



Effect of fibroin-based edible coatings enriched with mulberry leaf extract on postharvest quality and bioactive properties of table grapes

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Abstract

Natural edible coatings offer a sustainable approach to extending fruit shelf life; however, their potential for antidiabetic bioactivities and impact on the glycemic response of fresh fruits remain largely unexplored. This study proposes a novel edible coating leveraging the biocompatibility and film-forming ability of fibroin, enriched with the bioactive potential of *Morus alba* leaf extract (MLE), to simultaneously enhance shelf life and impart antidiabetic functionality to table grapes. Following the optimization of MLE extraction via response surface methodology (maximum 1-deoxynojirimycin (DNJ) content: 6.8 mg/g DW), fibroin-based coatings (8%) containing 2–8% MLE were formulated and characterized for their antioxidant, in vitro antidiabetic, and antimicrobial activities before being applied to ‘Ata Sarısı’ and ‘Red Globe’ grape varieties. During 20 days of storage at 4 °C and 21 °C, the coatings effectively maintained postharvest quality by reducing weight loss and preserving fruit firmness compared to uncoated controls. Furthermore, MLE-enriched coatings significantly enhanced total phenolic content, antioxidant capacity, and in vitro α -amylase and α -glucosidase inhibition, while effectively reducing the in vitro glycemic index (GI) and microbial growth, particularly under cold storage. Among the formulations, the RG-8-4 treatment exhibited the most potent effects (TPC: 225.44 mg GAE/100 g; CUPRAC: 73.24 μ mol TE/100 g; α -amylase inhibition: 42.37%; α -glucosidase inhibition: 53.65%; and GI: 46.25). These findings demonstrate that fibroin-based edible coatings enriched with MLE represent a promising functional solution for extending shelf life while developing fresh fruits with significant antidiabetic and antimicrobial potential.

Keywords *Morus alba* · Fibroin · Edible coating · Antidiabetic activity · Postharvest quality · Table grapes

Introduction

Rising global rates of diabetes mellitus are linked to shifting dietary routines and lifestyle changes. With projections indicating that 853 million adults will have diabetes by

2050 [1], effective management is critical. Conventional pharmacotherapy, including acarbose and metformin, is often associated with adverse effects such as abdominal discomfort and hepatic toxicity, prompting increased research into natural α -amylase and α -glucosidase inhibitors [2].

Mulberry (*Morus alba* L.) leaves, traditionally used in sericulture, are not commercially utilized. Beyond their established role in providing iminosugars, they exhibit potent antioxidant, anti-inflammatory, and antihypertensive properties. Their efficacy in regulating glucose metabolism, primarily driven by the concentration of 1-deoxynojirimycin (DNJ) and flavonoids like rutin and quercetin, has garnered scientific interest [3, 4]. These compounds inhibit starch digestion and improve insulin secretion, making ML a safe, non-toxic, and palatable option for metabolic health. Although the concentration of DNJ varies significantly

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among varieties, its potential to suppress postprandial glucose spikes is well-documented [5, 6].

Concurrently, there is a growing demand for biodegradable and sustainable food packaging. Fibroin, a protein derived from *Bombyx mori* cocoons, has emerged as a premier biopolymer for these applications. Unlike synthetic packaging, fibroin offers superior biocompatibility, excellent film-forming ability, and environmental friendliness. Crucially, when properly processed through degumming to remove sericin, fibroin is recognized as a safe, non-allergenic material, making it an ideal candidate for direct food-contact applications. Its high beta-sheet structure provides the necessary mechanical strength and gas barrier properties required for extending the shelf life of fresh produce [7].

Postharvest deterioration remains a major challenge in the fruit industry, causing significant economic losses and environmental footprints associated with food waste. After harvest, fresh produce—particularly table grapes—continues to undergo metabolic processes, primarily respiration and transpiration. While effective, conventional synthetic wax coatings face increasing scrutiny regarding chemical residues and poor biodegradability. Conversely, edible coatings act as semi-permeable barriers, modulating gas exchange and mitigating transpiration-related water loss. Creating a controlled microenvironment at the fruit surface, these bio-based matrices retard senescence and provide a scaffold for bioactive agents. This structural versatility facilitates ‘intelligent’ packaging, addressing both fruit physical stability and consumer nutritional needs [8, 9]. There exists a critical gap in research regarding the “dual-purpose” potential of such systems. While literature supports the individual benefits of fibroin (structural) and MLE (bioactive), their combined integration into a multifunctional coating system offers a distinct opportunity to bridge the gap between structural fruit preservation and the functional delivery of health-promoting compounds.

This study aims to develop and characterize fibroin-based edible coatings enriched with varying concentrations of MLE. The ability of the coatings to impart antidiabetic properties (α -amylase and α -glucosidase inhibition), antioxidant activity, and antimicrobial effects was evaluated. Furthermore, the efficacy of these coatings in maintaining the postharvest quality of two grape cultivars—Red Globe (RG, firm texture) and Ata Sarısı (AS, delicate structure)—was investigated during 20 days of storage at 4 °C and 21 °C. While these cultivars possess a comparable physical basis, their differing shelf-life stability makes them an ideal model for evaluating coating performance under varied physiological stress. To the best of current knowledge, this is the first report to integrate fibroin and MLE into a multifunctional coating system, offering an innovative approach to

functional food development that simultaneously provides structural functionality and metabolic health benefits.

Materials and methods

Materials

ML were collected from a designated site in Bursa, Türkiye (40°13'41.6"N 29°07'28.0"E). Leaves were selected based on size, physical integrity, uniform color, and absence of disease. The collected leaves were washed, dried for 48 h, ground, and stored at 4 °C. The drug-free, raw silk cocoons were sourced from Kozabirlik Company (Bursa, Türkiye). Cocoons of uniform size, free from foreign substances or surface contamination, were selected for use. Grapes from RG and AS varieties were harvested from the experimental vineyards of the Faculty of Agriculture, Bursa Uludag University. Clusters were selected based on uniformity in ripeness, color, and size. Any damaged, discolored, or diseased fruit was discarded to ensure experimental homogeneity.

Optimization of MLE extraction

The extraction of bioactive compounds (DNJ and phenolics) from ML was optimized using a response surface methodology (RSM) with a 4-factor, 3-level Box–Behnken design (variables: extraction time, temperature, ethanol, and phosphoric acid concentration). Ethanol and phosphoric acid were selected as safe, food-grade alternatives to methanol and hydrochloric acid. DNJ (as it is a trace compound with a key contribution to antidiabetic activity) content, quantified via HPLC (Agilent Infinity 1260, USA), was set as the dependent variable for optimization, and a calibration curve was plotted using HPLC [5]. Analytical methods were validated for sensitivity and precision. HPLC quantification of DNJ demonstrated linearity ($R^2 = 0.998$), with an LOD of 0.05 mg/g and LOQ of 0.15 mg/g. All bioactivity assays were performed in triplicate ($n = 3$), with a coefficient of variation (CV) consistently below 5%.

Extraction of MLE

Based on the optimized RSM results, 100 g of dried ML was extracted with 1000 mL of a solvent mixture (90% ethanol, 0.5% phosphoric acid, and 9.5% deionized water, v/v/v). The mixture was stirred in a shaking water bath (Nüve, ST 30, Türkiye) (40 °C, 170 rpm) for 60 min. Following extraction, the residue was removed by filtration, and the solvent was evaporated using a rotary evaporator (Büchi, Switzerland). The final extract was lyophilized (Toros, TRS 2, Türkiye) and stored at 4 °C.

Extraction of fibroin

Fibroin extraction was performed by modifying established protocols [10, 11] through the following sequential stages:

Degumming Silk cocoons were cut into small pieces and washed. To remove the sericin, the cocoon pieces were boiled in 0.02 M Na_2CO_3 for 30 min. The degummed silk was then rinsed with pure water, squeezed, and clarified by vigorous shaking in 1 L of pure water for 20 min. The cleaned fibroin was dried on aluminum foil overnight in an oven.

Dissolution For dissolution, a CaCl_2 /ethanol/water system was used. Degummed fibroin was dissolved in the solution at a solid/liquid ratio (minimum 15 g fibroin) and maintained at 70 °C for 5 h, resulting in an amber-colored, transparent suspension.

Dialysis and Purification To remove CaCl_2 , the fibroin solution was placed in a dialysis tube (MWCO: 3.5 kDa) and dialyzed for 48 h. The resulting suspension was purified via centrifugation (Hettich, 320R, Germany) (4 °C, 20 min, 9000 rpm). The final fibroin solution was lyophilized.

Characterization The concentration of the fibroin solution was determined using a rapid moisture analyzer (OHAUS MB45, Switzerland). Protein content was determined using the Bradford method; absorbance was measured at 595 nm, and the protein concentrations were calculated using a standard curve (with bovine serum albumin, BSA) [12].

Coating formulation

Coating solutions were prepared with distilled water to contain 8% (w/v) fibroin (as the bioactive agent) and 0, 2, 4, 6, and 8% (w/v) MLE (as the biactive agent) in the final volume. They were stirred for 2 h at room temperature until a homogeneous consistency was achieved. Coating solutions were freshly prepared and stored in an amber-colored bottle at 4 °C until use.

Coating application and fruit storage

Grapes were prepared by removing them from the bunches, leaving the stem attached to each grape. Each treatment consisted of three independent replicates ($n = 3$), with 20 berries per replicate to ensure statistical robustness. The uniformity of the coating was ensured by a standardized dipping procedure: clusters were immersed three times at 5-minute intervals for 30–40 s into coating solutions at room temperature and at a depth of 60 mm. The coated fruits were then hung

to dry for 4 h at 22 °C and 38% relative humidity (RH). Coated and uncoated fruits were stored in a climate-controlled chamber (Mikrotest, MIT-120, Türkiye) at 21 ± 1 °C and 50% RH, and at 4 °C and 85–90% RH for 20 days, and shelf life and biactivity analyses were performed on days 0, 5, 10, 15, and 20 [10, 11].

Postharvest quality analysis of coated grapes

Changes in **fruit color and shape** were documented via photography. **Coating thickness** was observed using a stereo microscope (Leica EZ4E, Germany), and determined by scaling images via an online image processing page [13]. **Grape weights** were measured (Mettler Toledo, MS204S, Switzerland) and the average values are reported ($n = 7$). Berries were homogenized using an Ultraturrax homogenizer (Daihan, WiseTis/HG-15D, South Korea), **brin values** were measured using a digital refractometer (Ohaus, Switzerland) and **pH** was determined using a pH meter (Ohaus, NJ, USA). **Titrateable acidity** (TA) was determined by titrating 10 mL of the homogenized sample with a standard NaOH solution to the endpoint, with results expressed as a percentage of the equivalent acid [14]. Peel and flesh **color** of the fruits were determined using a digital color measurement device (Hunter-Lab, UltraScanVis, VA, USA). Measurements were taken from at least five different points on the fruits, and the L^* , a^* , and b^* values were recorded ($n = 5$). To measure **the firmness** of the grapes, a texture analyzer (Stable Micro Systems TA.XT plus, UK) was used, equipped with a 5 mm diameter flat-tipped probe and a 10 N load cell. The maximum force required to penetrate to a depth of 8 mm at a test speed of 1 mm/s was determined as the skin strength (g), and the amount of elongation of the skin up to the maximum force was determined as the elasticity (mm) value ($n = 5$) [15].

