Vol. 15, No. 3 (2026): 1023 - 1036 http://dx.doi.org/10.23960/jtepl.v15i3.1023-1036

JURNAL TEKNIK PERTANIAN LAMPUNG

ISSN 2302-559X (print) / 2549-0818 (online)
Journal homepage : https://jurnal.fp.unila.ac.id/index.php/JTP

Jelai Starch–Na-Alginate Film Reinforced with Bacterial Cellulose and Glycerol Plasticizer for Minimally Processed Pineapple Coating

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Article History:

Received : 23 November 2025
Revised : 01 June 2026
Accepted : 03 June 2026

Keywords:

Adlay starch,
Bacterial cellulose reinforcement,
Edible film,
Fresh cut pineapple,
Glycerol,
Mechanical properties.

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ABSTRACT

Jelai is a natural source of starch that is widely found in East Kalimantan but has not been extensively explored for its utilization. Edible films from jelai starch–Na-alginate generally exhibit high hydrophilicity and poor mechanical properties. This research aimed to improve these characteristics by incorporating bacterial cellulose (BC) as a filler and glycerol as a plasticizer, and to evaluate the effectiveness of the optimal formulation on minimally processed pineapple. The study utilized a Factorial Completely Randomized Design with two factors: BC concentration (0.1%, 0.2%, 0.3%) and glycerol concentration (0.5%, 1.0%, 1.5%) with 3 replications. The data were analyzed using ANOVA, and continued with Tukey's test. The results showed that the interaction between BC and glycerol significantly affected solubility and tensile strength. Glycerol significantly affected thickness, Water Vapor Permeability (WVP), and elongation. The best treatment (0.3% BC and 1.0% glycerol) yielded a tensile strength of 14.0 MPa, elongation of 4.39%, solubility of 44.23%, and WVP of 0.03716 g·mm·kPa^{-1}·day^{-1}·m^{-2}. The optimized coating effectively maintained a significantly higher pH ($p < 0.05$) in minimally processed pineapple than the control during 8 days of storage, indicating its potential to slow acidification and preserve product stability. The addition of BC and glycerol successfully improved the mechanical properties of the film and showed potential for maintaining pH stability in fresh-cut fruits.

1. INTRODUCTION

Food packaging plays a pivotal role in preserving product quality and extending shelf life. However, the extensive use of non-biodegradable petroleum-based plastics has led to severe environmental issues and increased greenhouse gas emissions (Akilie, 2024; Uysal-Unalan *et al*., 2024). To mitigate these impacts, biodegradable packaging, particularly edible films, has emerged as a sustainable alternative. Edible films protect food from external factors, reduce plastic waste, and are safe for consumption (Martins *et al*., 2024; Sharma *et al*., 2024). Polysaccharides, such as starch, are widely used as film matrices due to their abundance, biocompatibility, and biodegradability (Sultana, 2025). Polysaccharide compounds are known to have good film-forming ability and serve as effective barriers against O_2 and CO_2 gases (Bertuzzi *et al*., 2007).

Jelai or jali (*Coix lacryma-jobi* L.) is an underutilized cereal in Indonesia containing approximately 70% starch, making it a potential source for edible films (Wang *et al*., 2020; Subroto *et al*., 2022). Kang & Song (2019) has successfully developed jelai starch film containing clove bud essential oil that effectively applied as anti-oxidative packaging material to maintain the freshness and quality of pork belly during storage. Fadhilah (2023) also succeeded in developing smart packaging based on jelai starch to preserve mackerel freshness. Despite its potential, native starch films often exhibit high hydrophilicity, brittleness, and poor mechanical properties (Fauziyah *et al*., 2024). To enhance film integrity, blending starch with other biopolymers like sodium alginate (Na-alginate) is essential. Na-alginate,

derived from brown seaweed, is valued for its excellent film-forming ability, compatibility, and non-toxicity (Vargas *et al*., 2024). Na-alginate is biocompatible with starch due to its abundance of hydroxyl groups in its structure, which enables the formation of hydrogen bonds between polymers and results in a new biopolymer with enhanced characteristics (Agustin *et al*., 2021). However, composite films based on starch and alginate still demonstrate sensitivity to moisture and limited mechanical strength (Ramadhia *et al*., 2024; Li *et al*., 2025).

To overcome these limitations, the incorporation of fillers and plasticizers is necessary. Bacterial cellulose (BC), produced by *Komagataeibacter xylinus*, is a promising reinforcing agent due to its high purity, crystallinity, and superior mechanical strength compared to plant cellulose (Agustin *et al*., 2024; Kalashnikova *et al*., 2024). Previous studies have shown that BC can improve the tensile strength and barrier properties of biopolymer films (Rahmayanti *et al*., 2024). Concurrently, glycerol is widely used as a plasticizer to improve film flexibility. Glycerol reduces intermolecular forces within the polymer chains, thereby increasing elongation and preventing the film from cracking (Ratna *et al*., 2024; Ramadhia *et al*., 2024). However, excessive use of glycerol can negatively impact the film's moisture barrier properties, as its highly hydrophilic nature and ability to increase free volume facilitate water vapor transmission through the matrix (Saidi *et al*., 2025; Tarique *et al*., 2021).

