



# Fabrication of Edible Film Derived from *Arenga pinnata* Starch using Polyethylene Glycol as Plasticizer and Carboxymethyl Cellulose as Additive

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## Abstract

Edible films have emerged as a sustainable and biodegradable alternative to conventional plastic packaging. This study investigates the effects of polyethylene glycol (PEG), carboxymethyl cellulose (CMC), and processing temperature on the mechanical and physicochemical properties of *Arenga pinnata* starch-based edible films. Mechanical properties, water absorption, and molecular interactions were evaluated using tensile testing, swelling analysis, Fourier Transform Infrared Spectroscopy (FTIR), and Scanning Electron Microscopy (SEM). The results showed that PEG (4–8%) enhanced film flexibility, increasing elongation from 17.33% to 27.83%, although excessive PEG reduced mechanical strength. Increasing CMC concentration (0.3–1.6%) improved tensile strength (up to 3.12 MPa) but decreased elongation and increased water absorption due to its hydrophilic nature. Higher processing temperatures promoted molecular packing, resulting in increased tensile strength and reduced water absorption. FTIR analysis confirmed enhanced intermolecular interactions among starch, PEG, and CMC, while SEM revealed a compact and cohesive morphology with minor microstructural defects. Response Surface Methodology (RSM) predicted optimal conditions at 70.89 °C, 6.99% PEG, and 1.10% CMC, yielding tensile strength and elongation values of 2.646 MPa and 27.518%, respectively. These findings demonstrate that *Arenga pinnata* starch is a promising and sustainable material for developing edible films with tunable mechanical properties for eco-friendly packaging applications.

**Keywords:** Edible film; *Arenga pinnata*; Polyethylene glycol; Carboxymethyl cellulose; Optimization.

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## 1. Introduction

The widespread use of plastic-based packaging materials in Indonesia is primarily attributed to their lightweight properties, mechanical strength, and relatively low production costs. Nevertheless, excessive reliance on plastics has raised significant environmental concerns, particularly due to the accumulation of plastic waste, which is difficult to recycle and highly resistant to microbial degradation.<sup>[1]</sup> Consequently, the development of biodegradable and environmentally safe packaging materials emerged as a crucial research priority to mitigate plastic pollution. Considerable efforts have focused on the utilization of renewable, naturally derived materials

with inherent biodegradability.<sup>[2-6]</sup> Among these, edible films represent a promising alternative for food packaging, offering advantages such as biodegradability, environmental safety, and direct consumption alongside packaged products.<sup>[3-6]</sup> In addition, edible films provide functional barrier properties by regulating mass transfer of moisture, oxygen, lipids, light, and solutes, thereby extending food shelf life.<sup>[7]</sup> Typically, such films are fabricated from natural polymers including polysaccharides,<sup>[8-12]</sup> proteins<sup>[13-16]</sup> and lipids,<sup>[17,18]</sup> which can form continuous thin matrices. Their biodegradability and edibility have positioned edible films as sustainable alternatives to conventional plastics, particularly those derived from agricultural and plantation-based feedstocks. One potential feedstock with significant promise is *Arenga pinnata*.

*Arenga pinnata* is widely available in Indonesia and its starch demonstrates functional attributes favorable for film formation.<sup>[19,20]</sup> Beyond starch, *Arenga pinnata* contains galactomannan, a polysaccharide with polymer-forming

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potential suitable for edible film production.<sup>[21]</sup> The abundance of carbohydrates and polysaccharides in *Arenga pinnata* underscores its potential as a sustainable raw material for edible film development. In contrast to conventional starch sources such as corn, potato, and cassava, which predominantly consist of a homo-polysaccharide system, *Arenga pinnata* provides a distinctive hetero-polysaccharide system comprising both starch and galactomannan.<sup>[22]</sup> This intrinsic compositional feature is advantageous, as it enables potential synergistic interactions during film formation, where starch contributes to matrix strength and galactomannan may enhance polymer flexibility and network integrity. Consequently, the presence of two naturally co-occurring film-forming polymers in *Arenga pinnata* expands the formulation space, which remains largely underexplored, particularly when combined with plasticizers and reinforcing agents. However, the physicochemical and barrier performance of edible films is highly dependent on formulation and processing parameters. Critical factors include the type and concentration of plasticizers, polymer composition, and processing temperature, which collectively influence tensile strength, elongation, and structural flexibility.<sup>[23-27]</sup> Plasticizers act as indispensable additives that alleviate brittleness, enhance elasticity, and minimize cracking during storage and handling.<sup>[23]</sup> Among available options, polyethylene glycol (PEG) is particularly notable for its hydrophilicity, non-toxicity, rheological properties, and biocompatibility. Previous studies have demonstrated that PEG effectively enhances film flexibility and hydrophilicity. PEG incorporation enhances polymer chain mobility and increases intermolecular spacing, thereby facilitating greater water uptake and elasticity compared to other plasticizers.<sup>[27]</sup> Despite these advantages, edible films derived from complex carbohydrates such as *Arenga pinnata* starch often exhibit limited mechanical strength, necessitating reinforcement with fillers such as carboxymethyl cellulose (CMC).<sup>[28]</sup> Furthermore, processing temperature further influences structural formation, as adequate thermal treatment promotes starch gelatinization and intermolecular bonding, whereas excessive heating increases rigidity and water absorption due to network disruption.<sup>[29]</sup>

To date, few studies have systematically evaluated the combined effects of PEG plasticization, CMC reinforcement, and thermal processing conditions on *Arenga pinnata*-based edible films. Therefore, Response Surface Methodology (RSM) was further employed to optimize formulation and processing parameters, as it enables efficient modeling of interactions among multiple independent variables while minimizing experimental runs and resource consumption.<sup>[25]</sup> The present study aims to develop an optimal edible film formulation with improved mechanical and physicochemical properties suitable for sustainable packaging applications. The findings indicate potential utility in food preservation systems, notably as edible coatings for fresh produce, aligning with SDG 9 through innovation in sustainable materials and

supporting SDG 12 by encouraging biodegradable substitutes that mitigate plastic dependency and environmental waste.

## 2. Experimental section

### 2.1 Materials

*Arenga pinnata* were obtained from Pakis Village, Limbangan District, Kendal Regency, Indonesia. Polyethylene Glycol (PEG 400, 99%, USP Grade) and Carboxymethyl Cellulose (CMC, 99%) were purchased from ByKimiaHerbal Indonesia and used without further purification.

