

Research Article

Optimization of Edible Film Properties Derived From Mature and Young Sugar Palm (*Arenga pinnata*) Fruits Using CMC and Glycerol

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Arenga pinnata fruit contains heteropolysaccharides and shows potential as a raw material for edible film production. Unlike previous studies that focused on isolating galactomannan from young fruits, this research introduces an innovative approach by utilizing whole extracts from both maturity stages (young and mature) without an isolation process, simplifying preparation and leveraging the natural complexity of fruit components. This study is aimed at optimizing edible film formulations by incorporating glycerol (1%, 2%, and 3% [v/v]) and carboxymethyl cellulose (0%, 0.25%, and 0.5% [w/v]) into extracts from both maturity stages. A $2 \times 3 \times 3$ full factorial design with three replications was employed to evaluate the effects of fruit maturity, glycerol concentration, and CMC concentration on film properties. Results demonstrated that glycerol and CMC supplementation increased film thickness and elongation at break while reducing water solubility, light opacity, and tensile strength. Glycerol addition elevated water vapor transmission rate (WVTR), whereas CMC incorporation significantly improved moisture barrier properties. Contact angle measurements revealed that films from mature fruits were hydrophobic ($CA > 90^\circ$), while those from young fruits were hydrophilic ($CA < 90^\circ$). Through a comprehensive analysis of physical and barrier properties, the optimal formulation was identified as mature fruit extract with 2% glycerol and 0.25% CMC, demonstrating effective packaging properties, that is, lower WVTR, higher elasticity, lower thickness, and lower solubility.

Keywords: edible film; food packaging; full factorial optimization; sugar palm fruits

1. Introduction

Synthetic plastic packaging has become popular owing to its ease of use, strength, and ability to protect food from moisture. However, growing concern for environmental sustainability caused by plastic waste accumulation has shifted the focus to sustainable packaging alternatives. Edible films made from natural biopolymers with high biodegradability offer a promising solution owing to their high biodegradability. It can be consumed as food and easily decomposed,

thereby aiding in the reduction of the negative environmental impact caused by plastic packaging [1].

Research on the manufacture of edible films made from natural resources, particularly polysaccharides, has demonstrated promising prospects for improving food production quality and durability with marked biodegradability [2]. Sugar palm fruit (*Arenga pinnata*) is a prominent source of polysaccharides because of its rich heteropolysaccharide constituents, which are primarily used in the fabrication of edible films. These constituents were found in young and

mature sugar palm fruits, indicating that both cohorts are useful for this purpose.

Previous studies have focused exclusively on the application of young sugar palm fruits in edible film development. These studies include film development from sugar palm fruit blended with beeswax [3, 4], while others have incorporated essential oils to enhance the films' physical properties [5, 6] and plasticizers to improve mechanical properties. Sugar palm fruit-based films require modification to meet specific performance standards of the food packaging industry [7], particularly in terms of mechanical strength (e.g., tensile strength [TS] and elongation) and barrier properties (e.g., water vapor transmission rate [WVTR]). For example, TS must comply with ASTM D882 (standard test method for tensile properties of thin plastic sheeting), WVTR should be evaluated according to ASTM [8] and E96 (standard test methods for gravimetric determination of WVTR of materials) [9], and general packaging properties may refer to JIS Z 1707 (*General Rules for Plastic Films for Food Packaging*) [10],

Water-soluble polymers, such as carboxymethyl cellulose (CMC) and glycerol, have been commonly used in the film formulation process to address these issues. CMC, a cellulose derivative, enhances solution viscosity and improves the mechanical properties of cast films [11, 12]. Glycerol, as a plasticizer, improves flexibility and impact strength under storage conditions [13, 14]. The combination of CMC and glycerol has been shown to improve TS and elongation, making edible films more suitable for the food packaging industry.