The application of edible coatings is particularly relevant for minimally processed fruits, such as pineapples, which are susceptible to physiological weight loss and quality deterioration due to respiration and transpiration (Zhang *et al*., 2024). Edible coatings act as a semi-permeable barrier, regulating gas exchange and moisture transfer, thus maintaining the physicochemical properties of the fruit (Saha *et al*., 2023). Information regarding jelai starch–Na-alginate composite films reinforced with BC and glycerol remains limited. Thus, this study aims to analyze the effect of BC and glycerol addition on the physical and mechanical properties of the edible film and evaluate the effectiveness of the optimal formulation as an edible coating for maintaining the quality of minimally processed pineapple.

2. MATERIALS AND METHODS

2.1. Materials and Equipment

The primary material used was jelai seeds (*Coix lacryma-jobi* L.) obtained from local farmers in Loa Sumber Village, Loa Kulu District, Kutai Kartanegara Regency, East Kalimantan. Fresh pineapples (*Ananas comosus*) used for the application test were acquired from a local fruit market in Loa Bakung, Samarinda. The materials used to make the edible film solution consisted of food-grade Na-alginate and glycerol purchased from a local chemical supplier (Samarinda Raya Chemical Store), and commercial bacterial cellulose (*Nata de coco*, Kara brand) as the filler source. Distilled water was used for all solution preparations.

The equipment used for starch extraction and film preparation included a grinder (Huangcheng HC-800) and an 80-mesh sieve (KZM) for flour preparation, a food chopper (YK Design) for bacterial cellulose homogenization, hot plate magnetic stirrers (TZT SH-2) for solution mixing, and ovens (Sanyo) for drying. Film characterization was performed using a calibrated micrometer (Syntek MIC7B) for thickness, a colorimeter (CHNSpec CS-10) for color analysis, a UV-Vis Spectrophotometer (InScienPro US-110PC) for opacity, and a Universal Testing Machine (ZwickRoell Z.05) for mechanical properties. For fruit quality analysis, a hand refractometer (Eclipse 45-02) was used to measure Total Soluble Solids (TSS), a pH meter (Graigar PH-016) for acidity, analytical balances (Ho-choice) for weight loss monitoring, and refrigerators (Panasonic) for cold storage.

2.2. Procedures

2.2.1. Preparation of Jelai Flour and Starch Extraction

The preparation of jelai flour followed the dry milling procedure adapted from Yusuf *et al*. (2022). The process began with washing the jelai seeds to remove impurities, followed by air-drying at ambient temperature (approx. 28–30 °C) for 10 min to remove surface moisture. The seeds were then dried in an oven at 60 °C for 12 h to reduce moisture content. The dried seeds were ground using a mechanical grinder and sieved through an 80-mesh screen to obtain fine jelai flour. Subsequently, starch extraction was performed using a modified water-steeping method by Ali *et al*. (2023). Jelai flour (100 g) was mixed with distilled water (500 mL) and stirred at 500 rpm for 30 min. The suspension was

allowed to settle at 4 °C for 24 h. The supernatant was decanted, and the sediment was washed three times to remove impurities. The resulting starch was dried in an oven at 55 °C for 24 h, ground, and sieved through 80-mesh screen, yielding 76.57 g of starch (represent 76.57% w/w yield based on the initial flour weight).

2.2.2. Preparation of Bacterial Cellulose (BC) Slurry

The preparation of bacterial cellulose (BC) slurry was performed according to the method modified from Mustapha & Wan (2022). Commercial *Nata de coco* was drained to remove the syrup, then rinsed and squeezed three times with distilled water (1:2 ratio). To ensure the complete removal of sugar, the cellulose pellicles were subjected to hot water soaking four times to increase the solubility of residual sugars trapped within the dense cellulose network. Each soaking cycle lasted for 30 min with 5 min of stirring, followed by a 24-h interval between cycles to allow sufficient time for the internal sugars to completely diffuse out from the pellicle matrix into the surrounding water. Finally, the purified pellicles were drained and homogenized using a food chopper to produce a fine BC slurry.

2.2.3. Preparation of Edible Films

Edible films were prepared using the solvent casting method modified from Kang & Song (2019) and Kowalonek *et al*. (2024). For each formulation, a total of 100 mL of film-forming solution was prepared. First, 2 g of Na-alginate was dissolved in distilled water to form a 2% (w/v) solution, which was then divided into two portions. Glycerol (0.5, 1.0, or 1.5 g, corresponding to the respective w/v percentages) was dissolved in a 10 mL portion. Meanwhile, 5 g of jelai starch and the purified BC slurry (0.1, 0.2, or 0.3 g dry weight) were dispersed into the remaining 90 mL portion. The starch-BC mixture was heated to 50 °C under continuous moderate stirring (adjusted to maintain a stable vortex without inducing excessive aeration or cavitation). Once the temperature was reached, the glycerol-alginate solution was added. Heating was continued up to 95 °C and maintained for 5 min to ensure complete gelatinization. The solution was subsequently cooled to 50 °C, poured into 150 mm diameter petri dishes (30 mL per plate), and dried in an oven at 55 °C for 8 h.

2.2.4. Application on Minimally Processed Pineapple

The optimal edible film formulation (containing 0.3% BC and 1.0% glycerol) was selected based on the De Garmo effectiveness index. In this calculation, variable weights were assigned according to their relative importance for food coating applications: water vapor permeability (1.0), solubility (1.0), opacity (1.0), thickness (0.4), tensile strength (0.5), and elongation at break (0.6). This selection prioritized these properties while complying with the Japanese Industrial Standard (JIS) (2019) criteria: a maximum thickness of 0.25 mm, a minimum tensile strength of 0.39 MPa, and an elongation at break of 10–50%. This optimized film was applied to fresh-cut pineapple cubes (2 cm × 2 cm × 2 cm) using the dipping method modified from Saha *et al*. (2023). The fruit pieces were immersed in the film-forming solution for 30 s, drained for 1 min, and air-dried at room temperature for 10 min to ensure a uniform coating. Both coated samples and uncoated controls were prepared in triplicates (n = 3) for each observation day, packed in closed plastic containers (300 mL), and stored at 4 °C for 10 days.