### 2.2 Preparation of *Arenga pinnata* starch

The preparation of *Arenga pinnata* starch began with peeling and thoroughly washing the seeds. The cleaned seeds were thinly sliced to facilitate drying and dehydrated at 50 °C for 2.5 h. After drying, the samples were cooled to room temperature, ground into powder, and sieved through a 100-mesh screen to obtain fine starch particles.

### 2.3 Fabrication of edible films

For the fabrication of edible films, 30 mL of distilled water was placed in a beaker and preheated in a water bath to the designated experimental temperature. *Arenga pinnata* starch (0.6 g) was then added, followed by CMC and PEG at predetermined concentrations. The mixture was homogenized at 500 rpm for 15 min under constant heating. After homogenization, the mixture was allowed to stand for 10 min to facilitate air bubble removal. The film-forming solution was cast onto a petri dish and spread evenly to form a uniform thin layer. Drying was carried out at 45 °C for 24 h in an oven to remove residual moisture. The resulting edible film was detached from the petri dish and stored for subsequent characterization.

The mechanical properties of the edible films were evaluated according to ASTM D882-12. Rectangular samples (5 x 1 cm) were subjected to tensile testing to determine tensile strength (TS) and elongation at break (EAB). Water absorption was measured using 3 x 3 cm film samples. Each sample was initially weighed, immersed in distilled water for 10 s, and periodically removed, gently blotted to remove surface moisture, and reweighed until a constant mass was reached, which was taken as the equilibrium swelling condition. The degree of swelling (DS) was calculated using the following equation:  $DS(\%) = ((\frac{W_t - W_0}{W_0}) \times 100$ , where  $W_0$  is the initial dry weight of the film and  $W_t$  is the weight of the swollen film at time  $t$  (or at equilibrium). All mechanical and water absorption measurements were conducted under controlled and identical experimental conditions to ensure consistency. Fourier Transform Infrared Spectroscopy (FTIR) was performed to identify functional groups and assess molecular interactions within the film matrix.

### 2.4 Experimental design and data analysis

The experimental design was constructed using a Central

Composite Design (CCD), consisting of 14 factorial runs and 6 center-point replications. Operating temperature ( $X_1$ ), PEG concentration ( $X_2$ ), and CMC concentration ( $X_3$ ) were selected as independent variables, while TS and EAB were defined as the response variables. For Response Surface Methodology (RSM) analysis, the real values of the independent variables were transformed into coded variables. The relationship between the response variables and the independent variables was described using a second-order polynomial model shown in Eq. (1).

$$Y = \beta_0 + \sum_{i=1}^k \beta_i X_i + \sum_{i=1}^{k-1} \sum_{j=2}^k \beta_{ij} X_i X_j + \sum_{i=1}^k \beta_{ii} X_i^2 + \varepsilon \quad (1)$$

where  $X_i$  and  $X_j$  are the independent variables,  $Y$  is the response variable, while  $\beta_0$ ,  $\beta_i$ ,  $\beta_{ii}$ , and  $\beta_{ij}$  are the regression coefficients, and  $k$  is the number of variables.

In this study, three independent variables were used, namely operating temperature ( $X_1$ ), PEG concentration ( $X_2$ ), and CMC concentration ( $X_3$ ). The response variables ( $Y_i$ ) were defined as Tensile Strength (TS) and Elongation at Break (EAB), as expressed in Eq. (2) as follows:

$$Y_i = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \beta_3 X_3 + \beta_{12} X_1 X_2 + \beta_{13} X_1 X_3 + \beta_{23} X_2 X_3 + \beta_{11} X_1^2 + \beta_{22} X_2^2 + \beta_{33} X_3^2 \quad (2)$$

After optimization using RSM, additional experiments were conducted to confirm and verify the validity of the developed model equation as well as the statistical experimental design employed. Moreover, the software was used to generate graphs of the predicted response values in two-dimensional (2D) and three-dimensional (3D) plots. The significance evaluation between the mean TS and EAB under different experimental treatments was statistically determined at a significance level of  $p < 0.05$ .

### 3. Results and discussion

#### 3.1 Effect of PEG concentration

Edible films derived from *Arenga pinnata* starch were prepared by varying the concentration of polyethylene glycol

(PEG), carboxymethyl cellulose (CMC), and processing temperature to assess their effects on elongation, tensile strength, and water absorption. These parameters were systematically investigated to determine the optimal formulation and processing conditions for producing mechanically stable and functional edible films. The influence of PEG concentration on the mechanical properties of the films is presented in Fig. 1a. PEG acts as a plasticizer that increases the flexibility of polymer matrices by reducing intermolecular forces and enhancing chain mobility. PEG concentrations between 4–8% (v/v) produced elongation values ranging from 17.33% to 27.83%. Increasing PEG concentration from 4% to 7% significantly increased elongation from 17.33% to 27.83%, demonstrating the plasticizing effect of PEG which improves polymer chain mobility. However, when PEG concentration was increased to 8%, elongation decreased to 18.83%. This reduction indicates that excessive PEG disrupts the structural integrity of the polymer network due to phase separation and weakening of intermolecular interactions.<sup>[30]</sup> Tensile strength ranged from 2.43 to 3.51 MPa and showed a decreasing trend with increasing PEG concentration. This observation is consistent with typical plasticizer behavior, where increased plasticizer content reduces cohesive forces among polymer chains, resulting in lower stiffness but higher ductility.

The effect of PEG on the mechanical properties is governed by the balance between plasticization, intermolecular hydrogen bonding, chain mobility, and phase behavior within the polymer matrix. At moderate concentrations, PEG acts as an effective plasticizer by inserting between starch chains and partially disrupting intermolecular hydrogen bonding. This increases free volume and reduces cohesive energy density, thereby enhancing segmental chain mobility and resulting in higher elongation.<sup>[27]</sup> However, as PEG concentration increases further, the excessive disruption of hydrogen bonding weakens intermolecular cohesion to a level that compromises mechanical integrity, leading to reduced tensile strength. In addition, limited thermodynamic compatibility between PEG and the starch-based matrix may promote microphase separation at higher PEG content, resulting in the formation