Existing research demonstrates significant limitations including an almost exclusive focus on young fruits, underutilization of mature fruits despite their potential to yield superior film properties, and a lack of comprehensive optimization approaches addressing multiple film properties simultaneously. This study introduces a dual novelty through the direct use of whole sugar palm fruit extract without complex isolation processes, a comparative exploration of young and mature fruits—an approach not previously undertaken—and an innovative methodological approach employing a full factorial experimental design using Design-Expert software with a $2 \times 3 \times 3$ configuration. This integrated approach enables systematic evaluation of both individual and interaction effects between fruit maturity stages (young vs. mature), glycerol concentration gradients (1%, 2%, and 3%), and CMC concentration variations (0%, 0.25%, and 0.5%).

The application of Design-Expert facilitates sophisticated multivariate optimization and identification of optimal formulations beyond the capabilities of traditional one-variable-at-a-time experimentation.

This study is specifically designed to investigate the fundamental influence of fruit maturity on various functional properties of edible films, including thickness, mechanical strength, water vapor barrier properties, hydrophobicity through contact angle (CA) measurements, and water solubility characteristics. This research is aimed at optimizing the characteristics of edible films derived from young and mature sugar palm fruits by incorporating CMC and glycerol.

The primary objective focuses on evaluating the impact of formulation variations on thickness, TS, elongation, water vapor permeability, and optical properties of the resulting films. This comprehensive study will significantly contribute to the development of environmentally friendly biopolymer-based food packaging with strong potential for widespread application across the food industry.

2. Materials and Methods

2.1. Materials. Sugar palm fruits were collected from farmers in Cihideung Ilir, Bogor Regency, Indonesia. Young sugar palm fruit (12–18 months old) exhibits yellow or yellowish-green skin, with a soft, elastic, and translucent endosperm. In contrast, mature sugar palm fruit (>18 months old) develops black or dark brown skin, and the endosperm hardens, becoming fibrous and ivory-white in color. Glycerol (98%, food grade) was obtained from CV Netafarm Sidoarjo, and CMC (food grade) was sourced from Mitra Jaya Chemical, Bekasi. Distilled water (Aquadeg) was also used in this study.

2.2. Methods

2.2.1. Raw Material Characterization. Based on characterization data from previous studies [15, 16], significant differences were observed between young and mature sugar palm fruits, supporting their potential application as raw materials for edible films. Proximate analysis revealed that mature fruits exhibited higher carbohydrate content ($95.47\% \pm 5.59\%$) compared to young fruits ($89.02\% \pm 1.37\%$), while ash, fat, and protein content were lower in mature fruits. Thermal analysis demonstrated that mature fruits possessed better stability with a melting temperature (T_m) of 189.41°C and glass transition temperature (T_g) of 148.13°C , which were higher than those of young fruits (T_m : 171.81°C ; T_g : 137°C). Rheological characteristics indicated that mature fruits exhibited pseudoplastic behavior with viscoelasticity $G' > G''$, whereas young fruits showed Newtonian behavior. The crystallinity degree of mature fruits was also higher (66.16%) compared to young fruits (49.0%), suggesting a more ordered structure and potentially better barrier properties for edible film applications.

2.2.2. Preparation of Edible Film From Young and Mature Sugar Palm Fruits. Young and mature sugar palm fruits were boiled for 2 h, after which the thin skin on the surface was removed, and the fruits were thoroughly washed. After cutting into small pieces, the materials were weighed at a fruit-to-water ratio of 1:10 (w/v). Young sugar palm fruits were directly blended with water using a blender (Philips HR 2115), while mature fruits were first crushed using a herb grinder (Miller MKS-200) before water was added according to the specified ratio. The crushed mixture was filtered through a 60-mesh sieve. A total of 100 mL of the filtrate was transferred to a beaker glass and heated at 70°C for 15 min using a hot plate with a magnetic stirrer at a stirring speed of 500 rpm for both fruit types. Glycerol was added as a plasticizer (1%, 2%, and 3% v/v) and CMC (0, 0.25, and 0.5 g [w/v]). The mixture was left to stand for

10 min to remove air bubbles. Then, 35 mL of the solution was poured into a 9 cm diameter Petri dish and dried in a cabinet dryer at 50°C for 12 h. The edible films were conditioned in a desiccator at room temperature (28°C ± 2°C) for 2 days at a relative humidity (RH) of 75% before testing.