Total aerobic viable bacteria, mold and yeast counts were performed to determine the microbial load. Berries were randomly selected, placed whole in stomacher bags, and homogenized with a sterile 0.85% NaCl solution using a stomacher (Iul, Spain). To determine the total aerobic bacteria counts, serial dilutions were prepared in 0.85% NaCl. Samples (1 mL) were transferred to Plate Count Agar (PCA) and incubated at 30 °C for 3 days (mesophilic) and 7 °C for 10 days (psychrophilic) [16]. For the total mold-yeast count, inoculum (100 μL) from each dilution was transferred to Malt Extract Agar (MEA) and incubated at 25 °C for 5 days [16].

Sensory analysis were evaluated by a panel of 10 untrained panelists (5 male and 5 female, aged 18–40) representing typical consumers. To eliminate bias, the assessment was conducted under blind-testing conditions; samples were randomly coded and presented on standardized white plates. Panelists evaluated the samples using a validated 9-point

hedonic scale (1 = extremely disliked/terrible, 9 = extremely liked/excellent). The assessed criteria included appearance (glossy, matte, or dry), external color (green-brown), shell integrity (cracked or broken), odor, hardness (hard-soft), texture/consistency, flavor, and overall acceptability [17].

Bioactivity analyses of coating solutions and coated grapes

Bioactivity analyses were performed on both the coating solutions prepared in different formulations and on the coated grape samples throughout their shelf life.

The Folin-Ciocalteu solution was used to determine the **total phenolic content (TPC)**, and measurements were taken at a wavelength of 750 nm by UV-VIS spectrometer (Rigol/3660UV, Chinese). The total phenolic content in the samples was measured as gallic acid equivalent (GAE), and the results were expressed as mg GAE/g DW [18].

The CUPRAC and DPPH methods were applied to determine the **antioxidant capacity** of the samples. For the CUPRAC method, a neocuproine solution was used, and absorbance values at 450 nm were read spectrophotometrically [19]. The DPPH radical scavenging capacity was determined by measuring the absorbance at 517 nm, according to the method described by [18].

The in vitro **antidiabetic activity** was determined by α -amylase and α -glucosidase enzyme inhibition assays [20]. For in vitro α -amylase inhibition activity, a mixture of 500 μ L of α -amylase and 100 μ L of sample was incubated at 37 °C for 10 min. Subsequently, 500 μ L of starch solution (1%) was added, followed by incubation at 37 °C for 10 min. The reaction was terminated by adding 500 μ L of 3,5-dinitrosalicylic acid (DNSA) and boiling for 5 min. After cooling, 1.9 mL of distilled water was added, and absorbance was measured at 540 nm.

For in-vitro α -glucosidase inhibition activity, a mixture of 200 μ L of α -glucosidase (1 U/mL) and 100 μ L of sample was incubated at 37 °C for 10 min. Then, 100 μ L of p-nitrophenyl α -D-glucopyranoside (pNPG, 0.02 M) was added and incubated at 37 °C for 10 min. The reaction was stopped with 1000 μ L of Na₂CO₃ (0.2 M), and absorbance was measured at 405 nm.

In both assays, Acarbose was used as the positive control, and distilled water or buffer served as the negative control. Inhibition activity was calculated as follows:

$$\text{Inhibition Activity (\%)} = \frac{A_{\text{control}} - A_{\text{sample}}}{A_{\text{control}}} \times 100$$

(A_{sample} : absorbance of the sample, A_{control} : absorbance of the control)

Glycemic index (GI) values were determined by modifying the Englyst method [21]. A homogenized sample containing 0.5 g of digestible carbohydrate was mixed with 5 mL of deionized water and 10 mL of gastric solution (2.195 U pepsin, 0.5 g guar gum). Proteins were hydrolyzed at 37 °C for 30 min in a shaking water bath. After adding 5.0 mL of 0.5 M sodium acetate (pH 5.2), 5 mL of intestinal solution (136 mg/mL pancreatin, 13.4 U/mL amyloglycosidase, 25.43 U/mL invertase) was added, and the total volume was adjusted to 100 mL with deionized water. Samples (0.5 mL) were collected at 30, 60, 90, 120, 150, and 180 min. Enzymes were denatured at 100 °C for 5 min, followed by centrifugation at 8000 rpm for 5 min. Finally, 0.1 mL of the supernatant was reacted with 3 mL of Glucose Oxidase Peroxidase (GOPD) enzyme solution at 50 °C for 20 min, and absorbance was measured at 510 nm. Hydrolysis index (HI): Obtained by dividing the area under the hydrolysis curve (AUC) of the sample to the AUC of the reference (white bread) over 180 min.

Glycemic index (GI): Calculated according to Goñi et al. [22]:

$$\text{GI} = 39.71 + 0.549 \times \text{HI}$$

The **antimicrobial activity** was determined using the agar well diffusion method [23]. All microbial assessments were performed in triplicate ($n = 3$). Strains included *Staphylococcus aureus* (ATCC 6538), *Escherichia coli* (O157:H7 NCTC 12900), *Bacillus cereus* (ATCC 14579), *Saccharomyces bayanus* (ATCC 10601), and *Botrytis cinerea* (ATCC 46522). Test microorganisms taken from the stock culture were incubated in Mueller-Hinton Broth (MHB) at 37 °C for 24 h for bacteria, and in Malt Extract Broth (MEB) at 25 °C for 24–48 h for yeast. Bacteria and yeasts were cultured in Mueller-Hinton Broth (MHB) and Malt Extract Broth (MEB), respectively. Mold spores were harvested from Petri dishes using 0.1% Tween 80. Turbidity was adjusted to 0.5 McFarland for bacteria/yeasts, while mold spore concentration was standardized to 1×10^6 CFU/mL.

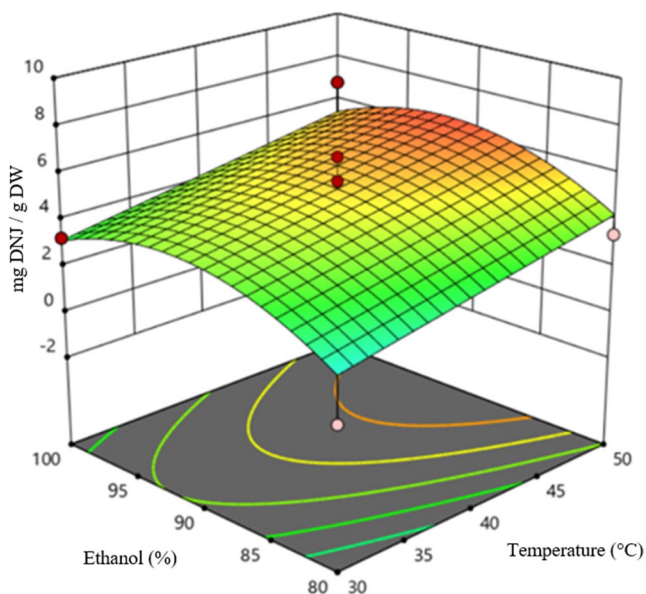
Inocula (100 μ L) were spread onto Mueller-Hinton agar (MHA) for bacteria and Malt Extract agar (MEA) for molds/yeasts. Wells (7 mm diameter) were punched, and 50 μ L of extract (50 mg/mL) was loaded. Plates were incubated (37 °C for 24 h for bacteria; 28 °C, 72 h for molds/yeasts). Antimicrobial activity was expressed as the clear zone diameter (mm).

Statistical analysis

All data obtained from the study were analyzed using one-way analysis of variance (ANOVA) and Tukey Post

Table 1 Presentation of the variables and levels of the Box-Behnken design

Variables	Level Values		
	Low (-1)	Medium (0)	High (1)
Extraction time (min)	60	90	120
Extraction temperature (°C)	30	40	50
Ethanol concentration (%)	80	90	100
Phosphoric acid concentration (%)	0	0.5	1

**Fig. 1** 3D representation of the DNJ extraction model

Hoc Test. Statistical significance levels were expressed as $p < 0.05$. All analyses were performed in triplicate ($n=3$), unless otherwise specified in the respective methodology sections where a higher number of replicates ($n>3$) was used. Results are presented as mean $\pm$ standard deviation (SD). The SPSS statistical package program (SPSS ver. 13.0 for Windows, SPSS Inc., Chicago, USA) was used.

Results and discussion

Analysis of MLE and fibroin extract

MLE An optimization study was conducted to determine the DNJ amount (Table 1). The HPLC analysis confirmed the presence of DNJ, identified by a distinct peak at a retention time of approximately 2.3 min. The calibration curve, described by the linear equation $y = 0.0585x + 0.541$ ($R^2 > 0.99$), enabled precise quantification of DNJ content in mulberry leaf extracts. The application of the Box-Behnken experimental design demonstrated the quadratic model's suitability for optimizing extraction conditions. Among the variables, extraction temperature, ethanol concentration,

and phosphoric acid concentration significantly influenced the yield, while time was found to be statistically insignificant within the studied range.

The model predicted optimal conditions at 40 °C, 90% ethanol, and 0.5% phosphoric acid. Under these conditions, the experimental DNJ yield was 5.432 mg/g, showing close alignment with the model's predicted value of 5.371 mg/g (also the highest yield was found to be 6.812 mg DNJ/g DW). This high degree of accuracy validates the predictive capability of optimized model. These findings fall well within the range of DNJ levels reported in literature (0.134–6.5 mg/g) [24], suggesting that this optimized extraction protocol is highly efficient for isolating this bioactive compound (Fig. 1).

Fibroin extract Regarding the coating matrix, fibroin was successfully extracted from silk cocoons using the CaCl_2 method with a yield of 6% (w/v). This result is consistent with previously reported yields (2–7%) using similar dissolution methods [25], confirming that protein isolation process is both efficient and reproducible. Furthermore, the extracted fibroin exhibited a high protein purity of 88.3%, ensuring a robust and suitable matrix for the subsequent edible coating applications.

Postharvest quality analysis of grapes in storage

The **visual assessment** of shelf life for AS and RG grapes is presented in Fig. 2a and b. For AS grapes, samples remained stable until day 10, whereas significant deterioration was observed from day 15 onwards. By day 15, uncoated (AS-21-B) and fibroin-only (AS-21-0) grapes stored at 21 °C had spoiled. However, high concentrations of MLE (6% and 8%) combined with cold storage (4 °C) successfully preserved the grapes up to day 20, demonstrating an extension of shelf life by at least 5 days compared to control groups. In RG grapes, ambient storage resulted in spoilage by day 15 for most samples; notably, only the 6% and 8% MLE-coated grapes maintained integrity. Under cold storage, the coating provided effective protection up to day 15, though all RG samples succumbed to spoilage by day 20. Overall, RG grapes exhibited a higher susceptibility to spoilage than AS grapes. When evaluated alongside Total Phenolic Content (TPC) and antioxidant capacity data, this difference suggests that RG grapes may experience a more rapid degradation of bioactive compounds during storage, limiting the protective efficacy of the coating over extended periods.

