

Article

Gellan Gum-Based Edible Coatings Enriched with *Scenedesmus* spp. Extract to Enhance the Postharvest Quality and Shelf Life of Mangoes

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Abstract

Mango (*Mangifera indica* L.) is one of the most important tropical fruits; however, its limited postharvest shelf life restricts its commercial distribution. This study aimed to assess the influence of edible coatings formulated with high-acyl gellan gum (HAG), low-acyl gellan gum (LAG), and their blends enriched with an aqueous extract of *Scenedesmus* spp. on the preservation of mango quality during postharvest storage. The film-forming solutions based on HAG, LAG, and their combination (HAG/LAG) were enriched with *Scenedesmus* spp. extract at two concentrations (1 and 2% *w/v*) and subsequently employed for coating whole mango fruits. The coated samples were analyzed throughout storage to assess their physicochemical and physiological quality attributes, including weight loss, soluble solids content, titratable acidity, color variation, malondialdehyde accumulation, antioxidant activity, respiration rate, ethylene production, and hydrogen peroxide content. The results showed that coated fruits exhibited reduced color changes, lower weight loss, and improved visual acceptability compared to controls. Coatings containing 2% *Scenedesmus* spp., particularly HAG-based formulations, significantly decreased malondialdehyde (MDA) and hydrogen peroxide (H₂O₂) accumulation, enhanced antioxidant capacity, and stabilized respiration rate and ethylene production, delaying ripening and senescence. These effects were associated with the oxygen barrier properties of gellan gum and the antioxidant compounds present in *Scenedesmus* spp. Overall, the findings highlight that HAG coatings enriched with *Scenedesmus* spp. represent a sustainable and efficient approach to extend shelf life and preserve the physicochemical and nutritional attributes of mangoes.

Keywords: edible coating; high acyl gellan; low acyl gellan; mangoes; microalgae

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1. Introduction

Fruits are essential sources of nutrients for human health, yet their high water content (75%–95%) and elevated metabolic activity make them highly perishable [1]. It is estimated that more than one-third of fruit production is lost annually due to postharvest deterioration, contributing significantly to food waste and economic detriment [2]. Among tropical fruits, mango (*Mangifera indica* L.) stands out as the most commercially important worldwide. Often described as the “king of fruits” [3], mango is prized for its appealing appearance, intense aroma, pleasant flavor, and rich nutritional profile, including vitamin C, carotenoids,

phenolic compounds, β -carotene, and minerals [4]. However, its postharvest quality is severely compromised by rapid ripening and softening, processes strongly driven by the climacteric rise in ethylene biosynthesis and respiration [5,6]. As a typical climacteric fruit, mango exhibits intense physiological metabolism after harvest, rendering it particularly vulnerable to senescence and decay during handling, storage, and transport [7]. For this reason, strategies that delay ripening and maintain fruit quality are critical for extending its shelf life.

Among the preservation approaches explored, edible coatings have emerged as a simple, biodegradable, and non-toxic technology to extend fruit storability [8]. These coatings act as semi-permeable barriers that regulate the transfer of gases (O_2 , CO_2), moisture, and solutes, thereby reducing respiration rates, water loss, and oxidative reactions [9,10]. Their effectiveness largely depends on the biopolymers employed, which include polysaccharides, proteins, and lipids, either alone or in blends [11]. Moreover, coatings developed from renewable and biodegradable sources are not only safe but also contribute to delaying postharvest quality losses and extending fruit longevity [12,13]. Gellan gum is an exopolysaccharide of microbial origin synthesized by *Sphingomonas paucimobilis* through fermentation. Its structure is composed of repeating tetrasaccharide units consisting of 1,3- β -D-glucose, 1,4- β -D-glucuronic acid, 1,4- β -D-glucose, and 1,4- α -L-rhamnose. In its native state, it is referred to as a high-acyl gellan gum (HAG) because it contains two acyl substituents—acetate and glycerate—attached to the A glucose residue. Exposure to strong alkaline conditions induces hydrolysis of these acyl groups, yielding low-acyl gellan gum (LAG). Both gellan gums have been employed in the formulation of edible coatings and in the controlled release of compounds [14]. Typically, both gums have been used to coat ready-to-eat mango bars. For example, Danalache et al. [15] developed a coating based on HAG and LAG and studied the firmness of the mango bars, syneresis, and color changes, finding that the coating can improve the sensory characteristics of the mango bars (appearance and firmness) as well as their stability in terms of syneresis, color, and volatile content during storage, thereby increasing the commercial value of the final product.