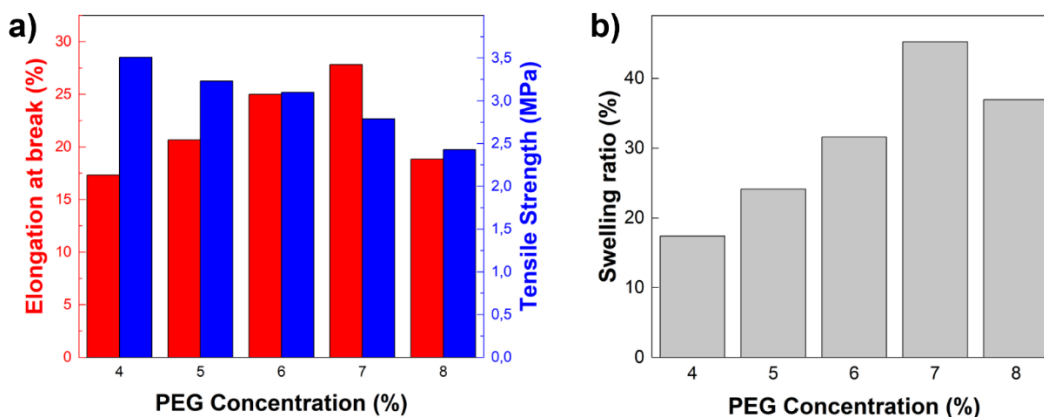


Fig. 1: Effect of PEG concentration on the mechanical properties (a) and swelling ratio of edible film (b).

of PEG-rich domains.<sup>[30,31]</sup> These heterogeneous regions introduce localized stress concentration points under mechanical loading and hinder uniform stress transfer, further contributing to the decline in tensile strength. Thus, the mechanical response reflects a transition from effective plasticization at moderate PEG levels to structural heterogeneity and weakened cohesion at higher concentrations.

The swelling behavior of the films is illustrated in Fig. 1b. Water absorption ranged from 17.39% to 45.24%. Increasing PEG concentration from 4% to 7% significantly increased water absorption, which can be attributed to the hydrophilic nature of PEG. PEG molecules contain ether and hydroxyl functional groups capable of forming hydrogen bonds with water molecules, thereby facilitating water diffusion into the polymer matrix.<sup>[32]</sup> Interestingly, further increasing PEG concentration to 8% reduced water absorption to 36.96%. Excess PEG may induce phase separation and reduce structural homogeneity, which limits the effective interaction between hydrophilic sites and water molecules.<sup>[31]</sup> These observations indicate that an optimal PEG concentration is necessary to achieve a balance between flexibility, mechanical strength, and water resistance.

### 3.2 Effect of CMC concentration

Based on the preceding results, the PEG concentration was fixed at 7% (v/v) to evaluate the influence of CMC concentration on the mechanical and swelling properties of the edible films (Fig. 2). As shown in Fig. 2a, increasing CMC

concentration led to a gradual decrease in elongation, indicating reduced film flexibility. This behavior is attributed to the increased solid content introduced by CMC, which forms a denser polymer network and restricts molecular mobility.<sup>[33]</sup> In contrast, tensile strength increased with increasing CMC concentration, as higher CMC content reinforces the polymer matrix through stronger intermolecular hydrogen bonding and improved structural cohesion.

These trends are consistent with previously reported starch-based edible films, as summarized in Table 1. The tensile strength (1.0–3.1 MPa) and elongation at break (12.26–29.67%) obtained in this study fall within the typical range reported for plasticized starch-based films, indicating moderate mechanical performance. Overall, the developed films exhibit a balanced combination of strength and flexibility. The decrease in elongation with increasing CMC concentration reflects the competing effects of network reinforcement and restricted polymer chain mobility.

As shown in Fig. 2b, water absorption increased from 19.05% to 68.97% with increasing CMC concentration. This trend is attributed to the hydrophilic nature of CMC, which contains numerous hydroxyl groups that readily interact with water molecules. Although higher CMC content enhances mechanical strength, it simultaneously reduces water resistance due to increased hydrophilicity. These findings highlight an important trade-off between mechanical reinforcement and moisture resistance. Therefore, an optimal CMC concentration is required to balance film strength, flexibility, and water stability.

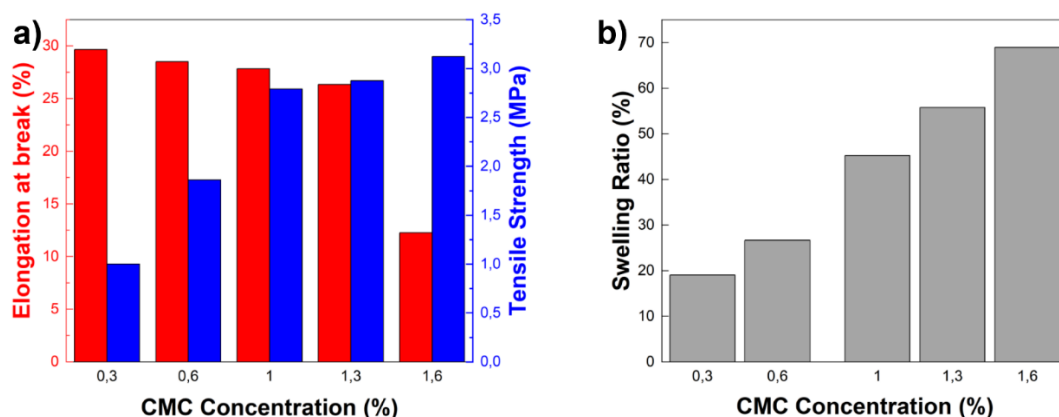


Fig. 2: Effect of CMC concentration on the mechanical properties (a) and swelling ratio of edible film (b).

Table 1: Comparison of mechanical properties of starch-based edible films reported in the literature.

| Material                           | Plasticizer        | TS (MPa)  | EAB (%)     | References |
|------------------------------------|--------------------|-----------|-------------|------------|
| Wheat starch film                  | Sorbitol           | 6.35–25.3 | 3.3–60.70   | [34]       |
| Wheat starch film                  | Glycerol           | 6.35–22.8 | 4.4–47.2    | [34]       |
| Wheat starch film                  | Fructose           | 7.6–18.99 | 9.41–47.5   | [34]       |
| Wheat starch film                  | Urea               | 1.12–5.64 | 32.3–54.1   | [34]       |
| Potato peel starch film            | Glycerol           | 0.3–0.56  | 2.2–2.8     | [35]       |
| Cassava starch film                | Glycerol           | 0.66      | 1.05        | [36]       |
| Sago starch film                   | PEG/ CMC           | 0.95–4.27 | 14.02–28.58 | [37]       |
| Dioscorea hispida starch           | Sorbitol/ glycerol | 2.64–8.59 | 14.41–16.10 | [38]       |
| This study (Arenga pinnata starch) | PEG/ CMC           | 1.0–3.1   | 12.26–29.67 | This work  |

### 3.3 Effect of processing temperature

The processing temperature was varied while maintaining PEG and CMC concentrations at 7% (v/v) and 1% (v/v), respectively. As shown in Fig. 3(a, b), increasing temperature slightly reduced elongation but increased tensile strength due to improved molecular packing and stronger intermolecular interactions. Higher temperatures promote evaporation of residual moisture within the polymer matrix, resulting in a denser structure with reduced extensibility.<sup>[39]</sup> The selected temperature range (60–80 °C) coincides with starch gelatinization, characterized by granule swelling, crystalline disruption, and amylose leaching, which enhance chain mobility and facilitate intermolecular interactions. Concurrently, elevated temperatures accelerate solvent evaporation, promoting closer packing of polymer chains and the formation of a denser matrix with reduced free volume.