2.3. Optimization Using Full Factorial Design and Statistical Analysis. Design-Expert V13 software (Stat-Ease, Minneapolis, Minnesota, United States) was used to construct a full factorial design with multilevel categories, aiming to generate experiments, analyze data (using analysis of variance [ANOVA] and statistical goodness-of-fit tests with $\alpha = 0.05$, significance level), and optimize and confirm the optimal formula. Three categorical independent variables were defined: type of sugar palm fruit (two levels: young and mature), glycerol concentration (v/v) at three levels (1%, 2%, and 3% of the sugar palm fruit solution weight), and CMC concentration (w/v) at two levels (0.25 and 0.5 g of sugar palm fruit weight). The dependent variables used as responses were the WVTR, percentage elongation at break (% EB), TS, transparency, solubility, and thickness. Further analyses were conducted to determine CAs.

This study employed a $2 \times 3 \times 3$ factorial design encompassing three factors: fruit maturity level (two levels), glycerol concentration (three levels), and CMC concentration (three levels). For statistical analysis, we developed separate response models for each fruit maturity level (mature and young). For each maturity level, the mathematical model representing the response of the 4 full factorial design was a linear polynomial model with interactions, as described in Equation (1).

$$Y_{ij} = \mu + A_i + B_j + (AB)_{ij} + \varepsilon_{ij}. \quad (1)$$

In this study, Y denotes the response variable, whereas A , B , and AB represent the independent variable codes corresponding to the glycerol concentration and CMC concentration, as well as their respective interactions. The indices are designated as follows: $i = 1, 2, 3$ (representing glycerol concentrations of 1%, 2%, and 3% [v/v]); $j = 1, 2, 3$ (representing CMC concentrations of 0, 0.25, and 0.5 g); and $k = 1, 2, 3$ (number of replications).

2.4. Analysis of Edible Film Young and Mature Sugar Palm Fruits

2.4.1. WVTR. The WVTR values were analyzed using a modified gravimetric method [14]. The modification involved the use of a saucer diameter. The edible film, which had been measured to be 6.5 cm in diameter, was adhered to the surface of an aluminum saucer using an adhesive. The saucer, which already contained 10 g of silica gel, was weighed to the nearest 0.001 g using an analytical scale. The dish was then placed in a desiccator set at 75% RH using a saturated NaCl solution. The sample was weighed every hour for a total of an hour to measure the WVTR using Equation (2).

$$\text{WVTR (g (m}^2/\text{h))} = \frac{n}{t \times A}, \quad (2)$$

where n is the weight change (gram), t is time (hour), and A is the surface film area (millimeter).

2.4.2. Thickness. The edible film thickness was measured using a modified method [4]. Film thickness was measured using a digital micrometer (Digital Thickness Gauge, China) with an accuracy of 0.01 mm. Measurements were performed at five random points on each film sample (15 × 20 cm), and the mean value was calculated and reported as the representative thickness.

2.4.3. Solubility. Solubility measurements of edible films from mature and young sugar palm fruits were conducted using the method described previously [17]. Edible film pieces measuring 3 × 3 cm were placed in aluminum dishes. The dishes were dried in an oven (WTC Binder, Tuttlingen, Germany) at 105°C for 30 min. The edible films were then soaked for 24 h. After soaking, the insoluble portion of the edible film was removed and dried in an oven (WTC Binder, Tuttlingen, Germany) at 105°C for 2 h. The dried edible films were placed in a desiccator for approximately 10 min.

$$\text{Solubility (\%)} = \frac{W_0 - W_1}{W_0} \times 100, \quad (3)$$

where W_1 is the initial dry weight and W_0 is the end insoluble dry weight.

