\ (\%) \tag{2}$$

where W_0 is the initial weight, and W_t is weight on day *t*.

2.4.2. Analysis of Fruit Color

Peel color was measured using a colorimeter (WR 10QC, FRU, China) to evaluate changes in fruit surface color during storage. Color parameters were recorded in the CIELAB color space, including $L*$ (lightness), $a*$ (green to red chromaticity), and $b*$ (blue to yellow chromaticity). These values are the color changes that result from the reflection of particular wavelengths of light from the surface of the fruit. To compensate for the natural color heterogeneity of the banana peel, measurements were taken at three different points on each fruit, approximately 120° apart around the equatorial region, and mean values were used for analysis. The color difference (ΔE) was calculated as the following:

$$\Delta E = \sqrt{(\Delta L^*)^2 + (\Delta a^*)^2 + (\Delta b^*)^2} \tag{3}$$

2.4.3. Fruit Firmness Analysis

Fruit firmness was measured with an analogue penetrometer (GY 3, Y Wang Qiang, China) to evaluate the changes of fruit texture during storage. Measurements were made by penetration of the fruit pulp to a maximum depth of 10 mm. Firmness was measured at two opposite points in the equatorial region of each fruit to minimize the effect of tissue variability and the average value was used for analysis.

2.4.4. Total Soluble Solids (TSS) Analysis

To evaluate the changes in sugar accumulation during fruit ripening, the total soluble solids (TSS) content was measured. TSS was measured from banana juice using a digital refractometer, and was expressed as percentage °Brix.

2.4.5. Ethylene concentration analysis

Ethylene production was measured to evaluate the effect of the coating treatments on ripening related ethylene evolution during storage. Ethylene concentration was determined using a portable ethylene analyzer (WASP XM E C2H4, Hunan Guorui Instrument Co., Ltd., Hunan, China). Individual banana fruits were placed in airtight containers and incubated at room temperature for 1 h to allow ethylene accumulation in the headspace. After incubation, headspace gas was sampled and analyzed for ethylene concentration. Ethylene production was expressed as the amount of ethylene produced per unit fruit mass per unit time and calculated using the following equation:

$$Ethylene\ production = \frac{C \times V}{W \times t} \tag{4}$$

where C is the ethylene concentration in the headspace (μL/L), V is the container volume (L), W is the fruit fresh weight (kg), and t is the incubation time (h). Results were expressed as $\mu L \cdot kg^{-1} \cdot h^{-1}$.

3. RESULTS AND DISCUSSION

3.1. Effect of combining salicylic acid (SA) and green tea extract (EGT) on fruit weight reduction

Weight change during storage is a critical postharvest indicator because it reflects water migration from the fruit surface and substrate consumption during respiration. In the present study, all banana samples showed a progressive decline in the values from day 0 to day 20, as shown in Figure 1. Because all samples had an initial weight retention of 100% on day 0, the values gradually decreased throughout storage. Based on the day-20 values, sample A3B2 (SA 5 g + GTE 35 mL) showed the highest weight retention (85.13%), corresponding to the lowest actual weight loss (14.87%). This performance was better than the control fruit, which retained 80.29% of its initial weight and therefore experienced 19.71% actual weight loss.

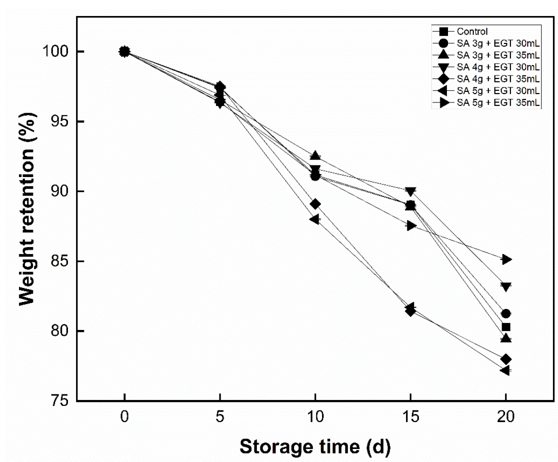

Figure 1. Effect of combined SA and EGT coating treatments on fruit weight reduction during 20 days of storage at room temperature (27–29 °C).