2.3. Characterization of Edible Films

2.3.1. Thickness

Film thickness was determined using a calibrated micrometer (Syntek MIC7B, China) with an accuracy of ±0.001 mm. Measurements were taken at five random positions for each film sample, and the average value was used for opacity and water vapor permeability (WVP) calculations, adopting the method described by Charles *et al*. (2022).

2.3.2. Color

The color parameters (L^*, a^*, b^*) were analyzed using a colorimeter (CHNSpec CS-10), and the total color difference (ΔE) was calculated relative to the control film as described by Hamzah *et al*. (2022):

$$\Delta E = \sqrt{\left(L_0^* - L_{sample}^*\right)^2 + \left(a_0^* - a_{sample}^*\right)^2 + \left(b_0^* - b_{sample}^*\right)^2} \quad (1)$$

where L_0^*, a_0^*, b_0^* and L_{sample}^*, a_{sample}^*, b_{sample}^* represent the standard color values of the control film ($L_0^* = 86{,}94$, $a_0^* = 0{,}87$, $b_0^* = 3{,}77$), and L_{sample}^*, a_{sample}^*, b_{sample}^*, represent the color values of the sample films.

2.3.3. Opacity

Film opacity was assessed by measuring absorbance at 600 nm using a UV-Vis Spectrophotometer (InScienPro US-110PC). This specific wavelength within the visible spectrum was selected because it primarily reflects the degree of physical light scattering caused by the internal structure of the film, minimizing interference from chemical absorptions that typically occur in the ultraviolet range. The opacity value was calculated according to the procedure by Charles *et al*. (2025):

$$Opacity = \frac{A_{600}}{X} \tag{2}$$

where A_{600} is the absorbance value at 600 nm and X is the average film thickness (mm).

2.3.4. Solubility

Film solubility in water was measured by determining the percentage of dry matter solubilized after immersion in distilled water for 24 h and drying the residue at 100 °C for 5 h, modified from the method used by Tarique *et al*. (2021):

$$Solubility\ (\%) = \left[\frac{W_i - W_f}{W_i}\right] \times 100\% \tag{3}$$

where W_i is the initial dry weight of the film and W_f is the final dry weight of the undissolved residue.

2.3.5. Water Vapor Permeability

Water Vapor Permeability (WVP) was measured gravimetrically using the cup method modified from ASTM E96/E96M-14. Film samples (4 cm × 4 cm) were sealed over cups containing NaCl desiccant to maintain a 75% RH gradient at 28 °C. The Water Vapor Transmission Rate (WVTR) was first calculated as per equation (4) (Janik *et al*., 2023), and the final WVP value was determined using the modified equation (5) (Lamanna *et al*., 2024):

$$WVTR = \frac{\Delta m}{\Delta t \times A} \tag{4}$$

$$WVP = \frac{WVTR \times d}{P_p \times \Delta RH} \tag{5}$$

where $\Delta m/\Delta t$ is the slope of weight gain over time (g/day), A is the exposed film area (m^2), d is the film thickness (mm), P_p is the partial vapor pressure at the desiccant surface ($P_{sat} \times RH_{NaCl}$) (kPa), and ΔRH is the relative humidity difference.

2.3.6. Mechanical Properties

Tensile strength and elongation at break were evaluated using a Universal Testing Machine (ZwickRoell Z.05) according to ASTM D882-12 standard. Film strips (5 cm × 10 cm) were mounted with an initial grip separation of 50 mm and stretched at a crosshead speed of 10 mm/min.

2.4. Analysis of Fruit Quality during Storage

2.4.1. Weight loss

Weight loss (%) was monitored by weighing the pineapple samples on each observation day using an analytical balance (Ho-choice). The percentage was calculated referring to the method described by Hanani *et al*. (2023):

$$Weight\ Loss\ (\%) = \left[\frac{W_0 - W_t}{W_0}\right] \times 100\% \tag{6}$$

where W_0 is the initial weight of the fruit on day 0, and W_t is the weight of the fruit at the specific sampling time.

2.4.2. Total Soluble Solids

Total Soluble Solids (TSS) content was determined using a hand refractometer (Eclipse 45-02). Pineapple juice was extracted using a filter cloth, and the TSS value was recorded °Brix after calibrating the device with distilled water, following the procedure reported by Zhang *et al*. (2024).

2.4.3. pH Value

The pH was measured using a digital pH meter (Graigar PH-016). The electrode was calibrated with standard buffer solutions (pH 4.0 and 7.0) before being immersed in the extracted fruit juice to obtain the pH reading, following the method described by Saha *et al*. (2023).