Additionally, water absorption decreased with increasing temperature because higher temperatures promote tighter polymer network formation and reduce available hydrophilic

sites for water interaction. Reduced water absorption enhances film stability and improves its suitability for food packaging applications.

### 3.4 FTIR characterization

FTIR analysis was conducted to identify functional groups present in native *Arenga pinnata* starch and the resulting edible film (Fig. 4). The starch spectrum (blue line) exhibits characteristic absorption bands of polysaccharides. The broad peak at 3200–3400  $\text{cm}^{-1}$  corresponds to O–H stretching vibrations associated with hydroxyl groups in polysaccharides. The peak near 2920  $\text{cm}^{-1}$  corresponds to C–H stretching of aliphatic groups, while the band around 1640  $\text{cm}^{-1}$  is associated with bound water molecules.<sup>[40]</sup> The fingerprint region at 900–1200  $\text{cm}^{-1}$  shows strong C–O and C–O–C stretching vibrations of glycosidic bonds in amylose and amylopectin.<sup>[41]</sup> After film formation (red line), the O–H stretching band became broader, indicating stronger hydrogen bonding interactions between starch, CMC, and PEG

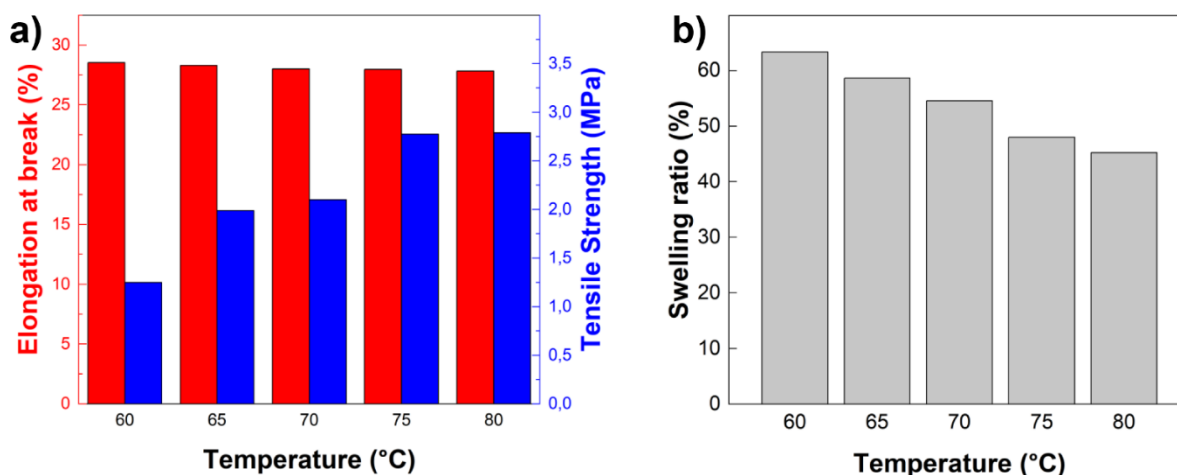


Fig. 3: Effect of temperature on the mechanical properties (a) and swelling ratio of edible film (b).

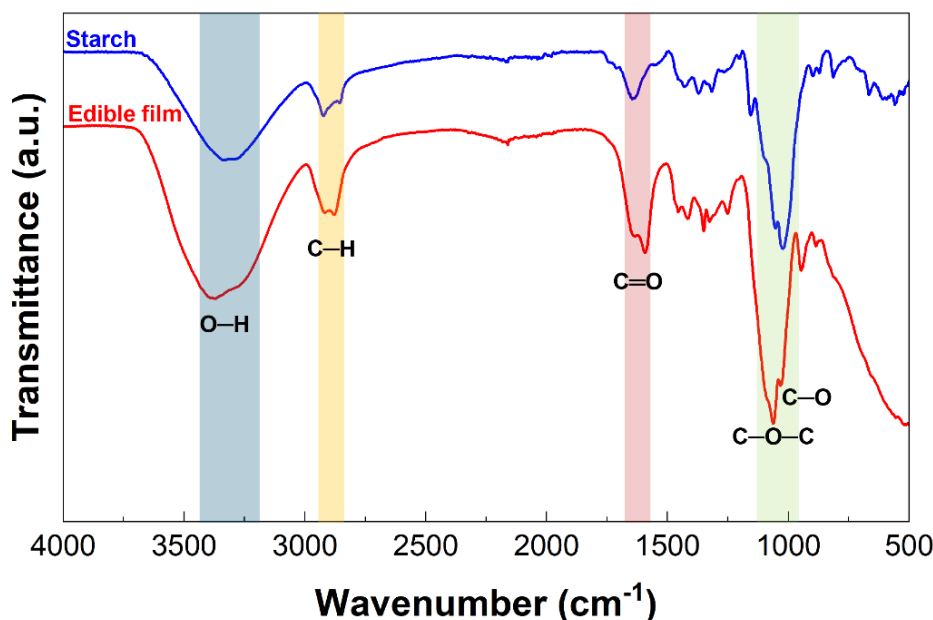


Fig. 4: FTIR spectrum of *Arenga pinnata* starch (blue line) and *Arenga pinnata*-based edible film (red line).

molecules. These spectral changes confirm the formation of intermolecular interactions and structural rearrangement within the polymer matrix.

### 3.5 SEM analysis

The microstructural characteristics of the optimized edible film were investigated using Scanning Electron Microscopy (SEM), as shown in Fig. 5. SEM analysis provides important insight into the surface integrity and internal organization of the polymer matrix, which strongly influence the mechanical performance and water absorption behavior of edible films. In the plane-view micrograph (Fig. 5a), the film surface exhibits a relatively dense and continuous morphology with moderate roughness and wrinkled features. The absence of large pores or severe fractures indicates that the starch matrix was successfully gelatinized and formed a cohesive network with PEG and CMC. This compact surface structure reflects good miscibility among the film components, supporting the improved elongation and tensile strength obtained under optimum formulation conditions. The slight surface irregularities may be attributed to polymer chain rearrangement during drying, as well as the presence of plasticizer-induced mobility within the matrix. Furthermore, fine microcrack-like patterns and heterogeneous domains can be observed across the surface. These minor discontinuities are commonly associated with internal stress development during solvent evaporation, where rapid moisture loss causes localized shrinkage of the biopolymer network.<sup>[42]</sup> Such microstructural defects may contribute to the remaining swelling capacity of the film by providing diffusion pathways for water penetration, consistent with the measured water absorption values.