2.4.4. Elongation and TS. TS and elongation at break were determined according to ASTM D882 with modifications as detailed in [18], using a texture analyzer (LLOYD TA1, Ametek). Film specimens were cut into 40 × 20 mm rectangles. Although ASTM D882 recommends a 50 mm gauge length, a 40 mm gauge length was employed due to the size limitations of the edible films, while maintaining consistency across all samples to ensure reliable comparability. The cross-sectional area was calculated based on the specimen width and the mean thickness, where thickness was measured at five random points using a digital micrometer (accuracy ± 0.01 mm). Each sample was mounted between the tensile tester grips with an initial grip distance of 40 mm and tested at a crosshead speed of 1 mm/s. TS was calculated as the maximum force at break divided by the initial cross-sectional area. Elongation at break (percent sign) was determined as the extension at break (ΔL) divided by the original gauge length (40 mm) and multiplied by 100. Three replicates were tested for each film formulation during this factorial design phase. A larger number of replicates (five) was specifically employed during the validation stage of the optimal formula.

2.4.5. Opacity Testing. The opacity of the edible films was determined according to a modified method based on [19], using a double-beam UV-Vis spectrophotometer (UV-1800, Japan) with standard rectangular cuvettes possessing an optical path length of 1 cm. Film specimens were cut and securely placed inside the cuvette, firmly attached to

one side of the cuvette wall to prevent air gaps. The edges of the film were slightly elongated to ensure stable positioning and to avoid any open gaps during measurement. The automated reference system was employed, where one cuvette contained the film sample while another empty cuvette served as the reference blank. Baseline correction was automatically performed by the instrument, eliminating the need for manual background subtraction. Light transmission was measured by scanning samples across wavelengths ranging from 200 to 800 nm. The film opacity was recorded at 600 nm and calculated as follows:

$$\text{Opacity} = \frac{A_{600}}{X}, \quad (4)$$

where A_{600} is the absorbance at 600 nm and X is the thickness (millimeter).

2.4.6. CA Measurement. CA measurements were conducted in strict accordance with the methodology detailed in [20]. The hydrophobicity of the films was then determined. Measurements were performed using a CA meter (CAM-PLUS, Tantec, Germany). The data obtained are the average of three independent determinations at different locations. The CA on each film surface was measured immediately after the addition of 1 μL of deionized water using the Sessile Drop Half-Angle tangent-line method.

The CA is the angle between the liquid droplet and the surface where it spreads. CA measurements provide an indication of surface properties. The CA was determined by the direct observation of a smooth, horizontal liquid droplet on a solid surface mounted on a microscope slide. Water droplets were individually dropped onto the film. The average CA was obtained by measuring the angle at three different positions on the same sample.

3. Results and Discussion

3.1. Optimized Process With Full Factorial Design

3.1.1. Number of Runs and Multiple Responses for Optimization. Design-Expert software (DX13), which offers a “multilevel category” option known as a general or conventional factorial (Stat-Ease, 2024), was used in this study. The experimental design, utilizing a full factorial approach, facilitated the simultaneous evaluation of the impact of glycerol and CMC on both mature and young palm fruits as well as their interaction effects on the targeted outcomes. Table 1 presents the 54 experiments allowed by the full factorial design. Process optimization was conducted using a full factorial design ($2 \times 3 \times 3 \times 3$). The run order was randomized to optimize the process variables along with the experimental and dependent variables, which included the thickness, solubility, WVTR, transparency, elongation, and TS.

3.1.2. ANOVA and Independent Variable Effect on Multiple Responses. The results of the ANOVA are presented in Table 2. The statistical significance of the models was confirmed by p values < 0.01 for all response parameters. However, model validity was further verified through a

comprehensive diagnostic analysis beyond p values to ensure robust statistical conclusions.