The improved retention in the A3B2 (SA 5 g + GTE 35 mL) treatment suggests that a higher concentration of salicylic acid combined with a greater volume of green tea extract formed a coating that more effectively reduced moisture loss. This result is consistent with the general function of edible coatings in bananas, which is to restrict gaseous exchange, reduce water loss, and slow physiological deterioration during storage (Shinga *et al*., 2025). The relevance of chitosan-based coatings is particularly important because their film-forming capacity can create a semi-permeable barrier on the fruit surface, thus modifying the diffusion of oxygen and carbon dioxide, and decreasing the loss of mass due to transpiration (Dai *et al*., 2025). Recent studies on chitosan-based coatings for banana corroborate this mechanism, indicating that modified chitosan layers can retard the changes associated with ripening by enhancing the gas and water barrier properties and preserving the physical quality during storage (Roidoung *et al*., 2025).

The incorporation of green tea extract could further enhance the coating performance due to the presence of catechins and other polyphenolic compounds. Green tea incorporated into edible coatings has been reported to result in less weight retention and better visual quality of fresh fruit during storage which means that phenolics derived from tea can be used as active coating constituents and not as mere additives (Jayamali *et al*., 2022). In the present banana samples, this mechanism may explain why A3B2 sample gave the strongest protection against mass reduction. Salicylic acid may also contribute indirectly by delaying ripening-associated metabolic activity; recent postharvest work has shown that salicylic acid is associated with ethylene evolution, membrane stability, and shelf-life regulation in climacteric fruit systems (Changwal *et al*., 2021). The statistical analysis of weight retention is presented in Table 1.

Table 1. MANOVA test results for weight retention during the storage time.

Effect		Value	F	Hypothesis df	Error df	Sig.
Intercept	Pillai's Trace	1.000	1390302480.7[b]	4.000	11.000	0.000
	Wilks' Lambda	0.000	1390302480.7[b]	4.000	11.000	0.000
	Hotelling's Trace	505564538.43	1390302480.7[b]	4.000	11.000	0.000
	Roy's Largest Root	505564538.43	1390302480.7[b]	4.000	11.000	0.000
SA oncentration×GTE Concentration	Pillai's Trace	2.000	576671.604	8.000	24.000	0.000
	Wilks' Lambda	0.000	611225.009[b]	8.000	22.000	0.000
	Hotelling's Trace	513995.699	642494.624	8.000	20.000	0.000
	Roy's Largest Root	386020.478	1158061.435[c]	4.000	12.000	0.000

However, the weight retention response was not linear for all formulations. Some treatments like A2B2 (SA 4 g + GTE 35 mL) and A3B1 (SA 5 g + GTE 30 mL) had lower retention final than the control. This suggests that increasing only one component was not necessarily beneficial for the coating performance. The non-balanced ratio between salicylic acid and green tea extract can affect the homogeneity of solution, adhesion of coating, surface coverage or film permeability. Therefore, the weight data should be interpreted as a concentration-dependent response. From the perspective of mass retention only, A3B2 (SA 5 g + GTE 35 mL) was the most favorable treatment, followed by A2B1 (SA 4 g + GTE 30 mL) and A1B1 (SA 3 g + GTE 30 mL).

3.2. Effect of Combining SA and GTE on Fruit Firmness

Fruit firmness declined markedly in all treatments during storage, confirming the expected softening behavior of climacteric banana fruit. Initial firmness values were approximately 22-24 N, whereas day-20 values decreased to around 1.1-3.0 N depending on the formulation, as shown in Figure 2. The highest firmness at the end of storage was recorded in sample A3B1 (SA 5 g + GTE 30 mL) (3.0 N), followed by the control (2.3 N), sample A2B1 (SA 4 g + GTE 30 mL) (2.1 N), and sample A1B1 (SA 3 g + GTE 30 mL) (2.0 N). However, the sample A3B2 (SA 5 g + GTE 35 mL) showed the lowest final firmness (1.1 N), which means the fastest texture deterioration among the tested coatings. Sample A3B1 (SA 5 g + GTE 30 mL) remained firm, indicating that this formulation was more efficient in delaying the softening of tissues than the other combinations. Banana softening is closely associated with climacteric ripening, a process in which ethylene initiates a series of biochemical changes, including starch conversion, cell wall disassembly, pectin modification, and hemicellulose degradation. A recent review on banana edible coatings emphasises that ripening is related to enzymatic degradation of cell wall structures which directly result in fruit softening and low marketability (Shinga *et al*., 2025). Comparative postharvest work on banana, mango, and papaya has also shown that texture changes are associated with cell wall composition and ripening regulation during cold storage (Li *et al*., 2023). Therefore, the higher final firmness in sample A3B1 (SA 5 g + GTE 30 mL) can be regarded as a slower softening response, rather than a simple physical surface effect. The statistical analysis supporting these observations is presented in Table 2.