The **coating thickness** (Fig. 2c; Supplementary Table 1) revealed that uncoated grapes (B) possessed the lowest surface thickness. Application of fibroin alone significantly increased the thickness ($p < 0.05$), confirming the formation of a stable protective layer. Furthermore, coating thickness

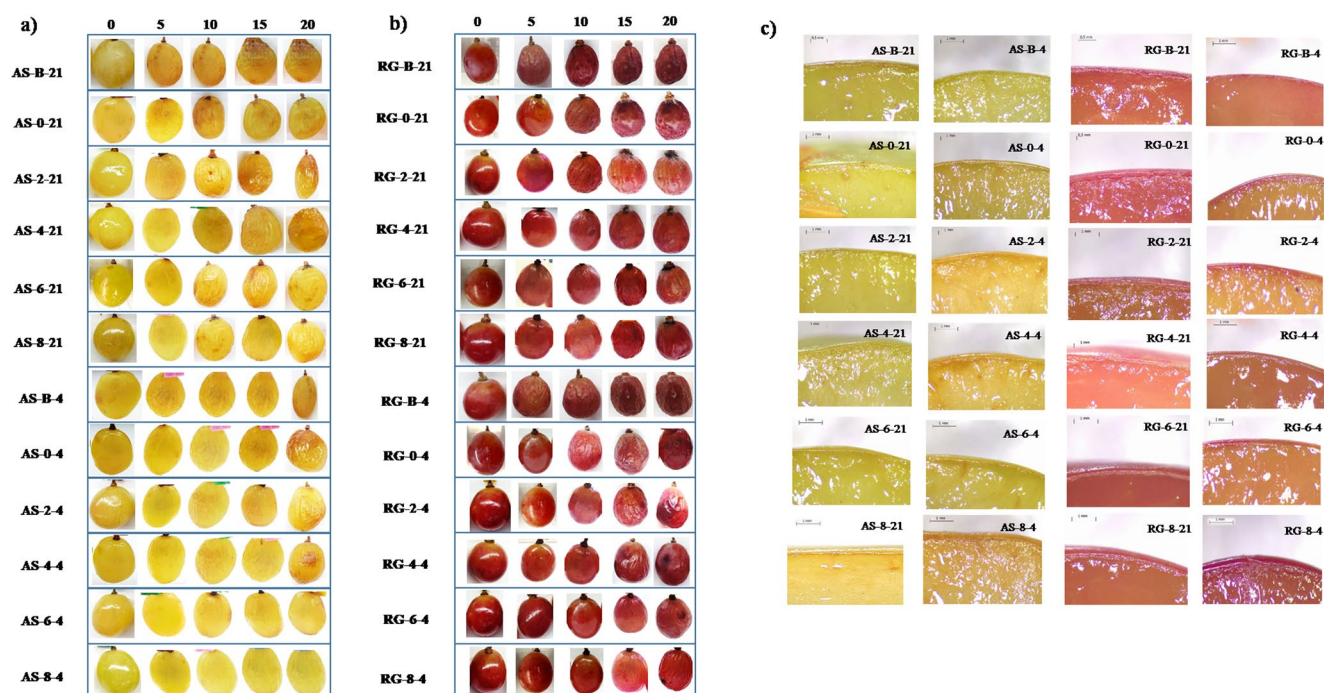


Fig. 2 Changes in weight (a), Brix (b), pH (c) and titratable acidity (d) of grapes coated with different formulations during storage. Error bars represent the SD ($n=3$). AS: Ata Sarısı grape, RG: Red Globe grape. B: uncoated grape, 0:coated with 8%fibroin, 2:coated with 2%

MLE+8% fibroin, 4:coated with 4% MLE+8% fibroin, 6:coated with 6% MLE+8% fibroin, 8:coated with 8% MLE+8% fibroin. 21:Storage at 21 °C, 4:Storage at 4 °C

increased in a concentration-dependent manner, showing statistically significant increases as the MLE ratio rose ($p < 0.05$). Interestingly, RG grapes consistently displayed higher coating thicknesses than AS grapes, suggesting that the skin structure of RG may facilitate greater absorption or affinity for the fibroin-MLE matrix. These findings are consistent with previous reports on fibroin-based coatings, which indicate that the interaction between the biopolymer matrix and fruit surface plays a crucial role in coating stability and barrier performance [26].

Figure 3a shows the weight changes of AS and RG stored under different temperature conditions with various coating types. Uncoated grapes experienced the most rapid weight loss; for example, AS-B-21 samples decreased from 11.38 g to 5.84 g, resulting in a 48% weight loss within 15 days. Conversely, fibroin-MLE coatings significantly reduced this loss in a concentration-dependent manner ($p < 0.05$). The RG-8-4 samples demonstrated the highest moisture retention, with only 8.7% weight loss after 15 days. A direct correlation was observed between coating thickness and moisture retention capacity; thicker, denser films provided superior barrier properties against transpiration. These results are consistent with literature on edible coatings, where treated fruits consistently maintain higher turgor and freshness compared to control groups [27, 28].

Figure 3b illustrates the evolution of Brix during storage. Uncoated grapes showed a rapid increase in Brix—rising

from 21.7 to 25.2 in the AS-B-21 group—driven by excessive water loss and subsequent sugar concentration. In contrast, the fibroin-MLE coated samples exhibited significantly more stable Brix values, reflecting the coating's efficacy in regulating moisture loss. Stability increased with MLE concentration, with the most stable performance observed in RG-8-4 (6.8% increase). As reported in similar studies [27], control groups consistently exhibit the highest fluctuations in TSS due to rapid dehydration, whereas effective coatings delay these biochemical changes.

Figure 3c and d depict the profiles of pH and titratable acidity (TA), respectively. pH values generally increased across all groups, a natural consequence of organic acid consumption during fruit respiration and ripening [28]. Uncoated samples exhibited the most significant pH rise. Coating application, particularly with 8% MLE, effectively delayed this increase, suggesting that the fibroin-MLE matrix slows down the metabolic degradation of organic acids.

Correspondingly, TA values exhibited a gradual decrease throughout storage (Fig. 3d). RG grapes maintained higher initial TA values than AS. Uncoated samples suffered the greatest acidity loss ($\Delta = 0.05$), while the 8% MLE coating significantly enhanced acid retention ($\Delta = 0.003$). These findings align with recent literature; for example, a coating developed with soy protein and essential oils was applied to grapes, and the fruits were stored at 4 °C for 12 days. During

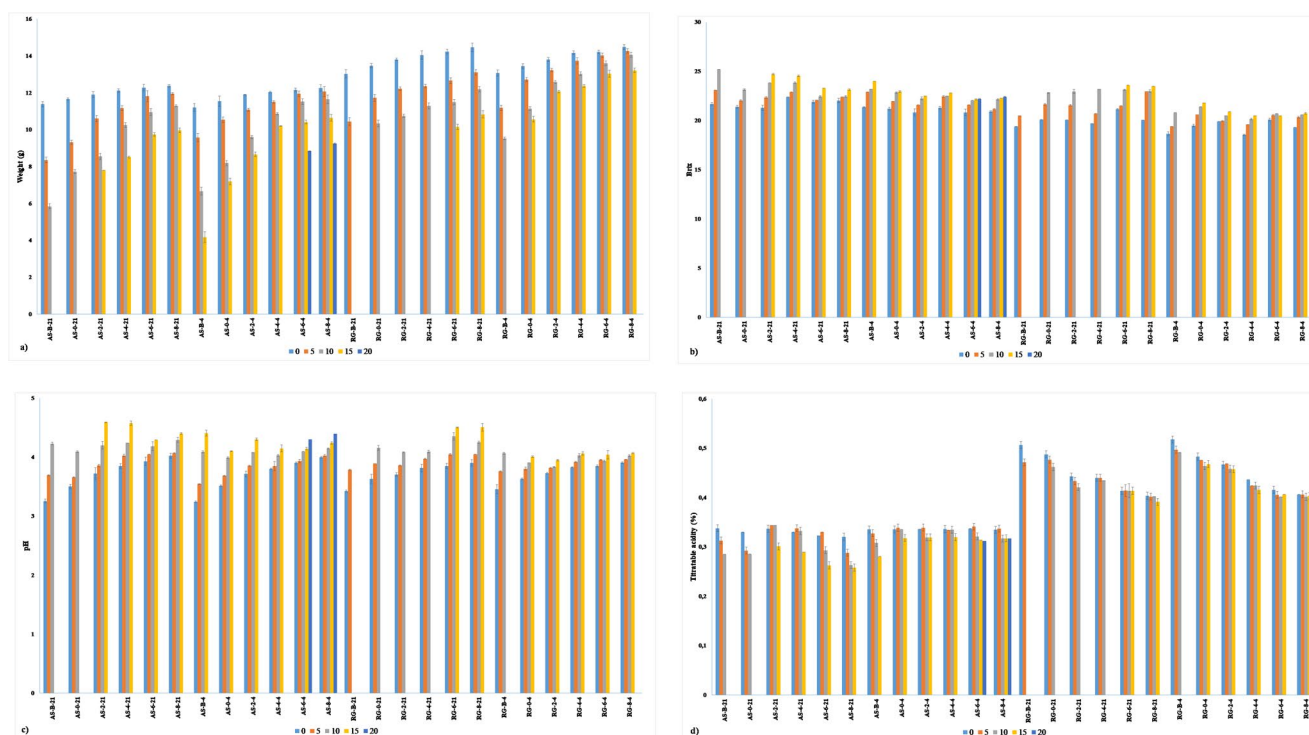


Fig. 3 Changes in L^* (a), a^* (b) and b^* (c) color values, shell strength (d) and elasticity (e) of grapes coated with different formulations during storage. Error bars represent the SD ($n=3$). AS: Ata Sarısı grape, RG: Red Globe grape. B: uncoated grape, 0:coated with 8%fibroin,

2:coated with 2% MLE+8% fibroin, 4:coated with 4% MLE+8% fibroin, 6:coated with 6% MLE+8% fibroin, 8:coated with 8% MLE+8% fibroin. 21:Storage at 21 °C, 4:Storage at 4 °C

the storage period, TA decreased rapidly in control samples, while acidity changed less in coated grapes, experiencing a loss of approximately 1% [29]. In another study, RG grapes were coated with alginate and chitosan and stored at 5 °C for 28 days. The initial acidity value of 0.47% decreased to 0.32% in the control group; the coated grapes showed minimal variation, ranging from 0.42 to 0.47 [28]. Collectively, these physicochemical parameters confirm that the fibroin-MLE coating serves as a robust barrier, successfully slowing down respiration rates and extending the shelf-life of table grapes by preserving internal chemical balance.

The surface color parameters (L^* , a^* , b^*) of grapes during storage are presented in Fig. 4a–c. The L^* values (brightness) of uncoated grapes were significantly lower than those of the coated samples throughout the storage period ($p < 0.05$). While all groups exhibited a gradual decrease in L^* , the decline was notably more rapid in uncoated controls, indicating that the coating forms an effective barrier in maintaining the surface brightness of the grapes. AS grapes stored at 4 °C showed better brightness retention than those at 21 °C. Notably, AS-8-4 displayed the lowest L^* loss (6.83%), whereas uncoated samples lost 11.33%. These results are consistent with literature suggesting that edible coatings significantly mitigate brightness loss by preserving surface integrity [30]. Regarding chromaticity, the a^* values

for AS grapes remained within a narrow range (−1.4 to −3.6), indicating a subtle greenish hue. While fibroin alone did not significantly alter a^* , the addition of MLE caused a slight negative shift, likely due to the natural green pigments inherent in the MLE. In RG grapes, a^* values remained dominant in the reddish spectrum (13.6–15). These findings align with similar studies [17, 28], where MLE and polysaccharide-based films showed a concentration-dependent influence on the surface color characteristics of table grapes. The b^* values of AS grapes showed a significant reduction in uncoated samples ($\Delta b^* = 11.14$) compared to the MLE-coated samples ($\Delta b^* = 6.1$), confirming that the coating stabilizes yellow pigment retention. Minimal changes were observed in the b^* values of RG grapes throughout the storage duration.