The incorporation of natural plant extracts, antioxidants, antimicrobials, and other bioactive compounds further enhances their functionality, providing an innovative strategy to preserve food quality and safety while extending shelf life [16]. Molaei Moqbeli et al. [17] developed edible coatings based on chitosan and *Moringa oleifera* leaf extract to evaluate their effect on the shelf life of mangoes (*Mangifera indica* L.) with over 50 days of storage. These authors found that the application of the coating delayed ripening indicators, as evidenced by lower total soluble solids and better retention of titratable acidity. In this context, microalgae have gained attention as promising sources of bioactives for food applications. They can be cultivated with minimal nutrient inputs, without pesticides, and on non-arable land, while offering continuous year-round production and high yields compared to terrestrial plants [18,19]. Microalgae can survive and produce bioactive compounds in a culture with minimal nutrient requirements [20]. Moreover, microalgae biomass and extracts are rich in antioxidant and antimicrobial metabolites and are recognized as generally recognized as safe (GRAS) by the FDA and EFSA. Among the most widely studied species are *Chlorella vulgaris*, *Euglena gracilis*, *Spirulina* sp., *Chlamydomonas reinhardtii*, *Dunaliella salina*, and *Dunaliella bardawil*. However, limited research has been conducted on *Scenedesmus* spp. Incorporating such extracts into edible films or coatings could open new possibilities for enhancing fruit preservation.

Several studies have reported successful applications of natural-based edible coatings to preserve mango quality, including formulations based on pectin with oregano essential oil [21], succinylated corn starch obtained via reactive extrusion [22], and cassava starch emulsified with lemongrass essential oil [23]. Nevertheless, research on the potential of

Scenedesmus spp. for mitigating postharvest deterioration of fruits and vegetables remains limited. Therefore, the aim of this study was to evaluate the effect of HAG, LAG, and their blends enriched with aqueous extracts of *Scenedesmus* spp. on the postharvest quality of mangoes during storage.

2. Materials and Methods

2.1. Fruit Material

Mango fruits were obtained from local producers (Department of Bolívar, Bolívar, Colombia) and transported in a refrigerated vehicle maintained at 15 °C to the Food Engineering Laboratory at the University of Cartagena. The selected fruits exhibited no pathological or physical defects (such as decay or bruising) and were characterized by appropriate maturity, firmness, uniform epidermal coloration, and well-defined shape. Prior to coating, the mangoes were disinfected by immersion in a sodium hypochlorite solution (200 ppm) for 1 min, subsequently rinsed with distilled water, and air-dried at room temperature (33 °C). The microalga *Scenedesmus* spp. was provided by a university located in eastern Colombia.

2.2. Preparation and Application of the Composite Coating

The edible coating solution was formulated by dissolving LAG (0.5% *w/v*) and HAG (0.2% *w/v*) (Modernish Pantry, Eliot, ME, USA, EEUU) in distilled water. The mixtures were heated at 90 °C for 10 min under continuous agitation (300 rpm) to ensure homogeneity. Following cooling to room temperature, aqueous extracts of *Scenedesmus* spp. (1% and 2%) were incorporated. It is important to mention that the *Scenedesmus* spp. culture was carried out in Gibco™ BG-11 medium (Thermo Fisher Scientific, New York, NY, USA) under a light intensity of 2500 lux at 25 °C. The resulting solutions were subjected to sonication for 30 min to eliminate air bubbles. Mango fruits were carefully washed with distilled water to eliminate surface dust and soil residues, followed by air-drying at ambient temperature. The coating was applied by dipping, with 40 fruits used for each treatment, and each fruit was immersed in the coating solution for 2 min. Fruits treated only with distilled water were used as the control. After coating application, the mangoes were placed in a sterile airflow cabinet at room temperature for 2 h to ensure proper drying of the coating layer. Quality attributes were subsequently evaluated during storage at 20 °C and 80% relative humidity (RH) for 30 days, with assessments conducted at regular intervals.

2.3. Weight Loss and Soluble Solids

To determine weight loss, whole mangoes were weighed, using approximately 20 fruits per measurement. The weights were recorded at 0, 6, 12, 18, 24, and 30 days of storage. Weight loss was calculated using Equation (1):

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

where W_0 is the initial weight of the fruit and W_t represents the weight at each sampling time.

For the determination of soluble solids (SS), the fruits were macerated using a mortar, and four drops of the homogenized pulp were placed on the prism of a refractometer (Extech Model 2132, Extech Instruments, Nashua, NH, USA). The results were expressed in °Brix.

2.4. Determination of the Titratable Acidity

Mango samples were blended to obtain a homogeneous mixture, and 10 g of the homogenate was diluted with distilled water. Titratable acidity (TA) was quantified by titrating with 0.1 N NaOH until reaching the phenolphthalein endpoint (pH 8.1). The acidity values were reported as the percentage of citric acid.