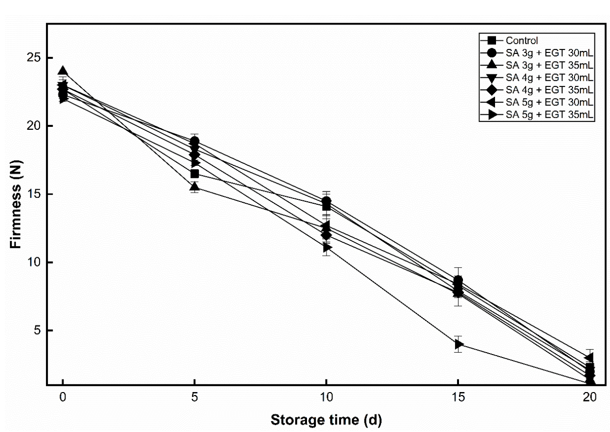

Figure 2. Effect of combined SA and EGT coating treatments on firmness changes of banana fruit during 20 days of storage at room temperature (27–29 °C).

Table 2. MANOVA test results for fruit firmness during the storage time

Effect		Value	F	Hypothesis df	Error df	Sig.
Intercept	Pillai's Trace	1.000	184651046.47[b]	5.000	10.000	.000
	Wilks' Lambda	.000	184651046.47[b]	5.000	10.000	.000
	Hotelling's Trace	92325523.23	184651046.47[b]	5.000	10.000	.000
	Roy's Largest Root	92325523.23	184651046.47[b]	5.000	10.000	.000
SA Concentration×GTE Concentration	Pillai's Trace	2.000	93829.707	10.000	22.000	.000
	Wilks' Lambda	0.000	93638.774[b]	10.000	20.000	.000
	Hotelling's Trace	102793.03	92513.730	10.000	18.000	.000
	Roy's Largest Root	72599.25	159718.359[c]	5.000	11.000	.000

The protective effect of sample A3B1 (SA 5 g + GTE 30 mL) might be due to a more balanced interaction between chitosan matrix, salicylic acid and green tea extract. Chitosan coatings can reduce the level of oxygen surrounding the fruit and slow down the rate of respiration while salicylic acid can control the ripening ethylene responses. Green tea polyphenols also have antioxidant activity and have the potential to reduce oxidative stress in fruit tissue. The difference between A3B1 and A3B2 though is considerable. Salicylic acid was comparable for both treatments. However the coating texture retaining ability decreased with increasing concentration of GTE from 30 mL to 35 mL. The higher dose of GTE did not seem to bring any extra protection against the loss of firmness and it may have affected the permeability of the coating, its interaction with the surface of the fruit or the internal response to ripening.

This result also shows that weight retention and firmness are controlled by different dominant mechanisms. Sample A3B2 (SA 5 g + GTE 35 mL) was the best treatment for reducing mass loss, but it was the weakest treatment for maintaining firmness. The discrepancy indicates that a coating can be effective as a water-loss barrier while still allowing or even accelerating internal texture degradation. For this reason, sample A3B1 (SA 5 g + GTE 30 mL) should be considered the most suitable treatment when the main quality target is texture preservation, whereas sample A3B2 is more suitable when the objective is to minimize mass loss.

3.3. Effect of Combining SA and GTE on TSS

Total soluble solids (TSS) indicate the accumulation of soluble sugars resulting from starch conversion, which increases as total starch content decreases over the 20-day storage period. This process is mediated by starch-degrading enzymes such as amylase and iso-amylase, whose activity is stimulated by endogenous ethylene signals (Chen *et al*., 2026). The increase in percentage indicates that the fruit is ripening as expected, but postharvest treatments keep this increase within the desired control range. The changes in total soluble solids (TSS) and peel color during storage are shown in Figures 3.