The changes in **skin strength** (Fig. 4d) further underscore the protective role of the coating. Uncoated AS and RG grapes experienced the fastest loss of strength during storage (15.5% and 13.6%, respectively), while coating with fibroin significantly increased skin strength (9.7% and 7.3% loss, respectively). It is thought that fibroin, a protein structure, strengthens the cell wall, making the skin more resistant. While strength increased in the groups with added MLE, those coated with 8% MLE were the groups that best maintained their strength throughout storage. Weak skin

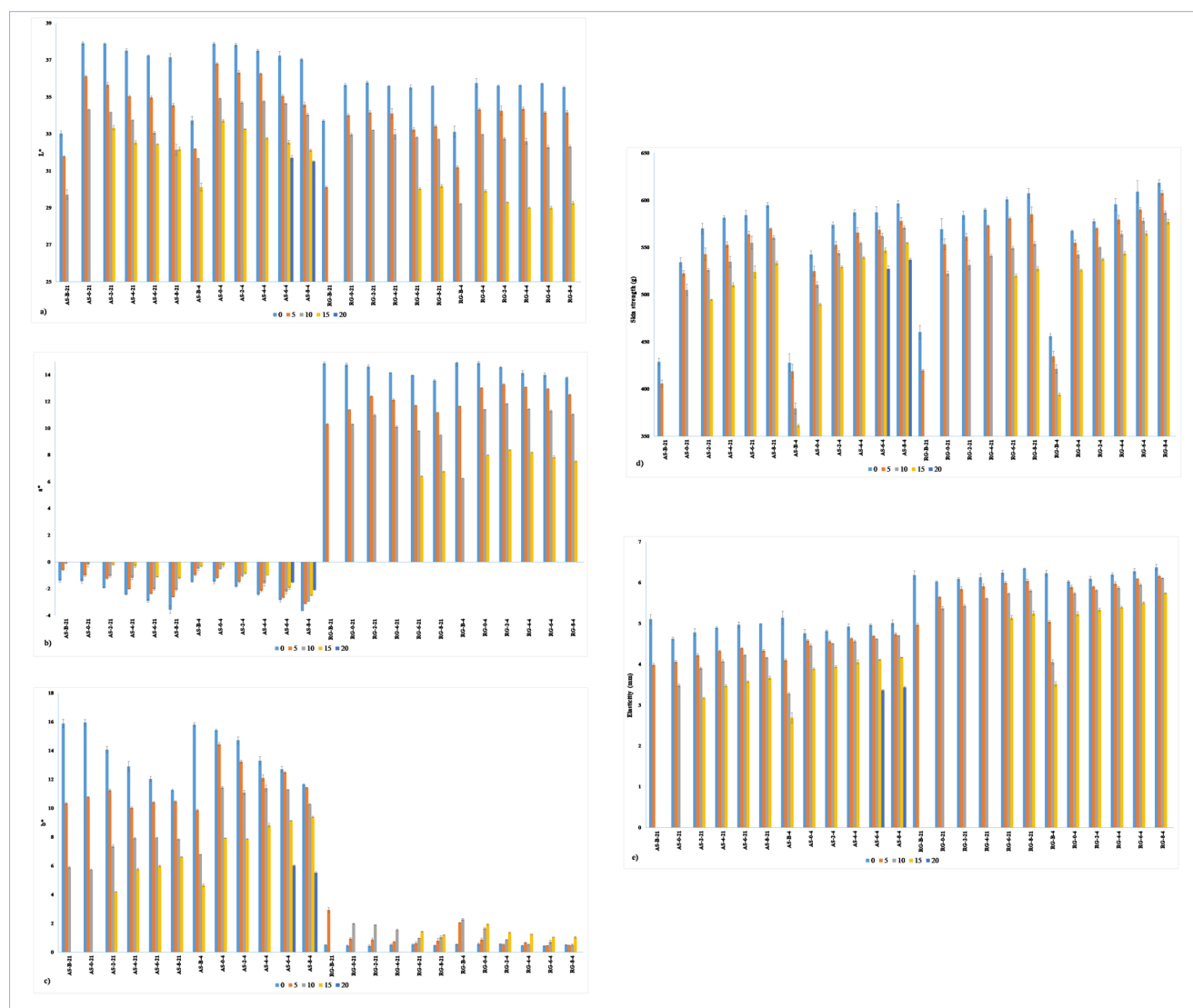


Fig. 4 Sensory evaluation results of grapes during storage. AS: Ata Sarısı grape, RG: Red Globe grape. B: uncoated grape, 0:coated with 8%fibroin, 2:coated with 2% MLE+8% fibroin, 4:coated with 4%

MLE+8% fibroin, 6:coated with 6% MLE+8% fibroin, 8:coated with 8% MLE+8% fibroin. 21:Storage at 21 °C, 4:Storage at 4 °C

strength can lead to rapid water loss and wrinkling of the fruit. When the results are evaluated together with the freshness images of the grapes, a linear relationship appears to exist.

Grapes with high skin strength appear to be more resistant to wrinkling and therefore less prone to weight loss. The initial strength of RG grapes (455–618 g) was found to be higher than that of AS (428–596 g). This result is attributed to the greater skin thickness of the RG variety. Grapes stored at 21 °C experienced faster strength loss than those stored at 4 °C. Overall, the results indicate that the presence of fibroin coating and the addition of MLE significantly preserved skin strength. The coating application acted as a barrier protecting the grape skin from external factors and increasing its physical strength.

The elasticity values of grapes during storage are given in Fig. 4e. Elasticity values express the capacity of the grape skin to maintain its flexibility. Although the initial elasticity values of uncoated AS and RG grapes were higher than those of coated samples, the most significant loss of elasticity during storage occurred in this group (47.6% and 43.6% loss, respectively). This suggests that the natural structure of grapes is more flexible; however, coating is a preservation method that maintains flexibility more effectively during storage. Grapes stored at room temperature lost elasticity more rapidly. Coated RG grapes stored in the refrigerator largely retained their elasticity even after 15 days. In coatings with added MLE, the loss of elasticity slowed down as the concentration increased, and the sample that preserved elasticity best was the group containing 8% MLE.

The microbial load in terms of Total Mesophilic Aerobic (TMA), Total Psychrotrophic Aerobic (TPA), yeast, and mold counts was evaluated to determine the preservative efficacy of the coatings (Table 2). Uncoated grapes showed the highest increase in TMA, TPA, yeast, and mold throughout all storage periods. This can be attributed to the direct exposure of the grape surface to microbial contamination. Grapes coated only with fibroin had a lower microbial load content compared to the uncoated group. This indicates that the fibroin coating partially inhibited microbial growth on the surface by forming a physical barrier. Fibroin coatings containing MLE were statistically the most effective group in suppressing microbial load ($p < 0.05$). As the MLE concentration increased, coatings containing 6% and 8% MLE stood out as the groups that most effectively limited the growth of TMA, TPA, mold, and yeast. This demonstrates that the antimicrobial activity of MLE is successful in preventing microbial spoilage of grapes. Grapes stored at 21 °C showed faster microbial growth from the earliest days of storage.

The **sensory evaluation** results (Fig. 5) are consistent with physical and chemical findings, demonstrating that cold storage (4 °C) is essential for preserving brightness, freshness, firmness, and aroma. Throughout the storage period, uncoated samples exhibited a rapid decline in sensory quality, whereas fibroin-coated grapes maintained higher scores. However, the analysis of the different formulations reveals a notable trade-off between preservative efficacy and consumer acceptability. While the 4% and 6% MLE formulations obtained the highest overall scores, the flavor ratings decreased in the 8% MLE group. This decline is likely attributed to the intrinsic bitter taste of mulberry leaf extract, which becomes more pronounced at higher concentrations. These results indicate an optimization trade-off, although increasing the extract concentration to 8% provides superior antimicrobial and physical protection, it compromises the organoleptic quality. Consequently, the sensory data suggest that moderate MLE concentrations (4–6%) represent the optimal range for balancing extended shelf-life with consumer preference. As observed, freshness and firmness were the most sensitive attributes, showing a significant decrease after 10–15 days of storage, further highlighting the role of the coating in delaying the natural senescence of the grapes.

Bioactivity analyses of coating solutions and coated grapes

Bioactivity analyses of coating solutions

To produce coating materials from fibroin and MLE, mixtures in various formulations were prepared, and bioactivity

analyses were performed (Table 3). It is observed that the amount of **TPC** increases regularly as the concentration of the samples increases. This increase may be associated with the release or synthesis of phenolic compounds, for example, through biological or chemical processes. 8MLE (181.40 mg GAE/g DW) has the highest TPC content. In the study by Panyatip et al. [31], the TPC of mulberry (*Morus alba* L.) leaves according to different processing methods was expressed as 129.93–390.89 mg GAE/g extract.

The TPC in the fibroin extract (43.43 mg GAE/g) is comparable to the literature. Fibroin nanoparticles containing mango leaf ethanolic extract were found to have a TPC of 76.39 ± 0.14 mg GAE/g dry powder weight [32].

Among the MLE samples, a statistically significant increase was observed as the concentration increased compared to all **antioxidant capacity** methods. This indicates that the increase in concentration is directly proportional to the effect of the antioxidant capacity-enhancing component in the MLE. Fibroin appears to have lower antioxidant capacity values. As a result, a linear and positive relationship exists between TPC and antioxidant capacity, which is clearly evident. Phenolic compounds play a crucial role in enhancing antioxidant capacity, reflecting their ability to facilitate electron transfer and scavenge free radicals.

There appears to be a significant increase in the **inhibition of both** in vitro α -amylase and α -glucosidase enzymes with increasing MLE concentration. While the inhibition values for α -amylase and α -glucosidase are generally similar, the inhibition values for α -amylase are higher. This may indicate that the tested substances are more effective inhibitors of α -amylase. These results indicate that MLE is a potential candidate for enzyme inhibition, and its efficacy increases especially with increasing concentration.

Antimicrobial activity revealed that fibroin did not exhibit an inhibitory effect on the tested microorganisms. However, the MLE groups exhibited a significant increase in their inhibitory effects on microorganisms, parallel to the increase in concentration. MLE groups were highly effective against Gram-positive bacteria (*S. aureus* and *B. cereus*), with zone diameters increasing alongside concentration. The antimicrobial effects of plant extracts are generally attributed to secondary metabolites, including phenolic compounds, terpenoids, alkaloids, glycosides, and essential oils. The greater effectiveness of the phenolic compounds in the MLE against Gram-positive bacteria and the lower inhibitory values against Gram-negative bacteria are thought to be due to differences in bacterial cell wall structure. Gram-positive bacteria lack an outer membrane and have a thick layer of peptidoglycan, allowing antimicrobial agents to penetrate easily. Gram-negative bacteria, on the other hand, have a more complex cell wall and a rich outer membrane. While porins in the outer membrane allow

Table 2 Changes in total aerobic viable microorganism counts of grapes coated with different coating solutions during storage