2.5. Determination of Color Change (ΔE)

Fruit surface color was evaluated using a CR-20 colorimeter (Konica Minolta, Tokyo, Japan). Measurements were taken at five random points on each fruit. The CIELAB color parameters— L^* (lightness), a^* (green to red), and b^* (blue to yellow)—were recorded at the beginning and end of the storage period:

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

2.6. Malondialdehyde Content

A total of 1 g of mango peel and pulp was homogenized in 15 mL of 10% trichloroacetic acid (TCA). The homogenate was then centrifuged at $12,000 \times g$ for 20 min at 4 °C. Subsequently, 2 mL of the supernatant was mixed with 2 mL of thiobarbituric acid solution and heated for 25 min. After cooling, the mixture was centrifuged again, and the absorbance of the supernatant was measured at 532, 600, and 450 nm. The malondialdehyde (MDA) concentration was expressed as nmol kg^{-1} .

2.7. Determination of the Antioxidant Activity

The antioxidant capacity based on DPPH (2,2-diphenyl-1-picrylhydrazyl) radical scavenging activity was assessed following the procedure described by Brand-Williams et al. [24], with minor modifications. In brief, 50 μL of the methanolic extract was combined with 950 μL of DPPH solution, prepared by dissolving 0.025 g of DPPH in 100 mL of 85% methanol. The mixture was incubated in darkness at room temperature for 30 min, after which the absorbance was recorded at 517 nm using a UV-VIS spectrophotometer. The inhibition percentage was determined using the following equation:

$$\text{Inhibition (\%)} = \frac{\text{control absorbance} - \text{sample absorbance}}{\text{control absorbance}} \times 100 \quad (3)$$

2.8. Rate of Respiration and Ethylene Production

To assess respiration rate and ethylene production, a single fruit from each treatment was placed in an airtight plastic container for 1 h to allow accumulation of headspace gases. The gas composition was subsequently analyzed using a gas analyzer (F-950, Felix Instruments, QA Supplies LLC, Norfolk, UK, USA). Respiration rate was expressed as $\text{mmol CO}_2/\text{kg/h}$ and ethylene production as $\mu\text{mol C}_2\text{H}_4/\text{kg/h}$. Ten mangoes were used per replicate for this analysis.

2.9. Hydrogen Peroxide (H_2O_2) Content

For the H_2O_2 assay, 1 g of mango pulp was homogenized in 5 mL of trichloroacetic acid (TCA) solution and centrifuged at $12,000 \times g$ for 10 min to obtain the supernatant. Then, 1 mL of the supernatant was mixed with 1 M KI prepared in 10 mM phosphate buffer (pH 7.0). Hydrogen peroxide content was measured at 390 nm using a spectrophotometer and expressed as $\mu\text{mol kg}^{-1}$ [25].

2.10. Statistical Analysis

All measurements were conducted in triplicate, and the results are presented as mean $\pm$ standard deviation. Differences among treatments were evaluated using one-way analysis of variance (ANOVA) at a 95% confidence level, followed by post hoc comparisons with the least significant difference (LSD) test.

3. Results and Discussion

3.1. Quality Characteristics of the Analyzed Mangoes

The rate of weight loss is a key indicator of fruit quality. Postharvest weight reduction in fruits primarily results from the loss of water from their surface [26]. Monitoring this parameter is highly relevant to the horticultural sector, as it plays a critical role in maintaining freshness and visual appeal; excessive moisture loss typically leads to fruit shriveling [27–29]. Weight loss, considered a natural attribute of horticultural commodities during storage, is mainly driven by respiration and transpiration processes [30]. Applying appropriate treatments that serve as effective barriers, such as edible coatings, can substantially reduce water loss from fruit surfaces.

In the present study, gellan gum-based coatings markedly reduced weight loss in mangoes (Figure 1a). Control fruits exhibited the highest weight loss (15.42%) by the end of storage, whereas coated fruits showed significantly lower values, ranging from 5.24% to 7.62%. This reduction is likely attributable to the protective effect of the coatings, which prevents surface degradation and slows down water evaporation [31]. Similar findings were reported by Ebrahimi and Rastegar [15], who observed weight loss of approximately 6.8% in mangoes coated with guar gum and aloe vera. Likewise, Wang et al. [32] reported weight losses between 6% and 8% in mangoes coated with konjac glucomannan, carboxylated cellulose nanofibers, and tannic acid during 12 days of storage. The ability of polysaccharide-based coatings to limit water loss is probably related to the formation of stronger hydrogen bonds between hydroxyl groups in the edible coatings and hydrophilic compounds such as phenolics [33].

Total soluble solids (TSSs) represent a key biochemical attribute that reflects the relative sugar concentration in fruits, including mango [34]. The determination of soluble solids is highly relevant for consumer acceptance, as it is closely associated with fruit sweetness and overall palatability. In the present study, higher TSS levels were recorded in control mangoes, which may be attributed to the rapid conversion of pectin into sugars [6]. As shown in Figure 1b, the soluble solids content of control fruits increased significantly with storage duration, reaching a maximum of 18.25% by the end of the storage period. This value is comparable to that reported by Ebrahimi and Rastegar [15], who observed 14.4% in mangoes stored at ambient temperature for three weeks.