2.5. Statistical Analysis

The physicochemical data of the edible films were analyzed using a Factorial Completely Randomized Design (CRD). The effects of BC concentration, glycerol concentration, and their interactions were evaluated using a two-way Analysis of Variance (ANOVA). Homogeneity of variance was tested using the Brown-Forsythe test. If the assumption was met, a Tukey's HSD test was performed ($p < 0.05$). In cases of heterogeneity, a robust ANOVA (20% trimmed mean) and a subsequent simple effects analysis using Welch's t-test were conducted utilizing the WRS2 package (Mair & Wilcox, 2020). For the fruit quality analysis during storage (weight loss, TSS, and pH), a paired t-test was used to compare the differences between coated and uncoated samples. All statistical computations were performed using SigmaPlot 15.0 and R software (version 4.5.2).

3. RESULTS AND DISCUSSION

3.1. Physical Properties

3.1.1. Thickness

Film thickness is a crucial parameter influencing the barrier properties and mechanical integrity of edible films are presented in Table 1. The thickness of the jelai starch–Na-alginate films ranged from 0.1940 to 0.2124 mm, complies with the JIS (2019) standard of a maximum of 0.25 mm. Statistical analysis revealed that the addition of glycerol significantly affected film thickness ($p < 0.05$), whereas the incorporation of bacterial cellulose (BC) and the interaction between factors did not show a significant effect ($p > 0.05$).

The increase in glycerol concentration resulted in thicker films. This phenomenon is attributed to the role of glycerol as a plasticizer, which increases the total solid content in the film-forming solution. As glycerol molecules occupy the intermolecular spaces within the polymeric matrix, they disrupt the network and increase the free volume, leading to a thicker structure. Additionally, the hygroscopic nature of glycerol enhances moisture retention within the matrix, further contributing to the increase in thickness. This finding is consistent with Eslami *et al*. (2023) and Yanti *et al*. (2024), who reported that higher plasticizer concentrations promote film swelling and thickness due to water absorption and solid accumulation.

In contrast, the addition of BC (0.1–0.3%) did not significantly alter the film thickness. This suggests that the amount of BC fibers incorporated was insufficient to modify the structural density or volume of the composite film significantly. Similar behavior was observed by Yekta *et al*. (2020), where the inclusion of bacterial nanocellulose at low concentrations did not produce a statistically significant difference in the thickness of biopolymer films.

Table 1. Thickness of jelai starch–Na-alginate edible films incorporated with bacterial cellulose and glycerol

BC (%)	Edible Film Thickness (mm)				
		Glycerol 0.5% ($G_{0.5}$)	Glycerol 1.0% ($G_{1.0}$)	Glycerol 1.5% ($G_{1.5}$)	Mean ± SD
	$S_{0.1}$	0.1972 ± 0.02	0.2094 ± 0.01	0.2081 ± 0.01	0.2049 ± 0.01
	$S_{0.2}$	0.2002 ± 0.00	0.2093 ± 0.00	0.2097 ± 0.01	0.2064 ± 0.01
	$S_{0.3}$	0.1940 ± 0.01	0.2119 ± 0.01	0.2124 ± 0.01	0.2061 ± 0.01
	Mean ± SD	0.1971^{b} ± 0.00	0.2102^{a} ± 0.00	0.2101^{a} ± 0.00	

Values followed by different superscript letters within the same column are significantly different ($p < 0.05$) according to Tukey's HSD test.

3.1.2. Color

The color characteristics (L^*, a^*, b^*) of the edible films are illustrated in Figure 1. Statistical analysis indicated that the addition of bacterial cellulose (BC) and glycerol did not significantly affect ($p > 0.05$), the film color. Generally, the films appeared whitish and slightly opaque with high lightness values ($L^* > 84$). The value of L* ranged from 85.85 – 87.16, while a* value ranged from 0.87 – 0.99 and b* value 3.42 – 5.22.

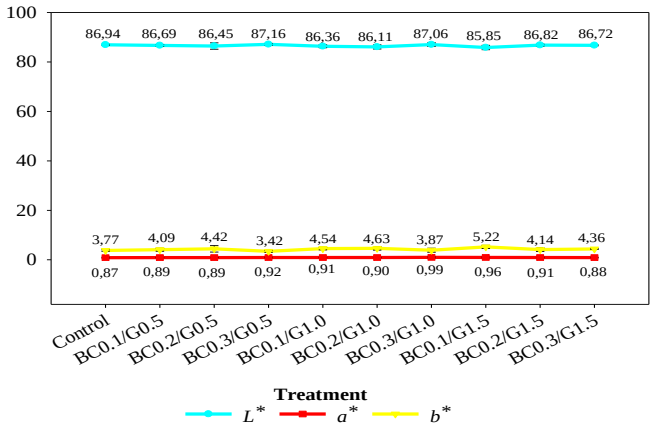

Figure 1. Color parameters (L^*, a^*, b^*) of jelai starch–Na-alginate edible films incorporated with bacterial cellulose and glycerol

The absence of significant color variation can be attributed to the dominant optical properties of the starch matrix. In this study, jelai starch was isolated using the water-steeping method. According to Zhang *et al.* (2019), this extraction method is less efficient in removing proteins and impurities compared to alkali extraction, resulting in starch granules with lower clarity and higher turbidity. This intrinsic opacity of the starch-alginate matrix likely masked the minor optical changes introduced by the low concentrations of BC (0.1–0.3%). This finding contrasts with Liu *et al.* (2020), where significant color changes in polysaccharide films were observed only when reinforced with a much higher concentration of bacterial cellulose nanofibers (up to 4%). Furthermore, the addition of glycerol did not alter the film color due to its transparent nature. Nordin *et al.* (2020) confirmed that glycerol acts as a colorless plasticizer that occupies intermolecular spaces without imparting pigment, thereby preserving the original appearance of the polymer matrix.