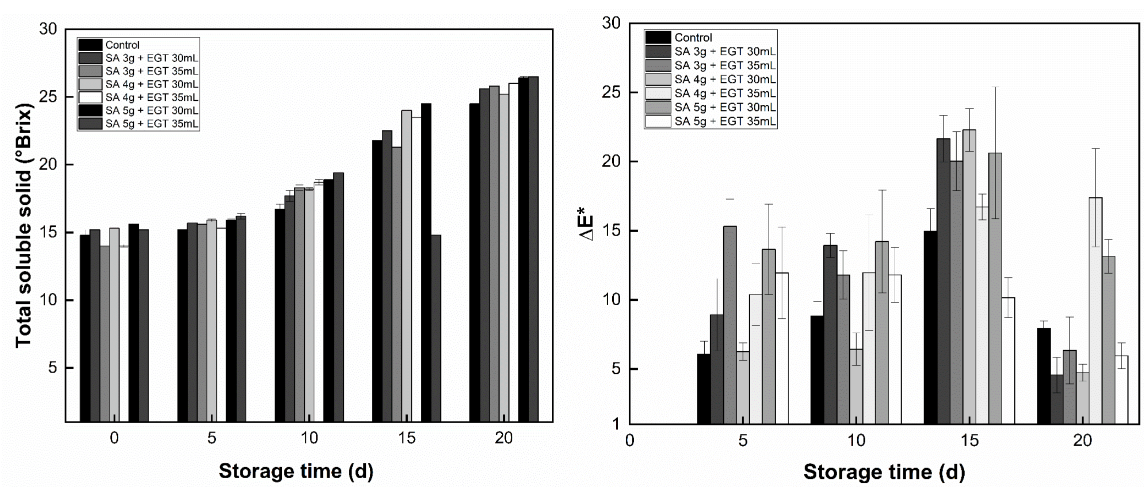

Figure 3. Effect of combined SA and EGT coating treatments on the total soluble solid (a) and color change (b) of banana fruit during 20 days of storage at room temperature (27–29 °C)

Figure 3a shows that on day 0, all treatments showed relatively uniform TSS values ranging from 14–15.6%, indicating that the accumulation of soluble sugars during the early stages of fruit storage was consistent across all treatments. By day 10, the treatments with SA and GTE began to show a faster increase in values compared to the control, particularly 35 mL of GTE treatment despite differing SA levels. This indicates that the polyphenol content in GTE began to inhibit ethylene release in the fruit, which indirectly slowed the enzymatic ripening cascade, resulting in a more gradual conversion of starch to sugar (Li *et al*., 2022; Luo *et al*., 2020). At the end of the storage period, all treatments recorded higher final TSS values than the control (24.5%), with the highest value (26.5%) is achieved by (SA 5 g + GTE 35 mL) and the lowest (25.2%) by (SA 4 g + GTE 30 mL) treatment. The higher final TSS values in the treatment groups compared to the control reflect the preservation of sugar content due to the inhibition of respiration rates by the coating layer. This relates to the inhibition or reduction of metabolic processes such as fruit respiration and transpiration, thereby better preserving soluble sugar content throughout the storage period. Control fruits without coating undergo unimpeded aerobic respiration, so that sugars formed from starch hydrolysis are continuously oxidized to meet the fruit's energy needs (Iglesias-Sanchez *et al*., 2026; Miranda *et al*., 2024).

The effect of SA concentration on TSS is evident in the trend, with 5 g of SA yielding a higher final value at the same GTE volume. This also relates to the barrier properties of the coating, where the type and concentration of edible coating components contribute to determining the physicochemical changes in the coated fruit, as polysaccharide and protein coatings possess good barrier properties against O_2 and CO_2 exchange. Higher SA concentrations form a tighter film, resulting in greater resistance to gas diffusion (Srivastava & Dwivedi, 2000).