For coated mangoes, the highest TSS value (11.87%) was observed in fruits coated with 1% LAG combined with *Scenedesmus* spp. extract, whereas the lowest value (10.04%) was found in fruits coated with 2% HAG and *Scenedesmus* spp. extract. These results are consistent with those of Ebrahimi and Rastegar [15], who reported TSS values between 10.33% and 11.10% in mangoes coated with guar gum, aloe vera, and *Scenedesmus* spp. Both coated and control mangoes exhibited an increase in TSS during storage; however, this increase was more pronounced in the control fruits.

Edible coatings are widely acknowledged for their ability to reduce abrupt changes in total soluble solids (TSSs) by limiting gas exchange, lowering respiration rates, and regulating metabolic activity in coated fruits [35]. The gradual increase in TSSs during storage may result from the hydrolysis of cell wall polysaccharides [36] or from an elevation in sugar concentration due to water loss or the conversion of starch to sugars, processes often linked to enhanced respiration [37]. During mango ripening, the levels of organic

acids generally decrease, as these compounds serve as key substrates for essential metabolic processes, including respiration.

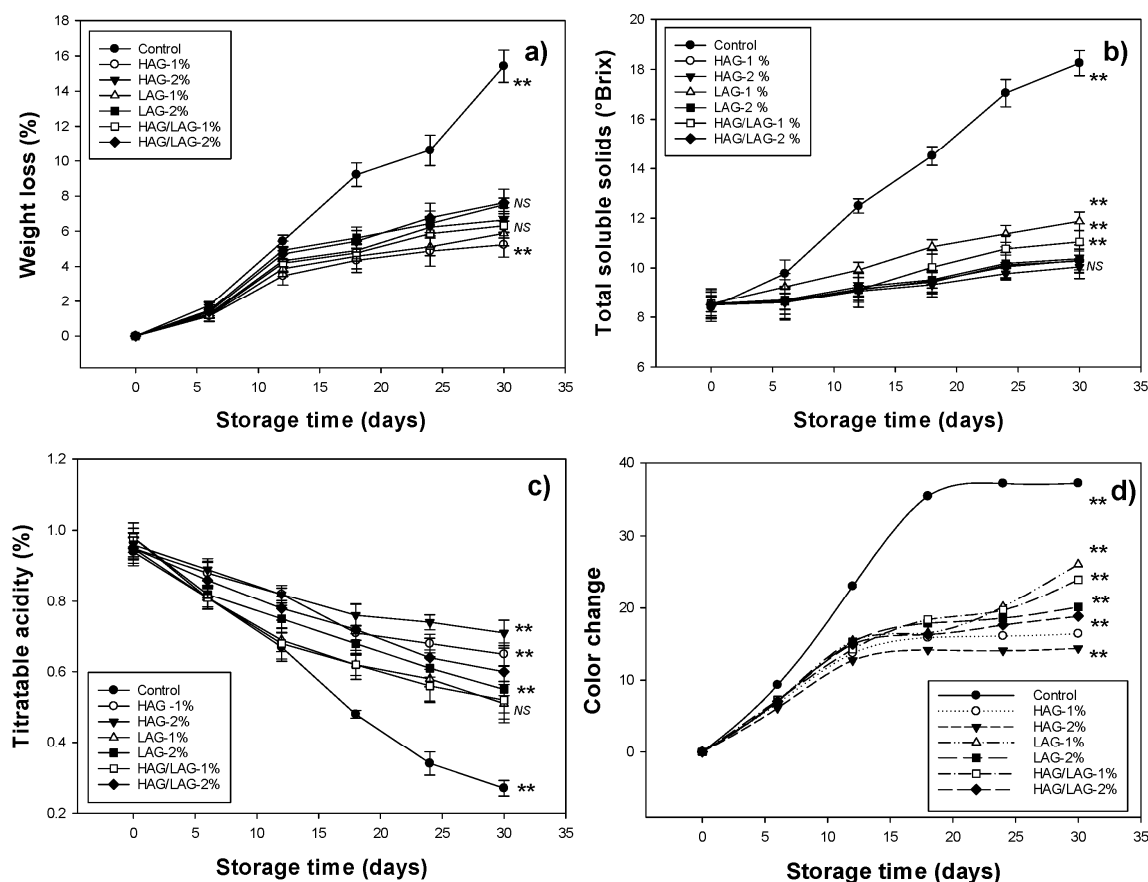


Figure 1. Quality attributes and behavior of control and gellan gum-coated mangoes during storage. (a) weight loss; (b) TSS; (c) titratable acidity; and (d) color change (** indicates a significant difference at $p < 0.05$ according to the LSD test at the end of the storage period; NS indicates no significant difference at $p < 0.05$). Vertical bars represent the standard error of the mean.