Table 2. Color difference (ΔE) and color representation of jelai starch–Na-alginate edible films reinforced with BC and glycerol

Treatment	ΔE ± SD	Hex Code	Color Representation	Description
Control	0.00 ± 0.00	#dfd9d3		Light grayish orange
BC0.1/G0.5	0.72 ± 0.59	#ded8d1		Light grayish orange
BC0.2/G0.5	1.74 ± 0.86	#ded7d0		Light grayish orange
BC0.3/G0.5	0.50 ± 0.23	#dfdad4		Light grayish orange
BC0.1/G1.0	1.01 ± 0.54	#ded7d0		Light grayish orange
BC0.2/G1.0	1.25 ± 1.30	#ddd6cf		Light grayish orange
BC0.3/G1.0	0.71 ± 0.20	#dfd9d3		Light grayish orange
BC0.1/G1.5	1.89 ± 1.19	#ddd6cd		Light grayish orange
BC0.2/G1.5	1.05 ± 0.11	#dfd9d2		Light grayish orange
BC0.3/G1.5	0.68 ± 0.19	#dfd8d1		Light grayish orange

The total color difference (ΔE) values relative to the control film are presented in Table 2. All formulations showed relatively low ΔE values, ranging from 0.50 to 1.89. According to the color perception classification by Karma (2020), a ΔE value between 1.0 and 2.0 indicates that the color difference is visible only upon close inspection, while values below 1.0 are considered not visible to the human eye. Edible coatings with low ΔE values are generally more transparent, thus they do not alter the original color of the product (Mari *et al*., 2024).

This minimal color deviation is supported by Wang *et al*. (2018), who reported that the incorporation of bacterial cellulose nanofibers into biopolymer films resulted in very small total color differences ($\Delta E < 1.0$), indicating that BC does not significantly alter the visual appearance of the film. In this study, the low BC content was insufficient to disrupt the light reflection properties or cause significant scattering. Consequently, the addition of BC and glycerol maintained the visual integrity of the original edible film.

3.1.3. Opacity

Opacity is a critical optical property that determines the visibility of the packaged product. A higher opacity value indicates lower transparency. An increase in film opacity is associated with light scattering effects and an enhancement of barrier function. High opacity provides better protection of food products against oxidation and photodegradation (Salama *et al*., 2024). The opacity values of the edible films ranged from 6.750 to 7.044 with average of 6.898 (Table 3). Statistical analysis showed that the addition of bacterial cellulose (BC) and glycerol, as well as their interaction, had no significant effect ($p > 0.05$) on the opacity of the films.

Table 3. Opacity of jelai starch–Na-alginate edible films incorporated with bacterial cellulose and glycerol

BC (%)	Opacity			
	Glycerol 0.5% ($G_{0.5}$)	Glycerol 1.0% ($G_{1.0}$)	Glycerol 1.5% ($G_{1.5}$)	Mean ± SD
$S_{0.1}$	6.818 ± 0.71	7.044 ± 0.33	7.029 ± 0.51	6.964 ± 0.13
$S_{0.2}$	6.808 ± 0.11	6.750 ± 0.22	6.833 ± 0.14	6.797 ± 0.04
$S_{0.3}$	7.036 ± 0.28	6.939 ± 0.16	6.826 ± 0.46	6.934 ± 0.11
Mean ± SD	6.887 ± 0.13	6.911 ± 0.15	6.896 ± 0.12	6.898 ± 0.12

The relatively high opacity values across all treatments suggest that the films were semi-transparent to opaque. This characteristic is largely governed by the internal structure of the polymer matrix. According to Guzman-Puyol *et al*. (2022), opacity in biopolymer films is primarily caused by light scattering as light passes through interfaces with different refractive indices, such as crystalline starch domains within the amorphous alginate matrix. The inherent turbidity of the jelai starch (extracted via water steeping) dominated the optical properties, creating a "background opacity" that masked any minor effects from the additives.

The non-significant effect of BC addition (0.1–0.3%) contrasts with findings by Liu *et al*. (2020), who observed a significant increase in opacity when higher concentrations of bacterial cellulose nanofibers (up to 4%) were added. Furthermore, the addition of glycerol did not significantly alter the opacity. Although glycerol is often expected to improve transparency, Nordin *et al*. (2020) reported that the addition of glycerol can contribute to light scattering within the starch matrix, thereby reducing transparency or maintaining high opacity. Additionally, Benlloch-Tinoco *et al*. (2025) noted that opacity is linked to the homogeneity of the microstructure; in this case, the heterogeneous nature of the starch-alginate blend likely maintained the high opacity values regardless of the plasticizer content.

3.1.4. Solubility

Solubility is a critical property for edible films, determining their water resistance and integrity when applied to high-moisture foods. The solubility values of the composite films ranged from 42.90% to 61.23% (Table 4). Statistical analysis revealed a significant interaction ($p > 0.05$) between bacterial cellulose (BC) and glycerol concentrations on the solubility of the films.

The highest solubility (61.23%) was observed in the film formulated with 0.3% BC and 0.5% glycerol (BC0.3/G0.5). This increase in solubility can be attributed to the agglomeration of BC fibers at higher concentrations within the low-plasticized matrix. The aggregation of BC likely disrupted the homogeneity of the starch-alginate

network, weakening the intermolecular hydrogen bonds and creating microscopic voids that facilitated water penetration. This finding is consistent with Mustapha & Wan (2022), who reported that the incorporation of *Nata de coco* into starch films could increase water solubility due to structural discontinuities and increased hydrophilicity of the composite matrix.