Additionally, the cross-sectional SEM image (Fig. 5b) reveals the internal structure of the edible film, showing a compact and layered morphology with irregular folds. The dense cross-section confirms the formation of a well-integrated polymer network reinforced by intermolecular

hydrogen bonding between starch and CMC chains, which contributes to the enhanced tensile strength of the film. The layered appearance suggests gradual structural consolidation during film casting and drying, where polymer chains align and pack more closely at elevated processing temperatures. However, minor voids and heterogeneous regions are also visible within the internal matrix. These microvoids likely originate from moisture evaporation and plasticizer redistribution during film formation. Although such features may slightly reduce structural uniformity, they can also enhance flexibility by preventing excessive brittleness, which aligns with the role of PEG as an effective plasticizer. Overall, SEM observations indicate that the developed edible film possesses a dense and integrated microstructure that supports both mechanical stability and functional performance.

### 3.6 Process optimization using response surface methodology (RSM)

Response Surface Methodology (RSM) was employed to evaluate the combined effects of processing temperature ( $X_1$ ), PEG concentration ( $X_2$ ), and CMC concentration ( $X_3$ ) on the mechanical properties of edible films, particularly tensile strength (TS) and elongation at break (EAB). The optimization range for the data was based on previous experimental results. A Central Composite Design (CCD) was selected because it efficiently estimates quadratic models while minimizing the number of experimental runs required for process optimization. To better predict errors, six replications were performed at the center point. The value of alpha ( $\alpha$ ), which represents the distance from the center point, can be at most  $2(k/4)$ , where  $k$  is the number of variables. Here, the value of  $\alpha$  was set to 1. Accordingly, each independent variable was tested at three coded levels ( $-1, 0, 1$ ), where  $+1$  represents the highest level,  $0$  is the center point, and  $-1$  is the lowest level. The experimental responses obtained from the CCD design are summarized in Table 2. The TS values ranged from 2.21 to 2.96 MPa, while EAB values varied between 24.39% and

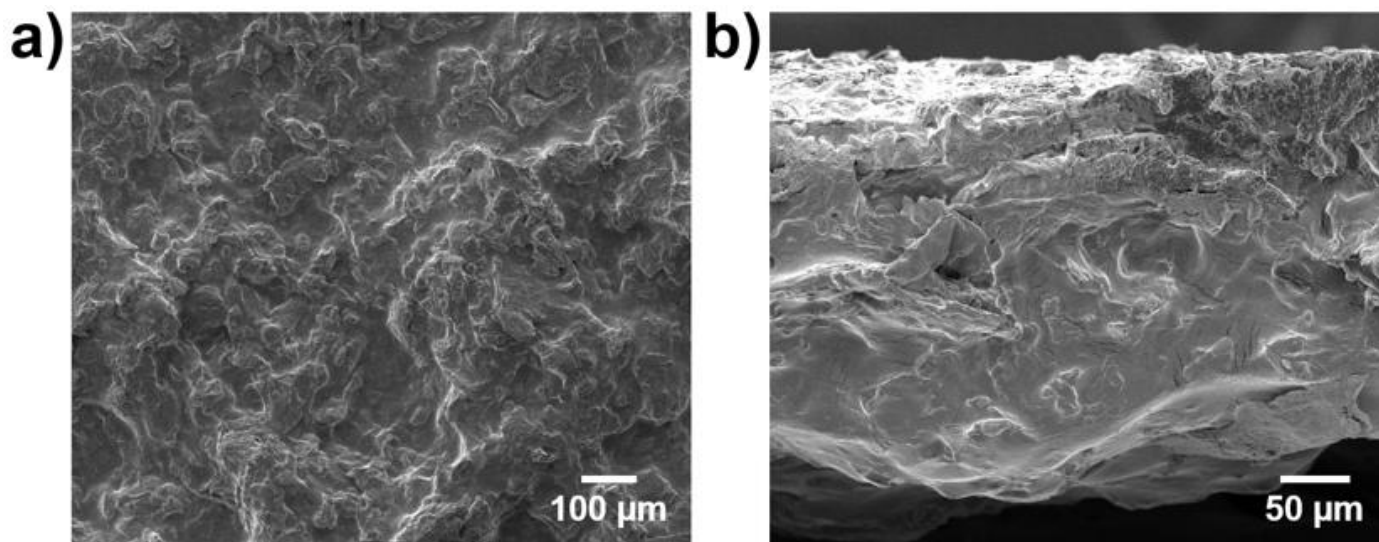
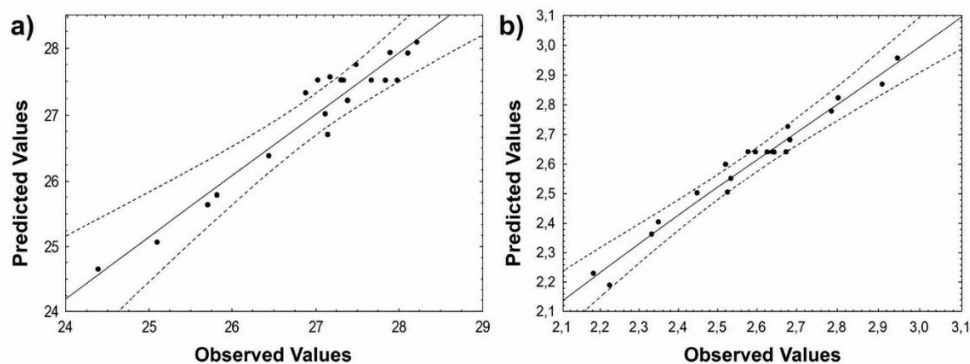


**Fig. 5:** SEM images of *Arenga pinnata* starch edible film: (a) plane-view surface morphology and (b) cross-sectional microstructure.