The titratable acidity (TA) of mangoes was significantly influenced by both the application of edible coatings and the storage period. As shown in Figure 1c, TA decreased progressively in both coated and control fruits, with a more pronounced reduction observed in the latter. By the end of storage (day 30), control mangoes reached the lowest TA value of 0.25%. In contrast, coated fruits retained higher acidity, with values ranging from 0.71% in mangoes treated with 2% HAG containing *Scenedesmus* spp. extract to 0.51% in fruits coated with 1% LAG combined with *Scenedesmus* spp. extract. The decline in TA was markedly greater in control mangoes compared with coated ones, which preserved approximately 2.8-fold higher acidity by day 30. Notably, HAG coatings enriched with 2% *Scenedesmus* spp. extract demonstrated the strongest preservation effect. This finding suggests that the application of HAG-based coatings with *Scenedesmus* spp. likely reduced the consumption of organic acids, thereby maintaining higher TA levels [6,38]. The enhanced TA conservation, coupled with a slower increase in TSS, contributed to a lower ripening index in coated mangoes, whereas non-coated fruits exhibited a substantially higher index.

Fruit color is a critical attribute influencing both the quality and market value of fresh produce, and it plays a decisive role in consumer acceptance. Freshly harvested fruits generally exhibit a bright and glossy appearance. The changes in fruit color during storage are shown in Figure 1d, highlighting the significant effect of coating application compared to the control fruits. By the end of storage, the greatest color change (37.21)

was recorded in uncoated fruits, followed by fruits coated with LAG (26.08) and with HAG/LAG (23.94), both containing 1% *Scenedesmus* spp. In contrast, the lowest color change (14.41) was observed in fruits coated with HAG containing 2% aqueous extract of *Scenedesmus* spp. In control fruits, color change plateaued after day 18, which may be associated with the complete degradation of chlorophyll. The initial green coloration of mangoes is primarily attributed to chlorophyll; as ripening progresses, chlorophyll degrades while other pigments are synthesized from the colorless precursor phytoene into β -carotene (orange), lycopene (red), carotene (pale yellow), xanthophylls, and other carotenoids (yellow) [39]. With fruit senescence, chlorophyll gradually disappears and anthocyanins and carotenoids accumulate, leading to a visible shift in the fruit's base color [40]. In coated fruits, a delay in chlorophyll degradation was particularly evident after day 12 of storage, especially in mangoes coated with HAG. Previous research has shown that edible coatings can slow pigment degradation and inhibit the formation of undesirable colors by modifying peel permeability, which affects gas exchange and diminishes oxidative reactions [30,41]. In general, coated fruits displayed notably higher visual acceptability compared to uncoated controls. These findings align with those of Saberi et al. [42], who found that guar gum–chickpea starch coatings effectively prolonged the shelf life of Valencia oranges.

In Figure 2, the visual alterations of whole mango fruits after storage are illustrated. It can be observed that fruits coated with HAG and HAG/LAG containing 2% *Scenedesmus* spp. extract still exhibited a greenish coloration (Figure 2A,B), while those coated with LAG-2% and HAG/LAG-1% (Figure 2C,D) showed a more uniform but slightly more yellowish color. Fruits coated with LAG-1% did not display a uniform coloration, probably due to the more porous surface of the LAG coating. In contrast, the control fruits (Figure 2E) showed particularly noticeable alterations. The coated samples exhibited only slight changes compared with the control; their color progressively darkened as the storage time increased. This suggests that the coating delayed the darkening of the mangoes, possibly due to a gradual release effect of the *Scenedesmus* spp. extract.



Figure 2. Appearance of control and coated mangoes stored for 30 days. (A) Coated with HAG-2%; (B) coated with HAG/LAG-2%; (C) coated with LAG-2%; (D) coated with HAG/LAG-1%; (E) control; and (F) coated with LAG-1%.

3.2. Malondialdehyde Content

Malondialdehyde (MDA) is a terminal product of membrane lipid peroxidation, capable of inducing crosslinking and polymerization of essential macromolecules, including proteins and nucleic acids, thereby intensifying membrane damage [43]. In this study, MDA content in mangoes showed a general upward trend during storage, although the increase was significantly higher in control fruits (see Figure 3). Similar findings were reported by Wang et al. [32], who observed reduced MDA accumulation in mangoes coated with konjac glucomannan, carboxylated cellulose nanofibers, and tannic acid. By the end of storage, the highest MDA concentration (28.88 nmol/kg) was recorded in control fruits, whereas the lowest levels were found in fruits coated with HAG containing 2% *Scenedesmus* spp. extract (19.22 nmol/kg) and HAG with 1% *Scenedesmus* spp. extract (20.21 nmol/kg).