The residual distribution was examined through normal probability plots of residuals, showing that the residual points followed the diagonal line with minimal deviation. This indicates that the residuals were approximately normally distributed with no violation of the normality assumption. Furthermore, the plot of residuals versus predicted values demonstrated random scattering without specific patterns, indicating homogeneous residual variance and no evidence of autocorrelation. The plot of residuals versus run order also showed random distribution, confirming residual independence. Cook’s distance analysis revealed that all values were below the threshold of 1, indicating no single observation excessively influenced the model.

The quantitative model adequacy was demonstrated through excellent R^2 , adjusted R^2 , and predicted R^2 values. For the thickness parameter, for example, $R^2 = 0.918$, adjusted $R^2 = 0.875$, and predicted $R^2 = 0.785$, with relatively small differences (< 0.2) indicating consistency between actual data and model predictive capability. Additionally, the adequacy of precision value of 17.748 far exceeded the minimum threshold of 4, confirming that the model has an adequate signal-to-noise ratio for design space exploration.

In the solubility parameter in Table 2, the difference between adjusted R^2 (0.724) and predicted R^2 (0.578) indicates potential overfitting, which may be attributed to the intrinsic complexity of the physicochemical properties of solubility involving multiple simultaneous mechanisms. However, the adequate precision ratio of 11.953, which exceeds the threshold of 4, along with the good model performance for other parameters (R^2 differences of 0.026–0.043), supports the overall validity of the model. Further experimental validation confirms the practical utility of the model in guiding the optimization process.

3.2. Main Factor and Interaction Effects on Thickness. The differences between edible films made from mature and young sugar palm fruits, as well as the interaction between glycerol and CMC in relation to various responses to thickness, are illustrated in Figure 1.

The research results indicate that the edible film made from young sugar palm fruit is thicker than the film made from mature sugar palm fruit (Figure 1). Although there is a difference in thickness between the two types of films, the thickness values still meet the JIS standard, which is less than 0.25 mm [4]. This difference in thickness was caused by variations in the morphological structures of the raw materials. Young sugar palm fruits have a semicrystalline structure, whereas the mature sugar palm fruit has a more crystalline structure [15]. The semicrystalline structure of young sugar palm fruit causes its molecules to be arranged randomly (amorphous), allowing the material to absorb more water or solvent during the film-making process. This enhances material dispersion, facilitates solubility, and enables the formation of a thicker film layer owing to the high amount of solvent or binding agent used during drying. Additionally, the more open amorphous structure also contributes to the increased film thickness. In contrast, mature

TABLE 1: The complete factorial design matrix that was run and some of the responses that were obtained.