**Table 2:** Response optimization of the edible film of the *Arenga pinnata*.

| Run | Code pattern |            |            | Factor |             |              | Experimental value |         | Prediction value |         |
|-----|--------------|------------|------------|--------|-------------|--------------|--------------------|---------|------------------|---------|
|     |              |            |            | T (°C) | PEG (% v/v) | CMC, (% v/v) | TS (MPa)           | EAB (%) | TS (MPa)         | EAB (%) |
| 1   | -1           | -1         | -1         | 65.00  | 5.00        | 0.75         | 2.361              | 25.820  | 2.366            | 25.777  |
| 2   | -1           | -1         | +1         | 65.00  | 5.00        | 1.25         | 2.699              | 25.100  | 2.684            | 25.067  |
| 3   | -1           | +1         | -1         | 65.00  | 7.00        | 0.75         | 2.213              | 28.217  | 2.232            | 28.087  |
| 4   | -1           | +1         | +1         | 65.00  | 7.00        | 1.25         | 2.551              | 27.493  | 2.510            | 27.737  |
| 5   | +1           | -1         | -1         | 75.00  | 5.00        | 0.75         | 2.546              | 27.153  | 2.604            | 26.692  |
| 6   | +1           | -1         | +1         | 75.00  | 5.00        | 1.25         | 2.961              | 25.713  | 2.959            | 25.626  |
| 7   | +1           | +1         | -1         | 75.00  | 7.00        | 0.75         | 2.475              | 28.103  | 2.508            | 27.919  |
| 8   | +1           | +1         | +1         | 75.00  | 7.00        | 1.25         | 2.813              | 27.387  | 2.825            | 27.213  |
| 9   | - $\alpha$   | 0          | 0          | 61.59  | 6.00        | 1.00         | 2.380              | 27.127  | 2.407            | 27.000  |
| 10  | + $\alpha$   | 0          | 0          | 78.41  | 6.00        | 1.00         | 2.922              | 26.893  | 2.871            | 27.328  |
| 11  | 0            | - $\alpha$ | 0          | 70.00  | 4.32        | 1.00         | 2.800              | 24.390  | 2.781            | 24.657  |
| 12  | 0            | + $\alpha$ | 0          | 70.00  | 7.68        | 1.00         | 2.560              | 27.893  | 2.555            | 27.934  |
| 13  | 0            | 0          | - $\alpha$ | 70.00  | 6.00        | 0.58         | 2.254              | 27.177  | 2.194            | 27.559  |
| 14  | 0            | 0          | + $\alpha$ | 70.00  | 6.00        | 1.42         | 2.692              | 26.444  | 2.728            | 26.369  |
| 15  | 0            | 0          | 0          | 70.00  | 6.00        | 1.00         | 2.663              | 27.303  | 2.646            | 27.518  |
| 16  | 0            | 0          | 0          | 70.00  | 6.00        | 1.00         | 2.690              | 27.345  | 2.646            | 27.518  |
| 17  | 0            | 0          | 0          | 70.00  | 6.00        | 1.00         | 2.616              | 27.977  | 2.646            | 27.518  |
| 18  | 0            | 0          | 0          | 70.00  | 6.00        | 1.00         | 2.656              | 27.667  | 2.646            | 27.518  |
| 19  | 0            | 0          | 0          | 70.00  | 6.00        | 1.00         | 2.600              | 27.033  | 2.646            | 27.518  |
| 20  | 0            | 0          | 0          | 70.00  | 6.00        | 1.00         | 2.645              | 27.833  | 2.646            | 27.518  |

**Fig. 6:** Comparison plots between observed and predicted values for (a) EAB and (b) TS.

28.21%, indicating that the selected factor ranges were suitable for exploring the response behavior of the edible film system.

Additionally, the validation plots comparing observed and predicted values are presented in Fig. 6. The data points are closely distributed along the diagonal line for both EAB (Fig. 6a) and TS (Fig. 6b), indicating a high predictive accuracy of the quadratic model. The tight clustering of the data around the regression line, together with their confinement within the confidence intervals (dotted lines), demonstrates strong agreement between experimental and predicted values. These results confirm the robustness and reliability of the model for predicting and optimizing the properties of edible films.<sup>[43]</sup>

The adequacy and statistical significance of the developed quadratic models were evaluated using analysis of variance (ANOVA), as presented in Table 3. For the TS response, the

model exhibited a high coefficient of determination ( $R^2 = 0.97249$ ), indicating that more than 97% of the variability in tensile strength can be explained by the independent variables included in the model. Similarly, the EAB model showed a satisfactory fit ( $R^2 = 0.92831$ ), confirming that the regression model adequately captures the relationship between the process variables and film elongation.

Based on the ANOVA results shown in Table 3, the TS response was significantly influenced by all linear variables ( $X_1$ ,  $X_2$ , and  $X_3$ ;  $p < 0.05$ ), with  $X_3$  identified as the most dominant factor ( $F = 321.788$ ;  $p = 0.00001$ ), followed by  $X_1$  and  $X_2$ . This indicates that TS is primarily governed by the individual contributions of each variable. The dominant effect of CMC ( $X_3$ ) can be attributed to its role in reinforcing the polymer network through enhanced intermolecular hydrogen bonding, leading to increased structural cohesion. The positive

**Table 3:** Analysis of variance (ANOVA) for the fitted quadratic polynomial model.

| Source                         | TS, MPa    |    |                    |         | EAB, %     |    |                    |         |
|--------------------------------|------------|----|--------------------|---------|------------|----|--------------------|---------|
|                                | Sum square | df | F value            | P value | Sum square | df | F value            | P value |
| X <sub>1</sub>                 | 0.259498   | 1  | 243.158            | 0.00002 | 0.13       | 1  | 1.0108             | 0.36086 |
| X <sub>1</sub> <sup>2</sup>    | 0.000081   | 1  | 0.0762             | 0.79356 | 0.2256     | 1  | 1.7541             | 0.24267 |
| X <sub>2</sub>                 | 0.061792   | 1  | 57.9009            | 0.00062 | 12.96283   | 1  | 100.789            | 0.00017 |
| X <sub>2</sub> <sup>2</sup>    | 0.000894   | 1  | 0.838              | 0.40196 | 2.69172    | 1  | 20.9287            | 0.00598 |
| X <sub>3</sub>                 | 0.343412   | 1  | 321.788            | 0.00001 | 1.71017    | 1  | 13.2969            | 0.0148  |
| X <sub>3</sub> <sup>2</sup>    | 0.061466   | 1  | 57.5957            | 0.00063 | 0.55166    | 1  | 4.2893             | 0.09312 |
| X <sub>1</sub> .X <sub>2</sub> | 0.000741   | 1  | 0.6945             | 0.44263 | 0.58644    | 1  | 4.5597             | 0.08582 |
| X <sub>1</sub> .X <sub>3</sub> | 0.000741   | 1  | 0.6945             | 0.44263 | 0.06337    | 1  | 0.4927             | 0.51405 |
| X <sub>2</sub> .X <sub>3</sub> | 0.000741   | 1  | 0.6945             | 0.44263 | 0.0648     | 1  | 0.5038             | 0.50954 |
| Lack of fit                    | 0.015357   | 5  | 2.8779             | 0.1354  | 0.79465    | 5  | 1.2357             | 0.411   |
| error                          | 0.005336   | 5  |                    |         | 0.64307    | 5  |                    |         |
| Total SS                       | 0.752203   | 19 |                    |         | 20.05528   | 19 |                    |         |
| R <sup>2</sup>                 | 0.97249    |    | Adj R <sup>2</sup> | 0.94773 | 0.92831    |    | Adj R <sup>2</sup> | 0.86379 |