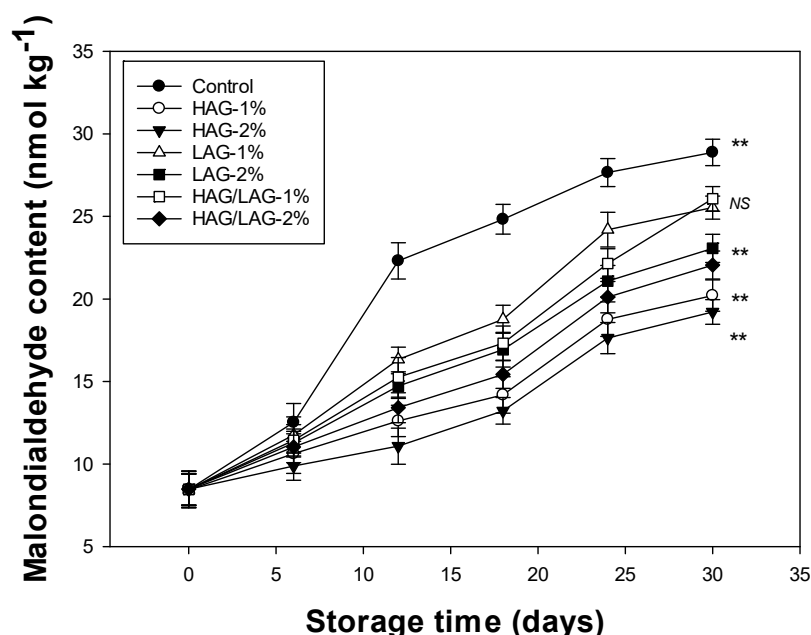


Figure 3. Malondialdehyde behavior of control and gellan gum-coated mangoes during storage. (** indicates a significant difference at $p < 0.05$ according to the LSD test at the end of the storage period; NS indicates no significant difference at $p < 0.05$). Vertical bars represent the standard error of the mean.

During storage, the progressive increase in MDA content is associated with fruit aging and senescence, which is why MDA is widely used as an indicator in studies of fruit aging physiology and stress resistance [31]. The application of HAG coatings enriched with aqueous *Scenedesmus* spp. extract significantly reduced the rate of MDA accumulation, likely by generating a micro-modified atmosphere that helped preserve mango quality [44].

3.3. Determination of the Antioxidant Activity

The antioxidant capacity of mangoes was significantly ($p < 0.05$) affected by both the coating type and the storage period. As shown in Figure 4, antioxidant activity gradually declined in both control and coated fruits. Nevertheless, at the end of the storage period, the highest antioxidant capacity was observed in mangoes coated with HAG containing 2% aqueous extract of *Scenedesmus* spp. (92.45%), followed by those coated with 1% HAG–*Scenedesmus* spp. (91.72%).

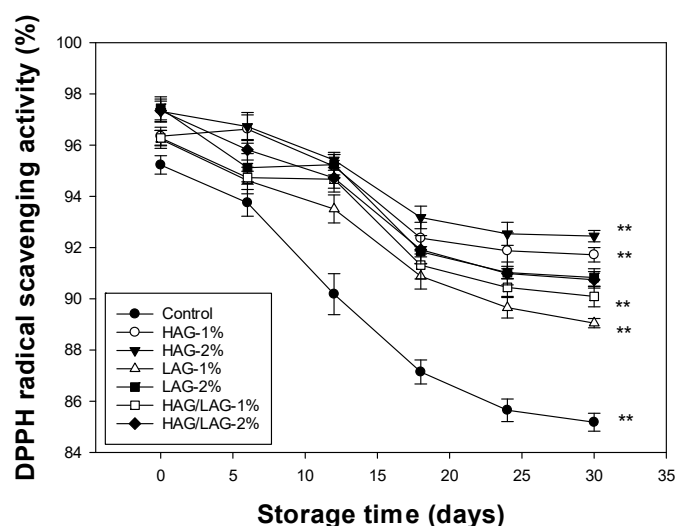


Figure 4. Antioxidant activity of control and gellan gum-coated mangoes during storage (** indicates a significant difference at $p < 0.05$ according to the LSD test at the end of the storage period). Vertical bars represent the standard error of the mean.

The improved antioxidant activity observed in mangoes coated with *Scenedesmus* spp. formulations can be attributed to the presence of various bioactive compounds, including fatty acids, chlorophyll, phenolic compounds, phycobilins, and phycocyanin, which collectively enhance antioxidant properties [45]. Additionally, HAG-based coatings were more effective than LAG in maintaining antioxidant capacity, likely because *Scenedesmus* spp. is a rich source of phenolic acids such as caffeic, chlorogenic, salicylic, synaptic, and trans-cinnamic acids [46].