Table 4. Solubility of jelai starch–Na-alginate edible films incorporated with bacterial cellulose and glycerol

BC (%)		Solubility (%)		
		Glycerol 0.5% ($G_{0.5}$)	Glycerol 1.0% ($G_{1.0}$)	Glycerol 1.5% ($G_{1.5}$)
	$S_{0.1}$	$54.53^{ab} \pm 0.03$	$55.96^{ab} \pm 0.05$	$44.29^{b} \pm 0.08$
	$S_{0.2}$	$42.90^{b} \pm 0.06$	$54.62^{ab} \pm 0.05$	$52.15^{ab} \pm 0.06$
	$S_{0.3}$	$61.23^{a} \pm 0.05$	$44.23^{b} \pm 0.10$	$55.58^{ab} \pm 0.12$

Values followed by different superscript letters within the same column are significantly different ($p < 0.05$) according to Tukey's HSD test.

Conversely, the lowest solubility (42.90%) was recorded for the film containing 0.2% BC and 0.5% glycerol (BC0.2/G0.5). In this specific ratio (BC 0.2% and glycerol 0.5%), BC fibers likely acted as effective reinforcing agents by filling the interstitial spaces of the polymer matrix, thereby hindering water diffusion. This phenomenon resembles an anti-plasticization effect, where the strong interaction between the filler and the matrix restricts polymer chain mobility and water uptake. As described by Eslami *et al*. (2023), the balance between plasticizer and filler concentrations is crucial; an optimal interaction can form a rigid network that reduces the accessibility of hydrophilic groups to water molecules. Furthermore, the interaction in treatment BC0.3/G1.0 significantly reduced solubility compared to BC0.3/G0.5, suggesting that the increase in glycerol at this specific BC level might have facilitated better dispersion of fibers or induced phase segregation that limited water interaction.

3.1.5. Water Vapor Permeability

Water Vapor Permeability (WVP) measures the ease with which moisture penetrates the packaging material, a crucial factor for maintaining food stability. The WVP values of the jelai starch–Na-alginate films are presented in Table 5. The values ranged from 0.03716 to 0.06104 g mm k/Pa.day. m². Statistical analysis showed that glycerol concentration had a significant effect ($p < 0.05$) on WVP, whereas the addition of bacterial cellulose (BC) and the interaction between factors were not significant ($p > 0.05$).

The WVP values significantly increased with higher glycerol concentrations. As a hydrophilic plasticizer, glycerol contains numerous hydroxyl groups (-OH) that attract water molecules. According to Tarique *et al*. (2021), the incorporation of glycerol increases the free volume between polymer chains by reducing internal hydrogen bonding. This structural modification enhances the mobility of the polymer chains and facilitates the diffusion of water vapor molecules through the film matrix. Additionally, the hygroscopic nature of glycerol promotes water absorption from the environment, further elevating the WVP values.

Table 5. Water vapor permeability of jelai starch–Na-alginate edible films incorporated with bacterial cellulose and glycerol

BC (%)		WVP (g.mm/kPa. day. m²)			
		Glycerol 0.5% ($G_{0.5}$)	Glycerol 1.0% ($G_{1.0}$)	Glycerol 1.5% ($G_{1.5}$)	Mean ± SD
	$S_{0.1}$	0.03963 ± 0,00	0.04704 ± 0.02	0.05447 ± 0.01	0.04705 ± 0.01
	$S_{0.2}$	0.04352 ± 0.00	0.04122 ± 0.01	0.04733 ± 0.01	0.04403 ± 0.00
	$S_{0.3}$	0.03725 ± 0.01	0.03716 ± 0.00	0.06104 ± 0.01	0.04515 ± 0.01
	Mean ± SD	$0.04013^{b} \pm 0.00$	$0.04181^{b} \pm 0.00$	$0.05428^{a} \pm 0.01$	

Note: Values followed by different superscript letters within the same column are significantly different ($p < 0.05$) according to Tukey's HSD test.

On the other hand, the addition of BC did not significantly affect the WVP. Theoretically, fillers can improve barrier properties by creating a tortuous path for gas diffusion. However, in this study, the hydrophilic nature of both the starch-alginate matrix and the BC fibers likely facilitated water transport rather than hindering it. As noted by Long *et al*. (2023), the compatibility and interfacial adhesion between the filler and the matrix are critical; poor adhesion can lead to the formation of micro-voids or discontinuities at the interface, which serve as preferential

channels for water vapor transmission. The inherent hydrophilicity of the biopolymers used in this study likely dominated the barrier performance, resulting in relatively high WVP values consistent with polysaccharide-based films described by Saidi *et al*. (2025).

3.2. Mechanical Properties

The mechanical performance of the films, characterized by tensile strength (TS) and elongation at break (EAB), showed varied responses to the treatments. The interaction between bacterial cellulose (BC) and glycerol significantly affected the tensile strength ($p < 0.05$). The TS values ranged from 9.5 to 19.6 MPa, with the highest strength observed in the formulation containing 0.2% BC and 0.5% glycerol (BC0.2/G0.5). This TS value of the produced edible films meets the JIS standard (2019), which specifies a minimum of 3.92 MPa. As shown in Table 6, increasing the glycerol concentration generally led to a reduction in TS.