3.4. Effect of Combining SA and GTE on Peel Color Change

Peel color change (ΔE) is a visual indicator of banana ripening during storage. All treatments showed an increase in ΔE until day 15 (Figure 3b), which is a reflection of the ripening progression through chlorophyll degradation and carotenoid accumulation, mainly lycopene. At the end of storage (day 20), fruits treated with SA 3 g + GTE 30 mL and SA 4 g + GTE 30 mL showed the lowest ΔE values, 4.57 ± 1.28 and 4.73 ± 0.62, respectively, compared with the control (7.94 ± 0.55). In contrast, SA 4 g + GTE 35 mL resulted in the highest ΔE value (17.39 ± 3.54), indicating greater color change and faster ripening.

The lower ΔE values observed in fruits treated with SA 3 g + GTE 30 mL and SA 4 g + GTE 30 mL may be attributed to the ability of salicylic acid to inhibit ethylene biosynthesis, thereby delaying chlorophyll degradation and fruit ripening (Srivastava & Dwivedi, 2000). Salicylic acid inhibits the activities of ACC synthase and ACC oxidase, resulting in a reduction of ethylene production and respiration rate and delaying the climacteric peak (Asrey, 2023). Also, Duguma *et al*. (2014) found that the efficiency of salicylic acid on delaying fruit ripening depends on the concentration and that the optimum concentration has more effects than low or high concentrations. Therefore, appropriate concentrations of SA and GTE could efficiently maintain the color of tomato peel during the storage. Moreover, the color change of the banana by its physical appearance is also shown in Figure 4. The corresponding MANOVA results are presented in Table 3.

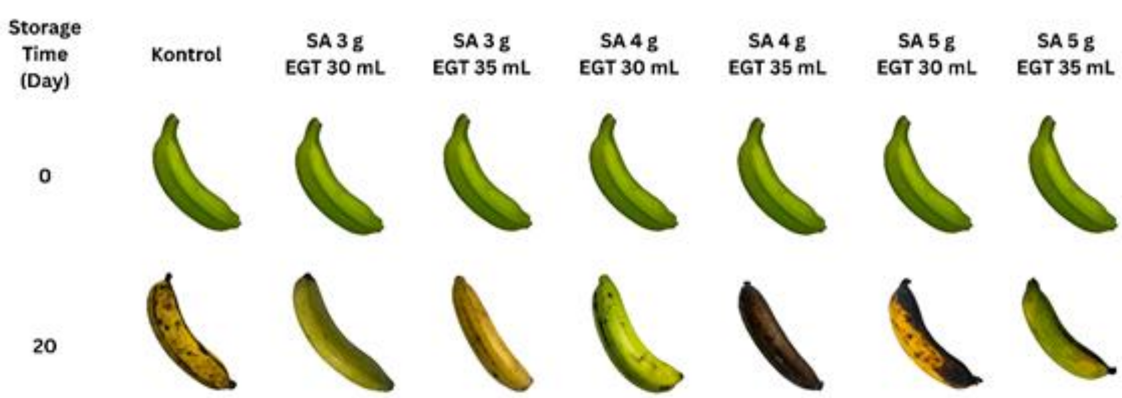

Figure 4. Physical appearance of bananas without and with film coating upon storage at 25 °C at 0 and 20 days

Table 3. MANOVA test results for peel color change during the storage time

Effect		Value	F	Hypothesis df	Error df	Sig.
Intercept	Pillai's Trace	1.000	59048118.444[b]	4.000	11.000	.000
	Wilks' Lambda	.000	59048118.445[b]	4.000	11.000	.000
	Hotelling's Trace	21472043.071	59048118.445[b]	4.000	11.000	.000
	Roy's Largest Root	21472043.071	59048118.445[b]	4.000	11.000	.000
SA Concentration×GTE Concentration	Pillai's Trace	2.000	1866804.744	8.000	24.000	.000
	Wilks' Lambda	.000	1876521.350[b]	8.000	22.000	.000
	Hotelling's Trace	1496559.477	1870699.346	8.000	20.000	.000
	Roy's Largest Root	1055349.716	3166049.147[c]	4.000	12.000	.000