Total aerobic viable microorganism counts (Log 10 CFU/g)														
Day 0					Day 5					Day 10				
TMA	TPA	Mold	Yeast		TMA	TPA	Mold	Yeast		TMA	TPA	Mold	Yeast	
AS-B-21	<1	<2	<2	<1	<1	<1	<2	<2	<1	<1	<1	2.19±0.02	<2	3.93±0.04
AS-0-21	<1	<2	<2	<1	<1	<1	<2	<2	<1	<1	<1	<2	<2	3.86±0.02
AS-2-21	<1	<2	<2	<1	<1	<1	<2	<2	<1	<1	<1	<2	<2	<1
AS-4-21	<1	<2	<2	<1	<1	<1	<2	<2	<1	<1	<1	<2	<2	<1
AS-6-21	<1	<2	<2	<1	<1	<1	<2	<2	<1	<1	<1	<2	<2	<1
AS-8-21	<1	<2	<2	<1	<1	<1	<2	<2	<1	<1	<1	<2	<2	<1
AS-B-4	<1	<2	<2	<1	<1	<1	<2	<2	<1	<1	<1	<2	<2	<1
AS-0-4	<1	<2	<2	<1	<1	<1	<2	<2	<1	<1	<1	<2	<2	<1
AS-2-4	<1	<2	<2	<1	<1	<1	<2	<2	<1	<1	<1	<2	<2	<1
AS-4-4	<1	<2	<2	<1	<1	<1	<2	<2	<1	<1	<1	<2	<2	<1
AS-6-4	<1	<2	<2	<1	<1	<1	<2	<2	<1	<1	<1	<2	<2	<1
AS-8-4	<1	<2	<2	<1	<1	<1	<2	<2	<1	<1	<1	<2	<2	<1
RG-B-21	<1	<2	<2	<1	<1	<1	<2	<2	3.38±0.03	<1	3.89±0.02	4.34±0.02	2.57±0.05	4.30±0.01
RG-0-21	<1	<2	<2	<1	<1	<1	<2	<2	<1	<1	<1	<2	<2	3.66±0.01
RG-2-21	<1	<2	<2	<1	<1	<1	<2	<2	<1	<1	<1	<2	<2	3.04±0.04
RG-4-21	<1	<2	<2	<1	<1	<1	<2	<2	<1	<1	<1	<2	<2	2.71±0.01
RG-6-21	<1	<2	<2	<1	<1	<1	<2	<2	<1	<1	<1	<2	<2	<1
RG-8-21	<1	<2	<2	<1	<1	<1	<2	<2	<1	<1	<1	<2	<2	<1
RG-B-4	<1	<2	<2	<1	<1	<1	<2	<2	<1	<1	<1	<2	<2	<1
RG-0-4	<1	<2	<2	<1	<1	<1	<2	<2	<1	<1	<1	<2	<2	<1
RG-2-4	<1	<2	<2	<1	<1	<1	<2	<2	<1	<1	<1	<2	<2	<1
RG-4-4	<1	<2	<2	<1	<1	<1	<2	<2	<1	<1	<1	<2	<2	<1
RG-6-4	<1	<2	<2	<1	<1	<1	<2	<2	<1	<1	<1	<2	<2	<1
RG-8-4	<1	<2	<2	<1	<1	<1	<2	<2	<1	<1	<1	<2	<2	<1

Results are presented as mean±SD (n=3). AS: Ata Sarısı grape, RG: Red Globe grape, B: uncoated grape. 0:coated with 8%fibroin, 2:coated with 2% MLE+8% fibroin, 4:coated with 4% MLE+8% fibroin, 6:coated with 6% MLE+8% fibroin, 8:coated with 8% MLE+8% fibroin. 21:Storage at 21 °C, 4:Storage at 4 °C, TMA: total mesophilic aerobic microorganisms, TPA: total psychrophilic aerobic microorganisms

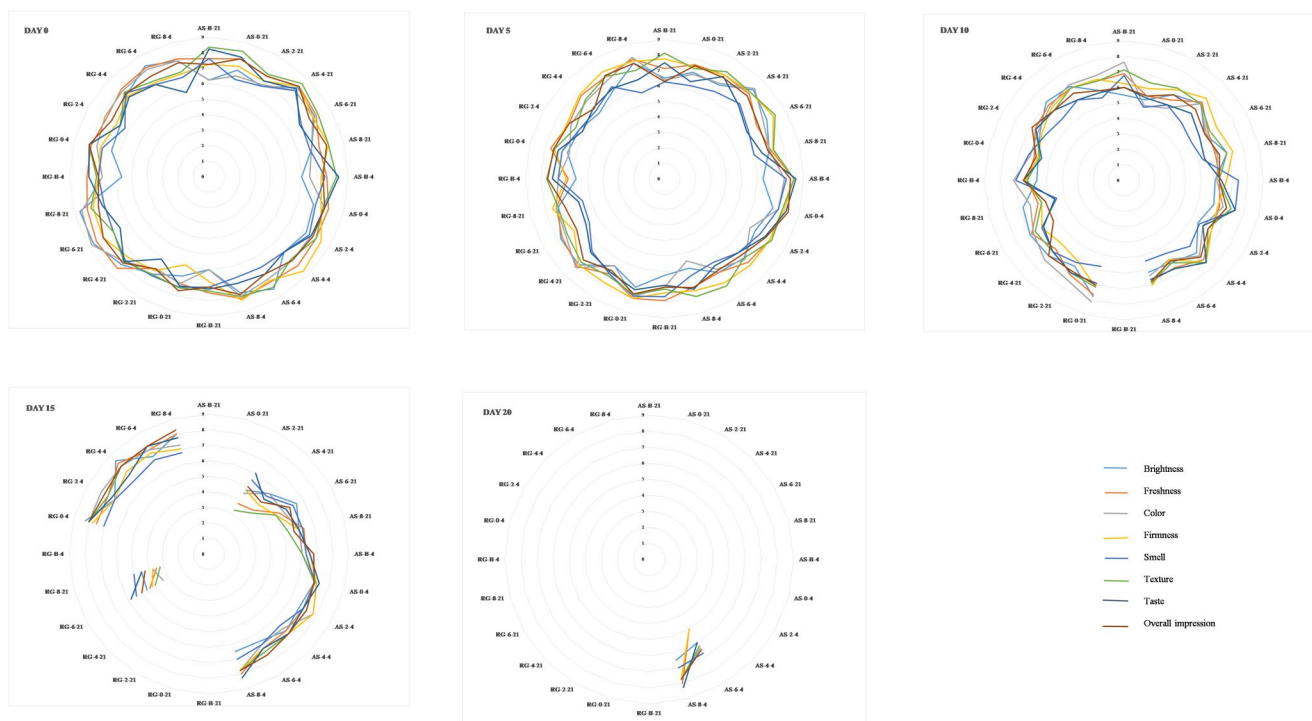


Fig. 5 Sensory evaluation results of grapes during storage. AS: Ata Sarısı grape, RG: Red Globe grape. B: uncoated grape, 0: coated with 8% fibroin, 2: coated with 2% MLE+8% fibroin, 4: coated with 4%

MLE+8% fibroin, 6: coated with 6% MLE+8% fibroin, 8: coated with 8% MLE+8% fibroin. 21: Storage at 21 °C, 4: Storage at 4 °C

Table 3 Bioactivity analyses of coating solutions results

Samples	TPC (mg GAE/g DW)	CUPRAC ($\mu\text{mol TE/g}$ DW)	DPPH ($\mu\text{mol TE/g}$ DW)	α -amylase (%)	α -glycosi- dase (%)	Zone Diameter (50 mg/mL) (mm)				
						<i>S. aureus</i>	<i>E. coli</i>	<i>B. cereus</i>	<i>S. bayanus</i>	<i>B. cinerea</i>
F	43,43 $\pm$ 0,42 ⁱ	4,17 $\pm$ 0,01 ^h	0,10 $\pm$ 0,01 ⁱ	19,02 $\pm$ 0,11 ⁱ	15,06 $\pm$ 0,97 ^h	nd	nd	nd	nd	nd
2MLE	80,28 $\pm$ 0,42 ^g	6,17 $\pm$ 0,19 ^c	0,17 $\pm$ 0,00 ^g	71,02 $\pm$ 0,43 ^c	69,61 $\pm$ 0,57 ^d	14,87 $\pm$ 0,35 ^e	12,38 $\pm$ 0,23 ^e	15,06 $\pm$ 0,20 ^e	nd	nd
4MLE	115,79 $\pm$ 0,34 ^e	7,43 $\pm$ 0,12 ^{cd}	0,42 $\pm$ 0,01 ^e	74,99 $\pm$ 0,31 ^c	72,50 $\pm$ 0,01 ^c	19,50 $\pm$ 0,73 ^c	14,22 $\pm$ 0,16 ^d	18,64 $\pm$ 0,53 ^c	nd	nd
6MLE	147,84 $\pm$ 0,41 ^c	9,13 $\pm$ 0,11 ^b	0,68 $\pm$ 0,03 ^c	78,85 $\pm$ 0,51 ^b	75,37 $\pm$ 0,74 ^b	20,38 $\pm$ 0,57 ^b	17,36 $\pm$ 0,52 ^b	20,87 $\pm$ 0,87 ^b	nd	nd
8MLE	181,40 $\pm$ 0,04 ^a	11,29 $\pm$ 0,09 ^a	1,00 $\pm$ 0,01 ^a	84,53 $\pm$ 0,05 ^a	82,62 $\pm$ 0,35 ^a	23,51 $\pm$ 0,51 ^a	19,43 $\pm$ 0,38 ^a	21,86 $\pm$ 0,38 ^a	nd	nd
F-2MLE	77,93 $\pm$ 0,25 ^h	5,12 $\pm$ 0,27 ^g	0,12 $\pm$ 0,13 ^h	61,06 $\pm$ 0,06 ^h	57,87 $\pm$ 0,17 ^g	13,86 $\pm$ 0,16 ^f	12,53 $\pm$ 0,44 ^e	17,24 $\pm$ 0,29 ^d	nd	nd
F-4MLE	109,24 $\pm$ 0,55 ^f	5,76 $\pm$ 0,00 ^f	0,32 $\pm$ 0,01 ^f	64,13 $\pm$ 0,15 ^g	60,49 $\pm$ 0,94 ^f	18,50 $\pm$ 0,44 ^d	16,54 $\pm$ 0,64 ^c	18,74 $\pm$ 0,27 ^c	nd	nd
F-6MLE	143,08 $\pm$ 0,25 ^d	7,17 $\pm$ 0,04 ^d	0,58 $\pm$ 0,01 ^d	67,43 $\pm$ 0,35 ^f	65,09 $\pm$ 0,83 ^e	19,52 $\pm$ 0,62 ^c	17,85 $\pm$ 0,31 ^b	22,24 $\pm$ 0,68 ^a	nd	nd
F-8MLE	170,64 $\pm$ 0,02 ^b	7,72 $\pm$ 0,01 ^c	0,77 $\pm$ 0,02 ^b	72,49 $\pm$ 0,56 ^d	69,39 $\pm$ 0,41 ^d	23,14 $\pm$ 0,46 ^a	19,04 $\pm$ 1,00 ^a	22,39 $\pm$ 0,32 ^a	nd	nd

Results are presented as mean $\pm$ SD (n=3). a-i Different letters within the same column indicate statistically significant differences between groups (p<0.05). F: 8% fibroin solution, 2MLE: 2% MLE solution, 4MLE: 4% MLE solution, 6MLE: 6% MLE solution, 8MLE: 8% MLE solution, F-2MLE: 8% fibroin solution+2% MLE solution, F-4MLE: 8% fibroin solution+4% MLE solution, F-6MLE: 8% fibroin solution+6% MLE solution, F-8MLE: 8% fibroin solution+8% MLE solution

the passage of specific molecules, the size and selectivity of these porins can limit the effectiveness of antimicrobials. Therefore, Gram-negative bacteria are more resistant to many antimicrobial agents, including herbal extracts, than Gram-positive bacteria [33]. The MLE samples tested were observed to be ineffective against *S. bayanus* and *B. cinerea*. This effect is thought to be due to the enzyme structures of fungi and yeasts. Studies have shown that fungi can inactivate phenolic compounds through detoxification enzymes,

including laccase, peroxidase, glutathione S-transferase, cytochrome P450 monooxygenase, and phenol hydroxylase [34]. According to the classification by Denev et al. [35], the zone diameters in the agar well diffusion test show that the effect of MLE samples on *S. aureus* increases in a dose-dependent manner and falls into the strong inhibition class at 6MLE and 8MLE. MLE samples provide moderate inhibition on *E. coli*. BDY groups, especially 6MLE and 8MLE, exhibit potent antibacterial activity on *B. cereus*.