influence of temperature (X<sub>1</sub>) is associated with improved starch gelatinization and tighter molecular packing, whereas the negative effect of PEG (X<sub>2</sub>) reflects its plasticizing action, which reduces intermolecular cohesion. Conversely, the quadratic effects (X<sub>1</sub><sup>2</sup>, X<sub>2</sub><sup>2</sup>, X<sub>3</sub><sup>2</sup>) and interactions among variables (X<sub>1</sub>.X<sub>2</sub>, X<sub>1</sub>.X<sub>3</sub>, X<sub>2</sub>.X<sub>3</sub>) were not statistically significant ( $p > 0.05$ ), indicating that the TS response is predominantly governed by linear effects and that no strong synergistic interactions occur within the investigated range. Therefore, the TS response is predominantly governed by linear relationships between the independent variables and the response.

For the EAB response, the linear effects of X<sub>2</sub> and X<sub>3</sub> were significant ( $p = 0.00017$  and  $0.0148$ , respectively), with X<sub>2</sub> being the most influential variable ( $F = 100.789$ ). This confirms that PEG plays a dominant role in enhancing chain mobility and flexibility due to its plasticizing effect, while the negative contribution of CMC is attributed to increased network rigidity, which restricts polymer chain movement. The non-significant effect of temperature (X<sub>1</sub>) suggests that elongation is less sensitive to thermal processing within the studied range. The quadratic effect X<sub>2</sub><sup>2</sup> exhibited a marginal effect ( $p = 0.0598$ ), indicating a possible but limited nonlinear influence of PEG at higher concentrations. However, since this effect is not statistically significant at the selected confidence level, its contribution is considered secondary. Similarly, the interaction terms were not significant, indicating that the effects of the variables are largely independent rather than synergistic. Furthermore, the lack of fit values for both responses were not significant ( $p > 0.05$ ), confirming that the quadratic model adequately describes the relationships between the independent variables and the responses.

In this study, a second-order polynomial was employed to describe the experimental data obtained from the optimized TS and EAB design. The primary objective of this approach was to develop an empirical model capable of accurately

representing the relationship between the independent variables and the responses. The resulting model provides deeper insight into the underlying mechanisms of the process and supports optimization during the production stage. The developed regression equations for tensile strength (TS) and elongation at break (EAB) are presented in Eqs. (3-4), respectively.

$$Y_{TS} = 2.645 + 0.275X_1 - 0.135X_2 + 0.317X_3 + 0.019X_1X_2 + 0.019X_1X_3 - 0.019X_2X_3 - 0.005X_1^2 + 0.016X_2^2 - 0.131X_3^2 \quad (3)$$

$$Y_{EAB} = 27.517 + 0.195X_1 + 1.948X_2 - 0.708X_3 - 0.541X_1X_2 - 0.178X_1X_3 + 0.180X_2X_3 - 0.250X_1^2 - 0.864X_2^2 - 0.391X_3^2 \quad (4)$$

TS and EAB are key mechanical properties evaluated in the optimization of edible film production from *Arenga pinnata*. TS represents the maximum force a film can withstand before breaking, whereas EAB indicates the extent to which the film can stretch prior to fracture. These parameters are commonly reported because they are essential for assessing the ability of edible films or coatings to resist mechanical stress while maintaining structural integrity.<sup>[32]</sup> The results indicate that the mechanical behavior of the films is predominantly governed by the linear effects of PEG, CMC, and temperature, with limited contributions from interaction and quadratic terms within the investigated domain. This suggests that the system exhibits relatively simple and predictable behavior within the studied range, thereby facilitating process optimization.

The response surface plots in further illustrate the interaction between PEG and CMC concentrations. As shown in Fig. 7, an increase in CMC concentration significantly increases tensile strength. Conversely, increasing PEG concentration decreases tensile strength but improves elongation. Processing temperature showed a moderate