3.5. Effect of Combining SA and GTE on the Ethylene Production

Ethylene production showed a typical climacteric pattern during storage. The changes in ethylene production during storage are shown in Figure 5. As presented in Figure 5, the values were relatively similar at day 0, increased as ripening progressed, reached a maximum around day 15, and then declined sharply by day 20. The control fruit exhibited the highest ethylene peak, reaching approximately 121 µL $C_2H_4 \cdot kg^{-1} \cdot h^{-1}$ at day 15. This indicates that untreated bananas experienced a strong climacteric burst, which is consistent with the role of ethylene as the principal regulator of banana ripening. Recent molecular evidence has shown that ethylene biosynthesis during banana ripening is regulated mainly through ACC synthase (ACS) and ACC oxidase (ACO), with MaACS and MaACO genes being strongly associated with ethylene-induced ripening (Wei *et al*., 2023). Another study also reported that MAP kinase-mediated phosphorylation of transcription factor bZIP21 enhances banana fruit ripening, further demonstrating that ethylene-related ripening is controlled by coordinated molecular regulation (Wu *et al*., 2022).

Among the coated samples, sample A1B1 (SA 3 g + GTE 30 mL) showed the lowest ethylene peak at day 15, approximately 43 µL $C_2H_4 \cdot kg^{-1} \cdot h^{-1}$, indicating strong suppression of the climacteric response. Sample A3B2 (SA 5 g + GTE 35 mL) and sample A3B1 (SA 5 g + GTE 30 mL) produced intermediate peaks of approximately 55 and 92 µL $C_2H_4 \cdot kg^{-1} \cdot h^{-1}$, respectively, while sample A1B2 (SA 3 g + GTE 35 mL) showed a relatively high peak of approximately 112 µL $C_2H_4 \cdot kg^{-1} \cdot h^{-1}$. The differences may reflect that the physiological response of banana fruit was highly dependent on the balance between salicylic acid and green tea extract. Salicylic acid is involved in this response as recent postharvest research has revealed that endogenous salicylic acid is associated with ethylene evolution and regulation of shelf-life in climacteric fruit (Changwal *et al*., 2021). In addition, chitosan-based edible coatings can reduce ripening intensity by changing the fruit micro-atmosphere and limiting gas exchange, which can reduce respiration and ethylene-related metabolic activity (Dai *et al*., 2025; Shinga *et al*., 2025).

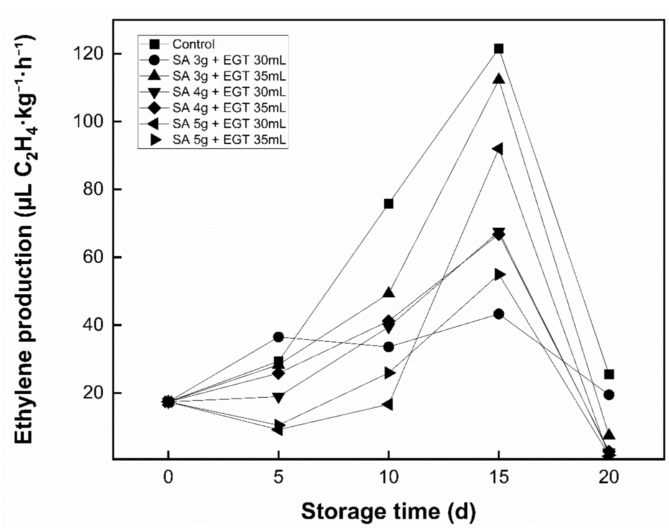

Figure 5. Effect of combined SA and EGT coating treatments on the ethylene production of banana during 20 days of storage at room temperature (27–29 °C).

The sharp decline of ethylene production after day 15 does not mean that the fruit quality is better. Ethylene in climacteric fruit typically increases to a peak during ripening and decreases as the fruit nears advanced ripening or senescence. Thus, the low ethylene values at day 20 may be an indication that the fruit was already past the climacteric maximum rather than an indication that ripening was successfully delayed. That's why ethylene data is best considered in conjunction with firmness and weight retention." In this study, the formulation A1B1 (SA 3 g + GTE 30 mL) was the most effective in suppressing the ethylene peak and the formulation A3B1 (SA 5 g + GTE 30 mL) was the most effective in maintaining firmness. The control treatment exhibited the highest peak of ethylene along with high firmness loss, confirming that the absence of coating accelerated the metabolic changes during ripening.