This analysis supports the evaluation of MLE as a potential antibacterial agent.

Regarding the interaction between the coating components, it is observed that fibroin functions primarily as a structural film-forming matrix. While it provides the physical barrier necessary for fruit protection, it does not demonstrate significant individual antimicrobial or enzyme-inhibitory activity. Therefore, the enhanced bioactivity observed in the coated samples is attributed to the concentration-dependent release of bioactive compounds from the MLE, with fibroin acting as a neutral carrier rather than a synergistic agent.

Bioactivity analyses of coated grapes

Table 4 shows TPC and CUPRAC data for AS and RG grapes across different storage times, temperatures, and coating formulations. Visibly moldy or spoiled samples were excluded from analysis.

Uncoated grapes showed the fastest decrease in TPC, while grapes coated with fibroin and MLE preserved TPC well. Storage at 21 °C resulted in a rapid decrease over the storage period; however, this decrease slowed as the MLE percentage increased. TPC remained more stable in samples stored at 4 °C. Grapes coated with 8% MLE preserved TPC at the highest rate. At the beginning of storage, the TPC of RG grapes was higher than that of AS grapes, but as the storage period progressed, TPC loss was greater in RG grapes, especially after the 10th day. For instance, the TPC of AS-2-4 dropped from 171.9 to 163.36 mg GAE/100 g over 15 days, while RG-2-4 declined from 191.88 to 174.63 mg GAE/100 g. This trend was consistent across all samples. These findings align with literature [36], which reports TPC values of 120–360 mg GAE/100 g for similar white grape varieties.

At the beginning of storage, the antioxidant capacity values of RG were found to be higher than those of AS. However, over time, the loss in RG grapes was greater. Comparing day 0 to day 15, AS-2-4 lost 2.93 units, whereas RG-2-4 lost 7.81 units. These findings parallel our TPC results. Cold storage (4 °C) enhanced capacity retention, and higher MLE concentrations (6–8%) yielded superior stability. AS-8-4 and RG-8-4 maintained the highest stability. The coating acts as an oxygen barrier, limiting respiration and oxidative stress [27]. A strong positive correlation between TPC and antioxidant capacity was observed, with RG-8-4 exhibiting both peak TPC (225.44 mg GAE/100 g) and antioxidant capacity (73.24 μ mol Trolox/100 g). Uncoated grapes yielded the lowest values. Ultimately, MLE coatings effectively

mitigate oxidative deterioration, with results consistent with literature [36].

Table 5 presents the changes in vitro α -amylase and α -glucosidase inhibitory effects of AS and RG grapes. As the MLE ratio in grape coatings increased, both α -amylase and α -glucosidase inhibition activity increased significantly. RG grapes generally showed higher enzyme inhibition activity compared to AS grapes. Inhibitory activity decreased for both enzymes as the storage period progressed. However, coatings containing higher MLE content slowed this decrease. Inhibitory activity was maintained for a longer period in samples stored at 4 °C. At the α -amylase inhibition activity results, it appears that α -amylase inhibition activity remained at the lowest level in uncoated grape samples. Coatings containing MLE (especially 6% and 8%) significantly increased α -amylase inhibition activity and remained more stable throughout the storage period. Aumasa et al. [37] reported in their study investigating the inhibitory effects of phytochemicals in herbal teas on the digestion of rice starch that MLE inhibited α -amylase by approximately 15%. Teas made from baal fruit, mulberry leaves, gymnema leaves, and chrysanthemum flowers were reported to have the most potent starch digestion inhibitor. It was observed that coatings containing MLE exhibited a higher level of inhibitory effect compared to those containing fibroin. In particular, α -amylase inhibition of up to 40% in grape samples coated at 6% and 8% concentrations supports the notion that MLE has a strong inhibitory effect on digestive enzymes.

Uncoated grapes showed low α -glucosidase inhibition, whereas MLE coatings were more effective against this enzyme than against α -amylase. Consistent with Rasouli et al. [38], polyphenols exhibit a high affinity for the α -glucosidase active site. In contrast, the inhibition of α -amylase activity was provided by fewer polyphenol classes. This inhibition likely occurs because hydroxyl-rich polyphenols block enzyme active sites via hydrogen, hydrophobic, or electrostatic interactions, disrupting enzyme-substrate binding [38]. Furthermore, the pronounced α -glucosidase inhibition observed in this study can be attributed not only to the polyphenols but also to the significant DNJ content (5.432 mg/g) achieved through our optimized extraction protocol, as DNJ is a well-established and potent inhibitor of this specific enzyme.

In contrast, fibroin-only coatings showed no significant change in antidiabetic activity over time. This indicates that there is a factor different from the polyphenol mechanism in the MLE-coated samples. Since the fibroin protein

Table 4 TPC and CUPRAC levels in AS and RG grape varieties at different storage times and temperatures depending on coating with different solutions

TPC (mg GAE/100 g grape)						CUPRAC (μmolTrolox/100 g grape)					
Day 0	Day 5	Day 10	Day 15	Day 20		Day 0	Day 5	Day 10	Day 15	Day 20	
AS-B-21	126,78±0,14 ^{Ae}	118,34±0,16 ^{Bd}	105,00±0,49 ^{Ce}			32,82±0,95 ^{Ae}	20,48±0,02 ^{Bf}	14,86±0,24 ^{Ce}			
AS-0-21	136,09±0,30 ^{Ad}	126,14±0,05 ^{Bd}	115,31±0,41 ^{Cd}			33,97±0,61 ^{Ae}	30,05±0,14 ^{Be}	21,92±0,98 ^{Cd}			
AS-2-21	167,93±0,11 ^{Ae}	153,16±0,27 ^{Bc}	149,23±1,94 ^{Cc}	139,99±0,16 ^{De}		38,46±0,44 ^{Ad}	36,82±0,01 ^{Ad}	29,35±0,61 ^{Be}	22,78±1,50 ^{Cd}		
AS-4-21	176,60±1,84 ^{Ab}	168,16±0,27 ^{Bb}	164,60±0,71 ^{Cb}	153,70±2,40 ^{Pb}		45,21±0,90 ^{Ac}	42,36±1,64 ^{Be}	32,62±0,88 ^{Cc}	27,36±0,08 ^{De}		
AS-6-21	186,99±2,46 ^{Aa}	173,16±0,62 ^{Bb}	172,33±0,67 ^{Ba}	163,69±0,97 ^{Ca}		56,71±0,13 ^{Ab}	54,73±0,38 ^{Bb}	50,47±0,34 ^{Cb}	45,49±0,15 ^{Pb}		
AS-8-21	191,51±1,61 ^{Aa}	189,94±0,44 ^{Aa}	175,00±1,56 ^{Ba}	162,06±1,50 ^{Ca}		64,32±0,67 ^{Aa}	60,29±0,02 ^{Ba}	58,08±0,23 ^{Ca}	54,93±0,12 ^{Ba}		
AS-B-4	134,06±2,07 ^{Ad}	128,89±0,12 ^{Be}	127,75±1,91 ^{Bf}	124,14±2,70 ^{Ce}		33,69±0,22 ^{Ae}	29,62±0,13 ^{Bd}	24,45±0,20 ^{Ce}	15,88±0,05 ^{De}		
AS-0-4	138,20±0,57 ^{Bd}	140,03±1,39 ^{Ad}	139,16±2,56 ^{Ae}	133,11±2,03 ^{Cd}		34,25±1,01 ^{Ae}	31,14±0,13 ^{Bd}	29,65±1,02 ^{Bd}	24,88±0,09 ^{Cd}		
AS-2-4	171,90±3,25 ^{Ae}	167,00±1,38 ^{Bc}	168,30±0,28 ^{Bd}	163,36±1,33 ^{Cc}		41,55±0,45 ^{Ad}	42,91±0,07 ^{Ac}	39,32±0,45 ^{Be}	38,62±0,01 ^{Be}		
AS-4-4	181,90±1,03 ^{Ab}	178,81±1,57 ^{Bb}	173,10±0,71 ^{Cc}	176,33±1,38 ^{Bb}		46,11±0,37 ^{Ac}	44,49±0,07 ^{ABe}	42,95±0,25 ^{Be}	40,64±0,51 ^{Be}		
AS-6-4	189,06±0,41 ^{Aa}	182,01±0,83 ^{Bb}	180,85±0,35 ^{Bb}	181,85±2,47 ^{Bb}	180,01±0,18 ^{Bb}	57,31±0,98 ^{ABb}	58,53±0,16 ^{Ab}	55,54±0,87 ^{Bb}	53,99±0,01 ^{Bb}	50,15±0,06 ^{Cb}	
AS-8-4	193,25±0,14 ^{Ba}	193,55±0,07 ^{Aa}	196,66±0,62 ^{Aa}	190,66±1,18 ^{Ba}	189,02±1,67 ^{Ba}	64,78±0,66 ^{Aa}	63,73±0,03 ^{Aa}	60,05±0,61 ^{Ba}	59,20±0,09 ^{Ba}	54,28±0,04 ^{Ca}	
RG-B-21	163,36±0,02 ^{Ae}	155,14±0,02 ^{Bd}	139,76±0,94 ^{Cd}			40,46±0,07 ^{Ad}	35,97±0,07 ^{Bd}	23,78±0,35 ^{Cd}			
RG-0-21	164,60±0,28 ^{Ae}	157,16±0,02 ^{Bd}	145,83±1,80 ^{Cd}			42,54±0,20 ^{Ad}	37,55±0,12 ^{Bd}	31,59±0,73 ^{Cc}			
RG-2-21	186,91±0,34 ^{Ad}	178,88±0,04 ^{Bc}	169,78±0,04 ^{Cc}			44,98±0,38 ^{Ad}	36,32±0,03 ^{Bd}	28,62±0,45 ^{Cc}			
RG-4-21	195,51±0,65 ^{Ac}	182,73±0,11 ^{Bc}	174,15±0,07 ^{Cc}			49,48±1,17 ^{Ac}	41,91±1,00 ^{Bc}	34,62±0,98 ^{Cc}			
RG-6-21	201,44±0,05 ^{Ab}	194,24±0,16 ^{Bb}	189,24±0,51 ^{Cb}	175,60±4,24 ^{Pb}		60,81±0,45 ^{Ab}	56,32±0,09 ^{Bb}	50,39±0,45 ^{Cb}	44,98±0,03 ^{Pb}		
RG-8-21	219,29±0,12 ^{Aa}	210,49±0,02 ^{Ba}	201,08±0,74 ^{Ca}	194,48±2,30 ^{Pa}		71,40±0,20 ^{Aa}	64,85±0,03 ^{Ba}	61,06±0,41 ^{Ca}	57,17±0,26 ^{Pa}		
RG-B-4	162,86±0,16 ^{Ae}	155,76±1,75 ^{Be}	150,35±1,06 ^{Cc}			41,34±0,15 ^{Ad}	36,70±0,10 ^{Bd}	30,45±1,08 ^{Cd}			
RG-0-4	164,34±0,30 ^{Ae}	159,04±2,49 ^{Be}	150,18±2,02 ^{Cc}	147,71±0,30 ^{De}		41,62±0,54 ^{Ad}	39,45±0,01 ^{Ac}	31,20±0,50 ^{Bd}			
RG-2-4	191,88±0,46 ^{Ad}	182,85±0,71 ^{Bd}	180,51±1,29 ^{Bd}	174,63±0,11 ^{Cd}		43,33±0,79 ^{Ac}	41,64±0,08 ^{ABe}	38,69±0,98 ^{Be}	35,52±0,03 ^{Cc}		
RG-4-4	205,14±0,65 ^{Ac}	198,58±0,28 ^{Bc}	190,16±0,62 ^{Cc}	183,63±1,66 ^{De}		45,48±0,52 ^{Ac}	41,14±0,04 ^{Be}	40,08±0,44 ^{Be}	37,66±0,20 ^{Cc}		
RG-6-4	211,54±1,96 ^{Ab}	207,13±1,38 ^{Bb}	196,05±1,48 ^{Cb}	188,38±0,67 ^{Pb}		58,95±0,41 ^{Ab}	56,75±0,03 ^{Bb}	54,20±0,28 ^{Bb}	51,16±0,10 ^{Pb}		
RG-8-4	225,44±0,12 ^{Aa}	216,73±1,59 ^{Ba}	206,48±0,92 ^{Ca}	199,60±1,98 ^{Pa}		73,24±1,75 ^{Aa}	70,78±1,19 ^{Ba}	67,85±0,34 ^{Ca}	62,05±0,07 ^{Pa}		