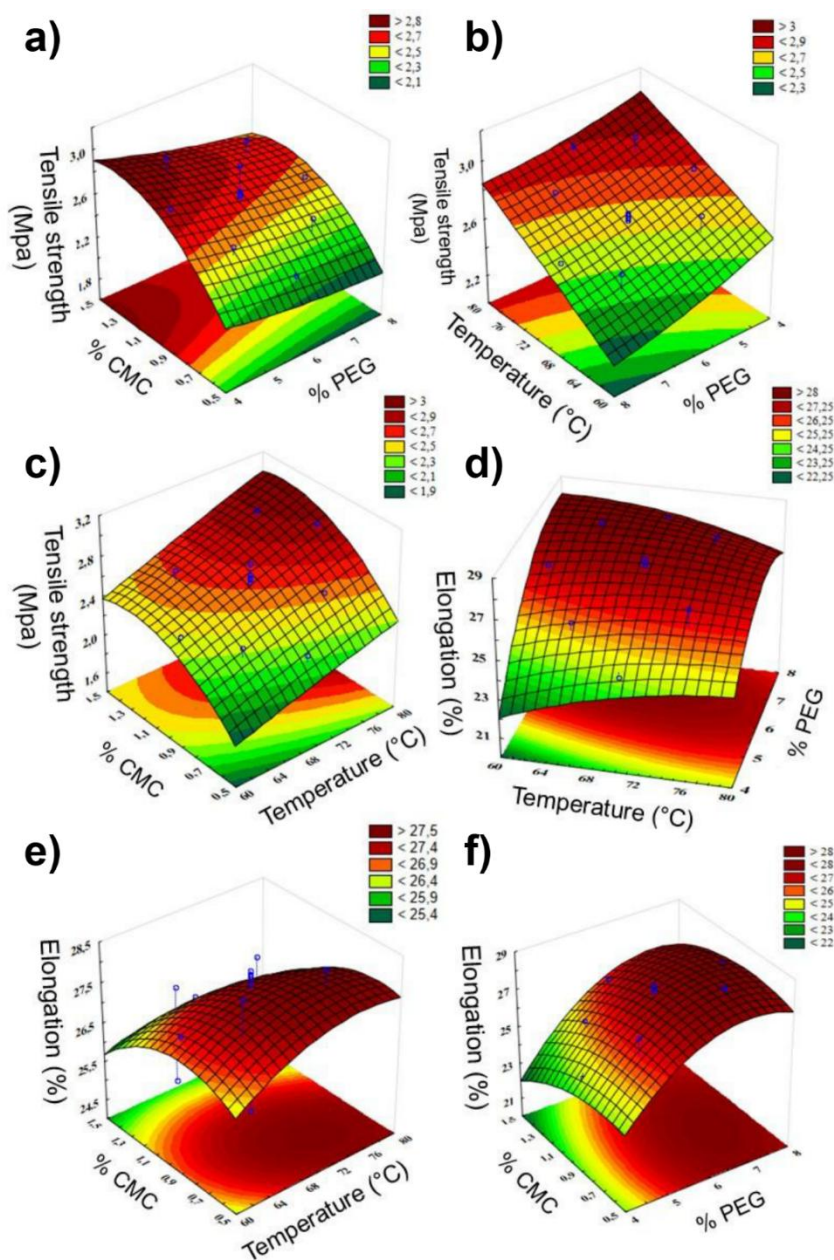


**Fig. 7:** Surface plot (3-D) for responses TS (a, b, c) and EAB (d, e, f).

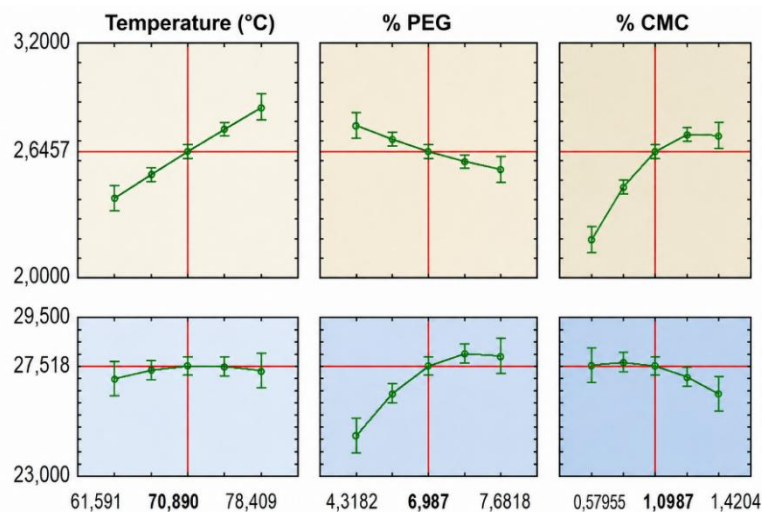


**Fig. 8:** Optimum formulation condition of edible films.

**Table 4:** Optimization response film formulation.

| Variables        | Optimum Conditions ( $X_{opt}$ ) |            | Value of response ( $Y_{opt}$ ) |                | Error  |
|------------------|----------------------------------|------------|---------------------------------|----------------|--------|
|                  | Coded                            | Real value | Predicted                       | Experiment     |        |
| Temperature (°C) | 0,178                            | 70.890     | TS = 2.646 MPa                  | TS = 2.618MPa  | 1.058% |
| PEG (%)          | 0.987                            | 6.987      | EAB = 27.518 %                  | EAB = 27.532 % | 0.051% |
| CMC (%)          | 0.395                            | 1.099      |                                 |                |        |

influence on the responses. Higher temperatures facilitate better gelatinization of starch and improve polymer chain mobility during mixing, leading to improved structural homogeneity of the film matrix. However, excessive temperatures may also reduce intermolecular cohesion due to increased plasticization effects, which can affect tensile strength. While these plots provide a visual representation of the response trends, their interpretation is consistent with the ANOVA results, indicating that the observed changes are primarily governed by the independent effects of each variable rather than statistically significant interaction effects.

Based on the developed regression models, the optimal formulation and corresponding response profiles are presented in Fig. 8. The desirability function predicted optimal processing conditions of 70.89 °C, 6.99% PEG concentration, and 1.10% CMC concentration. Under these conditions, the predicted responses were 2.646 MPa for TS and 27.518% for EAB. Experimental validation of the optimal formulation (Table 4) yielded values of 2.618 MPa for TS and 27.532% for EAB, with prediction errors below 1.1%, confirming the accuracy and reliability of the developed RSM model. These findings demonstrate that RSM is an effective statistical tool for optimizing the formulation of *Arenga pinnata* starch-based edible films and for elucidating the interactions between formulation parameters and mechanical properties.

#### 4. Conclusion

Edible films based on *Arenga pinnata* starch were successfully developed through the optimization of PEG concentration, CMC content, and processing temperature. PEG acted as an effective plasticizer, enhancing flexibility up to an optimal concentration, while CMC reinforced the polymer network, improving tensile strength at the expense of flexibility and water resistance. Processing temperature influenced film structure by promoting molecular packing and reducing water absorption. Response Surface Methodology (RSM) demonstrated high predictive capability, with strong agreement between experimental and predicted results and non-significant lack-of-fit values. The optimal conditions were identified at 70.89 °C, 6.99% PEG, and 1.10% CMC, yielding films with balanced mechanical performance. FTIR and SEM analyses confirmed the formation of a cohesive and well-integrated polymer network through enhanced intermolecular interactions. However, the optimization in this study primarily focused on mechanical properties (TS and EAB) and therefore does not fully encompass all aspects of packaging performance. Nevertheless, further characterization

and barrier-property assessment, particularly water vapor permeability, may help to confirm functional performance. These outcomes highlight the potential of *Arenga pinnata* starch as a sustainable and viable raw material for the development of functional edible films, contributing to environmentally friendly alternatives for food packaging applications.

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#### Conflict of Interest

There are no conflicts to declare.

#### Supporting Information

Not applicable.

#### CRedit Statement

**Prima Astuti Handayani:** Writing - Original draft, Investigation, Funding acquisition, Data curation, Visualization. **Nuni Widiarti:** Conceptualization, Validation, Writing - Review and editing. **Maulida Zakia:** Supervision, Validation, Writing - Review and editing. **Pinky Yogi Novitasari:** Formal analysis, Validation. **Muhammad Jiddan:** Investigation, Formal analysis, Writing – Review & editing. **Dwi Kharisma Luthfiani:** Validation, Project administration. **Ade Rahmania Yuningsih:** Data curation, Project administration. All authors have read and approved the final version of the manuscript.

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