The robust two-way ANOVA results for tensile strength showed significant differences in the jelai starch–Na-alginate edible films. The tensile strength parameter indicated a significant interaction between BC and glycerol ($p < 0.05$). This interaction was further examined using simple effects analysis to determine whether the effect of glycerol varied at each BC level. Simple effects analysis using Welch's one-way ANOVA followed by pairwise *t*-tests showed that at 0.1% BC, glycerol addition did not result in a significant difference ($p > 0.05$). However, at 0.2–0.3% BC, glycerol had a highly significant effect ($p < 0.05$).

Table 6. Tensile Strength of jelai starch–Na-alginate edible films incorporated with bacterial cellulose and glycerol

BC (%)	Tensile Strength (MPa)			
		Glycerol 0.5% ($G_{0.5}$)	Glycerol 1.0% ($G_{1.0}$)	Glycerol 1.5% ($G_{1.5}$)
	$S_{0.1}$	$12.7^{a} \pm 0.57$	$15.2^{a} \pm 1.07$	$11.5^{a} \pm 0.76$
	$S_{0.2}$	$19.6^{a} \pm 0.16$	$14.8^{b} \pm 0.53$	$10.1^{c} \pm 0.09$
	$S_{0.3}$	$17.8^{a} \pm 0.44$	$14.0^{ab} \pm 1.42$	$9.5^{b} \pm 0.38$

Note: Values followed by different superscripts in the same row indicate significant differences ($p < 0.05$) based on Welch's pairwise *t*-test.

This reduction is attributed to the plasticizing effect of glycerol, where small polyol molecules insert themselves between the polymer chains. This insertion disrupts the intermolecular hydrogen bonds and increases the free volume within the matrix, thereby reducing the film's rigidity and resistance to deformation (Tarique *et al*., 2021; Eslami *et al*., 2023). Conversely, the addition of BC resulted in fluctuating TS values rather than a linear increase. This suggests that while BC acts as a reinforcing agent, agglomeration of fibers at higher concentrations or poor interfacial adhesion with the hydrophilic matrix may create structural defects or stress concentration points that weaken the film integrity (Yekta *et al*., 2020; Muhammed *et al*., 2024).

Regarding flexibility, glycerol exerted a dominant and significant positive effect on EAB ($p < 0.05$), while the effect of BC and the interaction were not significant. The EAB values increased substantially from 1.69% to 16.35% as the glycerol concentration rose from 0.5% to 1.5%, as presented in Table 7. The value has not meet the elongation requirement for food packaging plastics/film sheets according to JIS (2019), which specifies a minimum of 70%.

Table 7. Elongation at break of jelai starch–Na-alginate edible films incorporated with bacterial cellulose and glycerol

BC (%)	Elongation at break (%)				
		Glycerol 0.5% ($G_{0.5}$)	Glycerol 1.0% ($G_{1.0}$)	Glycerol 1.5% ($G_{1.5}$)	Mean ± SD
	$S_{0.1}$	1.69 ± 0.00	2.74 ± 0.00	13.22 ± 0.02	5.88 ± 0.06
	$S_{0.2}$	2.10 ± 0.01	4.02 ± 0.00	16.35 ± 0.02	7.49 ± 0.08
	$S_{0.3}$	2.00 ± 0.00	4.39 ± 0.02	12.51 ± 0.03	6.30 ± 0.06
	Mean ± SD	$1.93^{c} \pm 0.00$	$3.72^{b} \pm 0.01$	$14.03^{a} \pm 0.02$	

Note: Values followed by different superscript within the same row indicate significant differences ($p < 0.05$) based on Welch's pairwise *t*-test.

This result confirms that glycerol effectively enhances the mobility of starch and alginate chains, transforming the brittle nature of the native starch film into a more flexible structure (Nordin *et al*., 2020; Agustin *et al*., 2024). The effect of BC on elongation was less pronounced compared to glycerol, indicating that the plasticization mechanism played a more critical role in defining the ductility of the composite films than the fiber reinforcement.

3.3. Application on Minimally Processed Pineapple

The application of the optimized edible coating (0.3% BC and 1.0% glycerol based on the Garmo effectiveness index) on fresh-cut pineapple demonstrated varied effects on fruit quality during cold storage. As shown in Figure 2, the coating was not statistically significant in reducing weight loss ($p > 0.05$) compared to the uncoated control. This result can be attributed to the inherent hydrophilic nature of the polysaccharide-based matrix (jelai starch and Na-alginate). As explained by Pavlath & Orts (2009) and Lacroix (2009), hydrocolloid films are generally efficient gas barriers but serve as poor moisture barriers due to their high affinity for water. Although the selected formulation showed favorable physical and mechanical properties, these properties mainly reflect film strength and integrity rather than moisture barrier efficiency. Since the coating was composed primarily of hydrocolloid-based biopolymers and did not contain hydrophobic components such as lipids or waxes, water vapor diffusion and transpiration could still occur during storage. Therefore, the formulation was effective in improving film structure but not sufficiently effective in limiting moisture loss from fresh-cut fruit.