Results are presented as mean $\pm$ SD (n = 3). a, bDifferent lowercase letters in the same column indicate statistical differences between samples in the same group. A, D Different uppercase letters in the same row indicate statistical differences within the same sample during storage. (p < 0.05). AS: Ata Sarısı grape, RG: Red Globe grape. B: uncoated grape, 0:coated with 8% fibroin, 2:coated with 2% MLE + 8% fibroin, 4:coated with 4% MLE + 8% fibroin, 6:coated with 6% MLE + 8% fibroin, 8:coated with 8% MLE + 8% fibroin. 21:Storage at 21 °C, 4:Storage at 4 °C

Table 5 in-vitro α -amylase and α -glucosidase inhibition activity levels in AS and RG grape varieties at different storage times and temperatures depending on coating with different solutions

	α -amylase Inhibition Activity (%)					α -glucosidase Inhibition Activity (%)				
	Day 0	Day 5	Day 10	Day 15	Day 20	Day 0	Day 5	Day 10	Day 15	Day 20
AS-B-21	6,61 $\pm$ 0,53 ^{ABf}	7,20 $\pm$ 0,74 ^{Ae}	6,16 $\pm$ 0,11 ^{Be}			6,45 $\pm$ 0,61 ^{Ae}	5,37 $\pm$ 0,10 ^{Bf}	4,94 $\pm$ 0,10 ^{Cf}		
AS-0-21	10,85 $\pm$ 0,42 ^{Ae}	10,52 $\pm$ 0,95 ^{Ad}	10,55 $\pm$ 0,21 ^{Ad}			11,53 $\pm$ 0,51 ^{Ad}	12,11 $\pm$ 0,71 ^{Ae}	10,89 $\pm$ 0,41 ^{Ae}		
AS-2-21	16,58 $\pm$ 0,11 ^{Ad}	12,11 $\pm$ 0,11 ^{Bd}	10,74 $\pm$ 0,63 ^{Cd}	8,92 $\pm$ 0,42 ^{Dc}		31,66 $\pm$ 0,61 ^{Ae}	28,08 $\pm$ 0,41 ^{Bd}	23,42 $\pm$ 0,91 ^{Cd}	17,77 $\pm$ 0,81 ^{Dd}	
AS-4-21	23,57 $\pm$ 0,74 ^{Ae}	19,41 $\pm$ 0,32 ^{Be}	15,02 $\pm$ 0,21 ^{Cc}	11,74 $\pm$ 0,63 ^{Dc}		38,47 $\pm$ 0,10 ^{Ab}	34,89 $\pm$ 0,91 ^{Bc}	31,02 $\pm$ 0,30 ^{Cc}	26,50 $\pm$ 0,61 ^{De}	
AS-6-21	29,60 $\pm$ 0,63 ^{Ab}	28,34 $\pm$ 0,32 ^{Bb}	25,51 $\pm$ 0,11 ^{Cb}	22,53 $\pm$ 0,11 ^{Da}		46,06 $\pm$ 0,71 ^{Aa}	42,26 $\pm$ 0,61 ^{Bb}	40,62 $\pm$ 0,51 ^{Cb}	37,75 $\pm$ 0,91 ^{Db}	
AS-8-21	32,88 $\pm$ 0,21 ^{Aa}	30,64 $\pm$ 0,63 ^{Ba}	28,41 $\pm$ 0,21 ^{Ca}	23,87 $\pm$ 0,32 ^{Da}		48,35 $\pm$ 0,10 ^{Aa}	45,27 $\pm$ 0,41 ^{Ba}	43,62 $\pm$ 0,71 ^{Ca}	40,90 $\pm$ 0,51 ^{Da}	
AS-B-4	6,68 $\pm$ 0,42 ^{Af}	5,98 $\pm$ 0,42 ^{Af}	6,16 $\pm$ 0,11 ^{Af}	6,01 $\pm$ 0,32 ^{Ae}		7,66 $\pm$ 0,91 ^{ABe}	8,09 $\pm$ 0,30 ^{Ae}	6,30 $\pm$ 0,81 ^{Be}	4,94 $\pm$ 0,71 ^{Ce}	
AS-0-4	11,22 $\pm$ 1,16 ^{Ae}	11,52 $\pm$ 0,95 ^{Ae}	10,33 $\pm$ 0,53 ^{Be}	10,03 $\pm$ 0,95 ^{Bd}		10,67 $\pm$ 0,71 ^{Ad}	10,12 $\pm$ 0,36 ^{Ad}	9,46 $\pm$ 0,41 ^{Ad}	7,74 $\pm$ 0,81 ^{Bd}	
AS-2-4	17,92 $\pm$ 0,32 ^{Ad}	14,94 $\pm$ 0,32 ^{Bd}	13,38 $\pm$ 0,42 ^{Cd}	10,55 $\pm$ 0,21 ^{Dd}		32,59 $\pm$ 0,10 ^{ABe}	32,45 $\pm$ 0,30 ^{Ae}	29,58 $\pm$ 0,30 ^{Bc}	25,29 $\pm$ 0,30 ^{Cc}	
AS-4-4	25,36 $\pm$ 0,32 ^{Ae}	22,16 $\pm$ 0,63 ^{Bc}	19,41 $\pm$ 0,32 ^{Cc}	16,51 $\pm$ 0,21 ^{De}		36,32 $\pm$ 0,91 ^{Ab}	35,54 $\pm$ 0,22 ^{Ab}	33,74 $\pm$ 0,51 ^{Bb}	30,73 $\pm$ 0,71 ^{Cb}	
AS-6-4	32,58 $\pm$ 0,63 ^{Ab}	31,39 $\pm$ 0,21 ^{Bb}	30,94 $\pm$ 0,84 ^{Bb}	28,04 $\pm$ 0,11 ^{Cb}	25,06 $\pm$ 0,34 ^{Db}	48,07 $\pm$ 0,51 ^{Aa}	47,14 $\pm$ 0,41 ^{Aa}	46,27 $\pm$ 0,41 ^{Ba}	45,56 $\pm$ 0,61 ^{Ba}	43,12 $\pm$ 0,37 ^{Ca}
AS-8-4	34,22 $\pm$ 0,42 ^{Aa}	33,92 $\pm$ 0,84 ^{Ab}	32,80 $\pm$ 0,32 ^{Ba}	30,94 $\pm$ 0,84 ^{Ca}	28,37 $\pm$ 0,16 ^{Da}	49,79 $\pm$ 0,10 ^{Aa}	48,28 $\pm$ 0,81 ^{Aa}	46,85 $\pm$ 0,20 ^{Ba}	45,05 $\pm$ 0,10 ^{Ba}	43,19 $\pm$ 0,24 ^{Ca}
RG-B-21	11,74 $\pm$ 0,63 ^{Af}	11,82 $\pm$ 0,53 ^{Ae}	11,67 $\pm$ 0,74 ^{Ad}			12,61 $\pm$ 0,00 ^{Af}	12,11 $\pm$ 0,71 ^{Af}	11,10 $\pm$ 0,10 ^{Af}		
RG-0-21	14,57 $\pm$ 0,84 ^{Ae}	14,65 $\pm$ 0,32 ^{Ad}	13,23 $\pm$ 0,63 ^{Bc}			15,19 $\pm$ 0,41 ^{Ae}	15,26 $\pm$ 0,30 ^{Ae}	13,54 $\pm$ 0,71 ^{Be}		
RG-2-21	22,53 $\pm$ 0,11 ^{Ad}	15,09 $\pm$ 0,11 ^{Bd}	12,18 $\pm$ 0,74 ^{Ccd}			35,39 $\pm$ 0,20 ^{Ad}	29,58 $\pm$ 0,30 ^{Bd}	22,49 $\pm$ 0,20 ^{Cd}		
RG-4-21	29,60 $\pm$ 0,63 ^{Ae}	23,65 $\pm$ 0,63 ^{Bc}	17,84 $\pm$ 0,42 ^{Cb}			42,48 $\pm$ 0,30 ^{Ae}	35,03 $\pm$ 0,71 ^{Bc}	29,58 $\pm$ 0,30 ^{Cc}		
RG-6-21	38,76 $\pm$ 0,32 ^{Ab}	32,80 $\pm$ 0,32 ^{Bb}	28,34 $\pm$ 0,32 ^{Ca}	20,75 $\pm$ 0,53 ^{Db}		50,38 $\pm$ 0,07 ^{Ab}	46,63 $\pm$ 0,51 ^{Bb}	42,34 $\pm$ 0,51 ^{Cb}	36,60 $\pm$ 0,51 ^{Db}	
RG-8-21	41,66 $\pm$ 0,42 ^{Aa}	35,93 $\pm$ 0,11 ^{Ba}	29,90 $\pm$ 0,21 ^{Ca}	21,04 $\pm$ 0,11 ^{Da}		53,41 $\pm$ 0,04 ^{Aa}	49,79 $\pm$ 0,10 ^{Ba}	46,63 $\pm$ 0,51 ^{Ca}	40,69 $\pm$ 0,81 ^{Da}	
RG-B-4	13,23 $\pm$ 0,63 ^{Af}	13,45 $\pm$ 0,32 ^{Af}	13,23 $\pm$ 0,63 ^{Ad}			13,75 $\pm$ 0,41 ^{Af}	13,54 $\pm$ 0,71 ^{Ae}	12,11 $\pm$ 0,71 ^{Ad}		
RG-0-4	14,79 $\pm$ 0,53 ^{Ae}	14,72 $\pm$ 0,63 ^{Ae}	13,45 $\pm$ 0,32 ^{Bd}			15,40 $\pm$ 0,10 ^{Ae}	15,26 $\pm$ 0,30 ^{Ad}	13,75 $\pm$ 0,41 ^{Bd}		
RG-2-4	25,51 $\pm$ 0,11 ^{Ad}	17,99 $\pm$ 0,21 ^{Bd}	13,83 $\pm$ 0,21 ^{Cd}	8,92 $\pm$ 0,42 ^{Dd}		35,03 $\pm$ 0,71 ^{Ad}	30,73 $\pm$ 0,71 ^{Bc}	26,50 $\pm$ 0,61 ^{Cc}	20,77 $\pm$ 0,61 ^{De}	
RG-4-4	33,92 $\pm$ 0,84 ^{Ae}	28,34 $\pm$ 0,32 ^{Bc}	23,87 $\pm$ 0,32 ^{Cc}	16,43 $\pm$ 0,32 ^{De}		41,98 $\pm$ 0,81 ^{Ae}	37,82 $\pm$ 0,81 ^{Bb}	35,32 $\pm$ 0,30 ^{Cb}	30,80 $\pm$ 0,61 ^{Db}	
RG-6-4	41,58 $\pm$ 0,53 ^{Ab}	38,61 $\pm$ 0,53 ^{Bb}	35,63 $\pm$ 0,53 ^{Cb}	29,68 $\pm$ 0,53 ^{Db}		51,50 $\pm$ 0,30 ^{Ab}	49,79 $\pm$ 0,10 ^{Ba}	46,92 $\pm$ 0,10 ^{Ca}	43,62 $\pm$ 0,71 ^{Da}	
RG-8-4	42,37 $\pm$ 0,11 ^{Aa}	40,32 $\pm$ 0,21 ^{Ba}	37,42 $\pm$ 0,11 ^{Ca}	32,88 $\pm$ 0,21 ^{Da}		53,65 $\pm$ 0,51 ^{Aa}	50,86 $\pm$ 0,61 ^{Ba}	47,78 $\pm$ 0,91 ^{Ca}	43,84 $\pm$ 0,41 ^{Da}	