When considering weight retention, firmness, and ethylene production together, the best treatment depends on the desired quality attribute. Sample A3B2 (SA 5 g + GTE 35 mL) had the highest weight retention, indicating that it was the most effective in preventing water loss during storage. However, this treatment gave the lowest firmness, indicating that better retention of moisture did not mean better texture preservation. On the other hand, sample A3B1 (SA 5 g + GTE 30 mL) kept firmness the best but was less effective at reducing weight loss. Meanwhile, sample A1B1 (SA 3 g + GTE 30 mL) was best at stopping ethylene production but only did moderately well in weight and firmness retention. These results show that there was no one formulation that proved to be the best in terms of all the quality parameters.

This varied response shows the necessity of careful consideration of treatment effects. The ability of fruit to retain weight mainly depends on surface barriers controlling moisture transfer whereas firmness and ethylene production are more related to internal processes of fruit ripening. So the best formulation should not be chosen based on a single response. For example, if the main goal is to reduce shrinkage and keep visual freshness, sample A3B2 (SA 5 g + GTE 35 mL) is most suitable. For maintaining texture, sample A3B1 (SA 5 g + GTE 30 mL) is better. If the aim is to reduce ethylene-driven ripening, sample A1B1 (SA 3 g + GTE 30 mL) is most effective. Overall, sample A3B1 is the most balanced for keeping postharvest texture, while A3B2 is best for minimizing weight loss.

The novelty of this study lies in the systematic evaluation of salicylic acid (SA) and green tea extract (GTE) incorporated into a chitosan-based edible coating for *Musa paradisiaca* L. cv. Raja under ambient storage conditions. This study evaluated their combined effects on major ripening-related quality attributes, including weight retention, peel color, firmness, total soluble solids, and ethylene production. The findings provide additional insights into the optimization of natural edible coating formulations as an eco-friendly approach to improve banana postharvest quality.

4. CONCLUSIONS

The incorporation of salicylic acid (SA) and green tea extract (GTE) into chitosan-based coatings significantly improved the postharvest quality of Musa paradisiaca cv. Raja bananas. MANOVA analysis showed significant effects of the treatments on major quality parameters like weight retention, peel color change (ΔE), firmness, total soluble solids (TSS) and ethylene production. The best tested treatment was the combination of SA 5 g + GTE 30 mL (A3B1), which reduced weight loss, delayed the change in peel color, retained firmness, regulated TSS accumulation and suppressed the production of ethylene. However, treatment with SA 4 g + GTE 35 mL (A2B2) was less effective than treatment with SA 2 g + GTE 70 mL (A1B1) with some quality attributes showing faster ripening. This points to the need for optimisation of treatment, as higher concentrations do not necessarily result in better preservation. In conclusion, the SA-GTE-added chitosan coatings could be an ecofriendly approach to prolong the shelf life of bananas and reduce the postharvest losses. Further work should be directed at validation of these results under refrigerated storage and real supply chain conditions where fluctuations in the environment can influence the efficacy of the treatment. Further optimisation of GTE dosage is indicated to maximise its antioxidant activity with minimal possible pro-oxidant effects at higher concentrations. A better understanding of the molecular and biochemical basis of the observed SA-GTE synergy would also provide a stronger scientific rationale for commercialisation.

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AUTHOR CONTRIBUTION

Author	C	M	So	Va	Fo	I	R	D	O	E	Vi	Su	P	Fu
HDA	✓			✓						✓	✓	✓	✓	
ANS	✓	✓			✓	✓		✓	✓					

C: Conceptualization	Fo: Formal Analysis	O: Writing - Original Draft	Fu: Funding Acquisition
M: Methodology	I: Investigation	E: Writing - Review & Editing	P: Project Administration
So: Software	D: Data Curation	Vi: Visualization	
Va: Validation	R: Resources	Su: Supervision	

DECLARATION OF GENERATIVE AI AND AI-ASSISTED TECHNOLOGIES IN THE MANUSCRIPT PREPARATION

During the preparation of this manuscript, the authors used ChatGPT (OpenAI) to assist in wording and language refinement. After using this tool, the authors carefully reviewed and edited the content as needed and take full responsibility for the content of this publication.

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