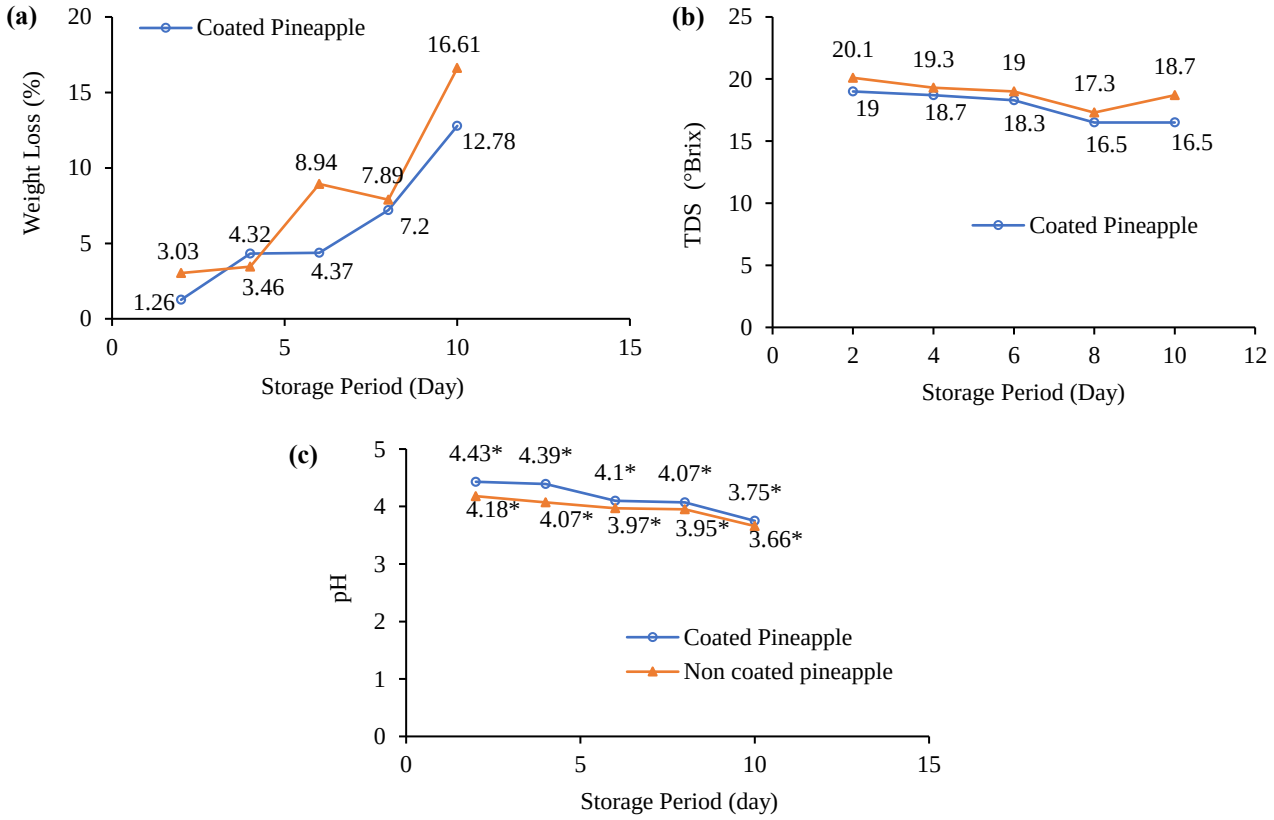

Figure 2. Effect of jelai starch–Na-alginate edible coating on (a) weight loss, (b) total soluble solids (TSS), and (c) pH of minimally processed pineapple during storage at 4 °C for 10 days. The asterisk (*) indicates a significant difference between the uncoated and coated samples at the corresponding storage time ($p < 0.05$) based on the paired *t*-test.

Similarly, the coating did not significantly affect the Total Soluble Solids (TSS) ($p > 0.05$). This may be because pineapple is a non-climacteric fruit, where drastic changes in sugar content post-harvest are less pronounced compared to climacteric fruits. Furthermore, the gas barrier properties of the coating might not have been strong enough to completely suppress the metabolic breakdown of carbohydrates into simple sugars under the specific storage conditions used (Saha *et al*., 2023).

In contrast, the coating was significantly effective ($p < 0.05$) in maintaining a higher pH from day 2 to day 8 of storage. The coated samples exhibited a slower rate of acidification compared to the control. This suggests that the

coating successfully created a modified atmosphere around the fruit surface, limiting oxygen availability and thereby slowing down the respiration rate and the enzymatic oxidation of organic acids (Peixoto *et al*., 2016; Saha *et al*., 2023). This pH stability contributes to preserving the fresh taste, color, texture, and shelf life of fresh-cut products (Azarakhsh *et al*., 2011). However, by day 10, the significant difference in pH was no longer observed. This result indicates that the ability of the edible coating to maintain pH stability may have diminished during extended storage. Since no direct structural analysis of the coating was conducted, the possible changes in coating integrity should be interpreted with caution and require further confirmation.

4. CONCLUSIONS

This study showed that the selected treatment (based on the Garmo effectiveness index), consisting of 0.3% bacterial cellulose (BC) and 1.0% glycerol, was the most suitable formulation for jelai starch–Na-alginate edible film. This formulation provided acceptable film characteristics, including tensile strength of 14.0 MPa, elongation of 4.39%, solubility of 44.23%, and WVP of 0.03716 g·mm·kPa^{-1}·day^{-1}·m^{-2}. When applied as a coating on minimally processed pineapple, the treatment was effective in maintaining pH stability for up to 8 days at 4 °C, although it did not significantly reduce weight loss or total soluble solids. Therefore, the 0.3% BC and 1.0% glycerol formulation can be recommended as the selected treatment for improving edible film properties and helping maintain the quality of fresh-cut pineapple.

AUTHOR CONTRIBUTION STATEMENT

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

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

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