Results are presented as mean $\pm$ SD (n=3). a, b Different lowercase letters in the same column indicate statistical differences between samples in the same group. A, D Different uppercase letters in the same row indicate statistical differences within the same sample during storage. (p < 0.05). AS: Ata Sarısı grape, RG: Red Globe grape. B: uncoated grape, 0: coated with 8% fibroin, 2: coated with 2% MLE+8% fibroin, 4: coated with 4% MLE+8% fibroin, 6: coated with 6% MLE+8% fibroin, 8: coated with 8% MLE+8% fibroin. 21: Storage at 21 °C, 4: Storage at 4 °C

has a more stable structure, it can be assumed that it undergoes less change over shelf life compared to secondary metabolites such as phenolics. However, the antidiabetic activity of samples coated only with fibroin remained statistically very low compared to samples with added MLE. The antidiabetic capacity of the fibroin protein is thought to be very limited.

Table 6 shows the in-vitro **glycemic index** (GI) and **hydrolysis index** (HI) of AS and RG grapes. Following the method by Germaine et al. [39], GI values were calculated relative to white bread (GI = 70). Generally, RG grapes exhibited lower GI and HI values than AS, likely due to RG's higher polyphenol content. This is because polyphenols can slow down the digestion of carbohydrates, leading to a more gradual release of glucose into the bloodstream [40]. Furthermore, when evaluated together with the antidiabetic activity results of the grapes, it appears that the α -amylase and α -glucosidase inhibition activities of RG grapes are higher than those of AS. This situation is thought to slow down the digestion of simple sugars in the structure. Uncoated (B) samples yielded the highest HI and GI values. The measured GI (RG: 49.14; AS: 52.62) falls within the literature-reported ranges (red: 47–53; yellow: 50–58) [41].

Fibroin-coated samples had no significant effect on GI values. It is understood that the presence of fibroin in the protein structure does not have a significant reducing effect on the GI value of grapes. The 8% fibroin concentration specified for coating the grapes may have been insufficient to affect the GI. Grapes coated with MLE (especially at 6% and 8%) showed significant decreases in GI and HI values. AS-8 and RG-8 had the lowest HI and GI values.

This result supports the notion that MLE may be an effective bioactive component in reducing the glycemic response. An addition of mulberry leaf tea reduced the rapidly digestible starch content of cooked rice and lowered its glycemic index from 78.11 to 67.26 [37]. Grapes stored at 21 °C had higher GI and HI values, while grapes stored at 4 °C generally had lower GI and HI values. As storage time increased, GI and HI results generally increased over time up to the 20th day. This is because complex carbohydrates can break down into simpler sugars that are digested more quickly, which can raise the GI. Grapes containing 8% MLE (AS-8 and RG-8) were found to have the most stable HI and GI levels. This indicates that the inhibitory effect of MLE on the glycemic index persists over time. These in vitro results provide a standardized screening of glycemic potential but serve as

estimates rather than absolute clinical values. In vivo outcomes may differ due to complex physiological factors, including gastric emptying, hormonal regulation, and gut microbiota, which cannot be fully replicated. Thus, these findings indicate metabolic trends that require future clinical validation.

Conclusions

This study demonstrates that fibroin-based edible coatings enriched with mulberry leaf extract (MLE) can serve as an effective multifunctional system to improve postharvest quality and physiological stability while introducing bioactive functionality to fresh table grapes. The integration of MLE into a food-grade fibroin matrix enabled the simultaneous enhancement of storage shelf-life and biological activity without compromising coating performance.

Optimization of MLE extraction confirmed that solvent composition and temperature were the primary factors influencing deoxynojirimycin yield, providing a robust extract for functional applications. Increasing MLE concentration significantly improved the antioxidant, antidiabetic, and antimicrobial properties of the formulations. Application of these coatings to Ata Sarısı and Red Globe grapes resulted in improved preservation of quality attributes and bioactive compounds during 20 days of storage, particularly at 4 °C.

A key finding was that the incorporation of MLE into the fibroin matrix substantially reduced the in vitro glycemic index of coated grapes, suggesting that edible coatings can be engineered to proactively influence the nutritional response of fresh fruits. This positions fibroin-MLE coatings as an emerging strategy in postharvest food systems to meet consumer demand for healthier produce. Overall, while the system showed excellent potential for balancing technological performance and sensory acceptability, the purified fibroin provides a safe, biocompatible, and non-allergenic alternative to synthetic coatings. By replacing non-biodegradable synthetic waxes, this system supports the transition toward a circular bio-economy, providing a sustainable solution to both food waste and plastic pollution. The degumming process yields a non-toxic and pure protein matrix. To advance this technology toward industrial application, future research should focus on optimizing upscaling processes for commercial use and conducting in vivo studies to validate glycemic outcomes. Furthermore, addressing regulatory

Table 6 in vitro glycemic index changes in AS and RG grape varieties at different storage times and temperatures depending on coating with different solutions

	Day 0			Day 5			Day 10			Day 15			Day 20		
	HI	GI		HI	GI		HI	GI		HI	GI		HI	GI	
White bread	100,00±0,64	70,00±0,26													
AS-B-21	57,21±0,08	52,62±0,03		57,27±0,10	52,64±0,06		59,20±0,03	53,43±0,01							
AS-0-21	56,62±0,47	52,38±0,19		56,69±0,02	52,41±0,04		58,52±0,40	53,15±0,16							
AS-2-21	53,22±0,06	51,00±0,03		53,28±0,04	51,02±0,01		54,78±0,04	51,63±0,01		56,67±0,05	52,40±0,02				
AS-4-21	52,56±0,08	50,73±0,03		52,59±0,02	50,74±0,01		53,74±0,02	51,21±0,01		55,44±0,06	51,90±0,02				
AS-6-21	50,14±0,06	49,75±0,02		50,19±0,01	49,77±0,01		50,92±0,08	50,06±0,03		52,25±0,02	50,60±0,01				
AS-8-21	49,11±0,05	49,33±0,02		49,14±0,02	49,34±0,00		49,73±0,04	49,58±0,01		50,61±0,04	49,94±0,02				
AS-B-4	57,22±0,06	52,62±0,02		57,28±0,04	52,65±0,01		58,73±0,05	53,24±0,02		60,80±0,07	54,08±0,03				
AS-0-4	56,54±0,06	52,35±0,02		56,61±0,03	52,38±0,01		57,65±0,06	52,80±0,03		59,08±0,04	53,38±0,01				
AS-2-4	53,23±0,11	51,00±0,04		53,37±0,03	51,06±0,01		53,86±0,03	51,26±0,01		54,62±0,02	51,57±0,01				
AS-4-4	52,60±0,04	50,75±0,02		52,69±0,02	50,78±0,01		52,94±0,04	50,88±0,01		53,44±0,04	51,09±0,01				
AS-6-4	50,31±0,08	49,82±0,03		50,36±0,06	49,84±0,01		50,16±0,08	49,76±0,03		50,25±0,08	49,79±0,03		50,72±0,16	49,98±0,04	
AS-8-4	49,23±0,11	49,38±0,05		49,30±0,13	49,41±0,03		49,21±0,06	49,37±0,02		49,32±0,08	49,41±0,03		49,51±0,10	49,49±0,06	
RG-B-21	48,63±0,15	49,13±0,06		48,70±0,13	49,16±0,05		50,69±0,16	49,97±0,06							
RG-0-21	48,43±0,11	49,05±0,04		48,49±0,11	49,08±0,05		50,54±0,13	49,91±0,05							
RG-2-21	45,27±0,15	47,77±0,06		45,30±0,13	47,78±0,04		46,76±0,08	48,37±0,03							
RG-4-21	44,83±0,04	47,59±0,01		44,87±0,03	47,61±0,05		45,97±0,04	48,05±0,01							
RG-6-21	42,14±0,11	46,50±0,05		42,20±0,08	46,52±0,01		42,99±0,04	46,84±0,01		44,29±0,01	47,37±0,01				
RG-8-21	41,46±0,06	46,22±0,02		41,52±0,10	46,25±0,03		42,15±0,08	46,50±0,03		43,13±0,04	46,90±0,01				
RG-B-4	48,64±0,76	49,14±0,31		48,72±0,81	49,17±0,04		50,14±0,69	49,75±0,28							
RG-0-4	48,45±0,56	49,06±0,23		48,80±0,14	49,20±0,33		49,82±0,09	49,62±0,04							
RG-2-4	45,22±0,08	47,75±0,03		45,28±0,11	47,77±0,06		45,81±0,07	47,99±0,03		46,77±0,06	48,38±0,02				
RG-4-4	44,78±0,08	47,57±0,03		44,84±0,08	47,59±0,04		45,13±0,10	47,71±0,04		45,93±0,04	48,04±0,02				
RG-6-4	42,08±0,02	46,47±0,01		42,18±0,04	46,51±0,03		42,12±0,05	46,49±0,02		42,28±0,04	46,55±0,02				
RG-8-4	41,53±0,03	46,25±0,01		41,57±0,09	46,27±0,01		41,46±0,08	46,22±0,03		41,58±0,06	46,27±0,03				

Results are presented as mean ± SD (n=3). a,bDifferent lowercase letters in the same column indicate statistical differences between samples in the same group. A,DDifferent uppercase letters in the same row indicate statistical differences within the same sample during storage. (p < 0.05). AS: Ata Sarısı grape, RG: Red Globe grape, 0:coated with 8%fibroin, 2:coated with 2% MLE+8% fibroin, 4:coated with 4% MLE+8% fibroin, 6:coated with 6% MLE+8% fibroin, 8:coated with 8% MLE+8% fibroin. 21:Storage at 21 °C, 4:Storage at 4 °C, HI: Hydrolysis index, GI: Glycemic index

compliance and safety standards will be critical for the widespread adoption of these fibroin-MLE coatings in the food industry.

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Data availability The data that support the findings of this study are available from the corresponding author upon reasonable request.

Declarations

Ethical Approval The sensory evaluation was conducted with the informed consent of all participants. The panelists were fully briefed on the study's scope and the safety of the edible coatings, which consisted of generally recognized as safe (GRAS) ingredients. All procedures were performed in accordance with the ethical standards for human sensory evaluation.

Competing interests The authors declare no competing interests.

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