In contrast, control mangoes exhibited the lowest antioxidant activity, with a final value of 85.18%. These findings are in line with those of Ebrahimi and Rastegar [15], who reported that mangoes coated with guar gum, *Aloe vera*, and aqueous extract of *Scenedesmus* spp. showed significantly higher antioxidant capacity than controls, with the lowest value (87.7%) recorded in the latter. Packaging or coating materials with antioxidant properties are crucial, as they can prevent rancidity, discoloration, and pigment degradation in fruits [47]. Overall, these results indicate that HAG-2 treatment is particularly effective in enhancing the antioxidant capacity of mangoes.

3.4. Rate of Respiration and Ethylene Production

Fruit quality is heavily influenced by multiple factors, with respiration rate being particularly critical, as mangoes exhibit a climacteric ripening pattern characterized by a marked increase in CO_2 production. In this study, both respiration rate and ethylene production progressively increased in coated and uncoated mangoes throughout storage. In control fruits, the peak respiration rate (24.31 mmol/kg/h) occurred on day 18, followed by a rapid decline to 14.64 mmol/kg/h, likely due to accelerated ripening and senescence. In contrast, coated fruits displayed a stabilization of respiration rates after day 18, as shown in Figure 5a, which may result from the polymeric matrix acting as a barrier to oxygen diffusion, which is consistent with previous reports on polysaccharide-based coatings [48]. High-acyl gellan gum (HAG) forms gels through multiple hydrogen bonds between gellan helices, producing a tightly interwoven and compact gel network [49]. Respiration rates in coated fruits ranged from 18.88 to 17.05 mmol/kg/h, with no significant differences observed at the end of storage. The effect of edible coatings on respiration is largely attributed to their capacity to limit oxygen permeability, reducing O_2 availability for metabolic activity [50]. These findings indicate that HAG-based coatings enriched with

Scenedesmus spp. effectively modulate the internal atmosphere of mangoes, contributing to the maintenance of key quality parameters, including reduced weight loss and slower degradation of organic acids and soluble solids during storage.

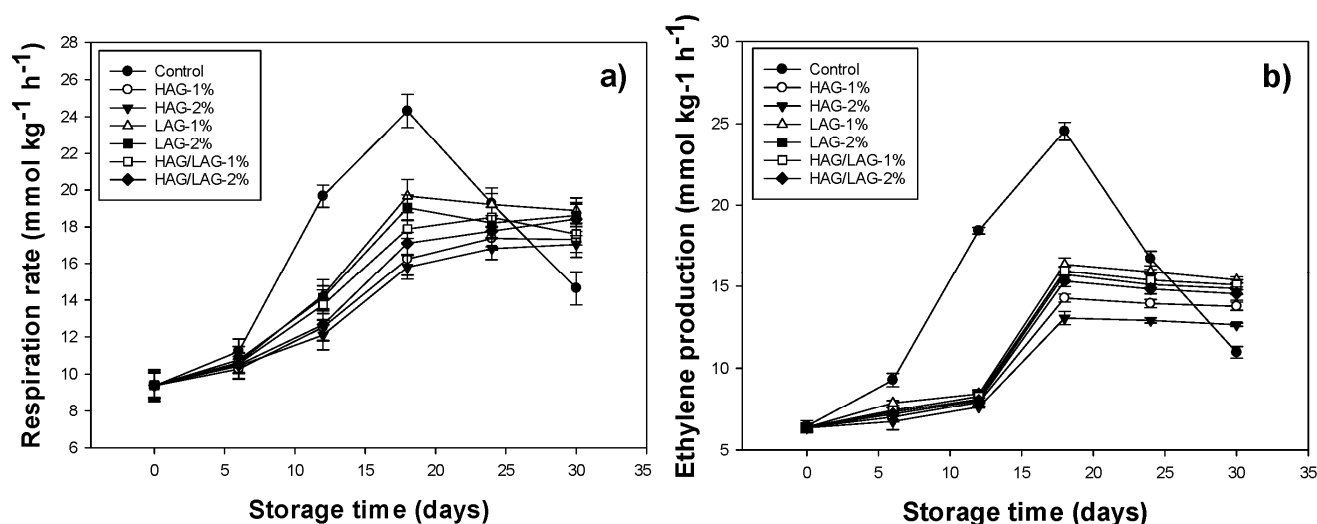


Figure 5. Respiration rate (a) and ethylene production (b) of control and gellan gum-coated mangoes during storage.

With respect to ethylene production, known as the ripening hormone in climacteric fruits, its endogenous biosynthesis represents the hallmark of the ripening process [51], including in mangoes [52]. Minimizing postharvest ethylene production is critical to delaying ripening and extending storage life. As shown in Figure 5b, ethylene production in control fruits peaked at day 18 (24.55 mmol/kg/h), then declined sharply to a final value of 10.97 mmol/kg/h. By contrast, coated fruits showed a stabilization of ethylene production after day 18. At the end of storage, the lowest ethylene production was observed in mangoes coated with HAG containing 2% aqueous *Scenedesmus* spp. extract (12.65 mmol/kg/h), followed by those coated with 1% HAG and *Scenedesmus* spp. (13.77 mmol/kg/h). The lower ethylene production observed in HAG-coated fruits can be attributed to the formation of a dense gellan network, as previously discussed. Overall, these results indicate that HAG coatings enriched with *Scenedesmus* spp. extract effectively reduced both oxygen consumption and ethylene generation in mangoes. By suppressing ethylene biosynthesis and respiratory activity, this coating strategy provides an effective means to delay ripening and prolong postharvest shelf life [53].

3.5. Hydrogen Peroxide (H₂O₂) Content

H₂O₂ is a reactive oxygen species generated during oxidative metabolism in stored mangoes [54], contributing to accelerated fruit ripening, a phenomenon also observed in other fruits [55,56]. Nguyen et al. [57] reported that oxidative stress can be alleviated through the application of edible coatings, potentially by sustaining higher antioxidant enzyme activity. In the present study, H₂O₂ levels progressively increased in both control and coated fruits throughout storage, as shown in Figure 6. Overall, control mangoes accumulated the highest H₂O₂ content by the end of storage, reaching 25.82 µmol/kg. Comparable results were observed by Qasim et al. [58] in mangoes coated with xanthan gum.

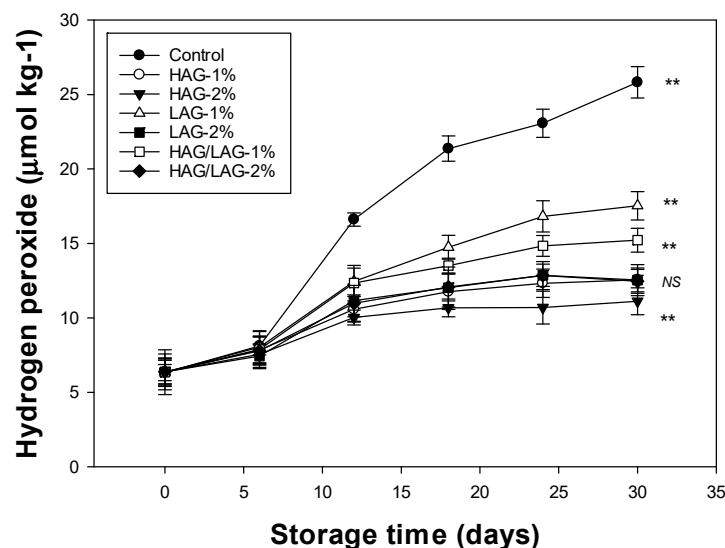


Figure 6. Hydrogen peroxide content of control and gellan gum-coated mangoes during storage (** indicates a significant difference at $p < 0.05$ according to the LSD test at the end of the storage period; NS indicates no significant difference at $p < 0.05$). Vertical bars represent the standard error of the mean.

Among the coated fruits, the highest H_2O_2 contents were observed in mangoes treated with LAG and with the LAG–HAG blend, both containing 1% aqueous extract of *Scenedesmus* spp., with values of 17.53 and 15.22 $\mu\text{mol/kg}$, respectively. In contrast, the lowest H_2O_2 levels were recorded in fruits coated with HAG and with the HAG–LAG blend, both containing 2% aqueous extract of *Scenedesmus* spp. These findings indicate that the application of coatings enriched with 2% *Scenedesmus* spp. extract significantly reduced H_2O_2 accumulation in mangoes during storage. This effect could be attributed to the antioxidant enzymes present in the extract, which may help alleviate oxidative stress and suppress mango senescence by scavenging reactive oxygen species.

4. Conclusions

The findings of this study demonstrate that edible coatings based on gellan gum (HAG and LAG) enriched with aqueous extract of *Scenedesmus* spp. are an effective postharvest strategy to preserve the quality of mangoes during storage. In particular, HAG coatings containing 2% *Scenedesmus* spp. extract significantly enhanced antioxidant capacity, reduced the accumulation of malondialdehyde (MDA) and hydrogen peroxide (H_2O_2), and stabilized both respiration rate and ethylene production, thereby delaying ripening and senescence. These effects can be attributed to the structural properties of HAG, which act as an oxygen barrier, and to the bioactive compounds present in *Scenedesmus* spp., which provide antioxidant protection by scavenging reactive oxygen species. Overall, the results confirm that bioactive coatings, especially HAG–2% formulations, represent a sustainable and efficient approach to extend the shelf life and maintain the nutritional and physicochemical attributes of climacteric fruits such as mango.

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