Run number ^a	Sugar palm fruits % (w/v)	Glycerol % (v/v)	CMC % (w/v)	Thickness (mm)	Solubility (%)	WVTR (g(m ² /h)	Opacity (A/mm)	EAB (%)	TS (MPa)
1	Matured	3	0.5	0.090	77.777	6.544	3.228	890.525	2.381
2	Matured	1	0.5	0.060	76.905	2.261	4.150	105.590	7.592
3	Matured	1	0.25	0.068	75.961	4.908	10.937	62.300	18.306
4	Matured	2	0	0.056	75.373	11.363	3	21.145	0.789
5	Young	1	0.5	0.060	76.536	5.716	2.406	39.000	21.796
6	Young	2	0	0.104	76.297	10.125	3.788	51.247	4.604
7	Young	1	0.5	0.060	75.881	4.604	2.765	43.000	211.462
8	Matured	1	0	0.050	75.094	6.142	10.620	23.156	0.422
9	Young	3	0.25	0.142	74.517	7.234	2.378	745.025	18.204
10	Young	3	0.5	0.164	74.023	5.146	1.528	913.325	16.598
11	Matured	3	0.5	0.094	77.969	5.880	2.404	873.937	2.455
12	Young	3	0.25	0.143	74.497	7.411	1.592	743.563	18.359
13	Matured	2	0.5	0.072	75.765	5.350	6.677	109.823	2.443
14	Matured	1	0	0.056	74.826	8.799	10.531	12.003	0.324
15	Young	1	0	0.051	75.194	9.142	11.78	36.520	2.963
16	Matured	2	0.5	0.078	75.106	5.129	5.128	126.734	3.180
17	Young	3	0	0.121	75.639	11.407	3.116	64.275	5.950
18	Young	2	0.5	0.124	76.989	4.925	2.184	85.400	28.986
19	Matured	2	0.25	0.056	75.710	6.992	5.053	107.645	5.735
20	Young	1	0	0.050	75.958	9.550	11.694	324.825	2.837
21	Young	3	0.5	0.162	74.213	6.266	1.625	96.980	17.070
22	Young	3	0	0.122	75.849	12.999	4.433	58.920	5.865
23	Matured	3	0.25	0.080	76.038	7.826	8.520	793.575	1.167
24	Matured	3	0.25	0.086	76.353	6.129	7.650	51.070	1.915
25	Young	2	0.25	0.098	76.802	6.995	2.500	71.910	35.603
26	Matured	2	0	0.050	76.089	12.69	9.139	22.145	0.780
27	Matured	2	0.25	0.058	74.436	6.632	6.879	147.713	5.818
28	Matured	1	0.25	0.060	75.226	4.156	10.977	661.725	18.306
29	Matured	3	0.5	0.094	76.351	5.962	3.924	873.937	2.530
30	Matured	2	0.25	0.056	75.083	6.853	6.075	114.364	5.901
31	Young	2	0.5	0.108	76.511	5.686	1.842	85.400	29.225
32	Matured	3	0	0.054	75.66	10.839	8.074	21.145	0.345
33	Young	3	0	0.112	75.753	11.55	6.750	63.565	5.000
34	Young	1	0.25	0.068	75.659	6.129	4.000	628.375	32.733
35	Young	2	0.25	0.098	76.656	6.716	1.602	73.925	33.881
36	Matured	1	0	0.056	75.105	8.622	10.769	25.225	0.503
37	Matured	1	0.25	0.062	76.602	4.343	12.387	70.045	11.229
38	Young	3	0.25	0.143	74.074	7.156	3.031	74.210	18.515
39	Young	1	0.25	0.062	75.593	5.686	3.047	69.745	34.260
40	Young	1	0.5	0.060	75.971	4.901	2.443	41.000	208.031
41	Matured	3	0.25	0.086	76.488	6.278	8.354	107.645	1.915
42	Matured	1	0.5	0.064	75.508	2.52	4.722	108.146	4.100
43	Matured	1	0.5	0.060	75.913	2.812	4.025	110.703	0.608
44	Young	3	0.5	0.104	74.089	6.448	2.605	986.275	17.543
45	Matured	3	0	0.052	74.770	10.302	8.733	21.456	0.987
46	Young	1	0.25	0.068	74.778	6.129	4.086	666.525	35.787
47	Young	2	0	0.111	76.607	10.578	3.290	51.947	4.207
48	Matured	2	0	0.052	76.035	11.727	9.038	23.334	0.404

TABLE 1: Continued.

Run number ^a	Sugar palm fruits % (w/v)	Glycerol % (v/v)	CMC % (w/v)	Thickness (mm)	Solubility (%)	WVTR (g/m ² /h)	Opacity (A/mm)	EAB (%)	TS (MPa)
49	Matured	2	0.5	0.072	75.173	5.387	5.653	126.734	3.916
50	Young	2	0	0.111	76.806	10.523	6.533	519.475	4.810
51	Young	2	0.5	0.108	76.943	5.520	2.154	82.885	29.465
52	Young	2	0.25	0.096	76.088	6.884	2.088	73.925	32.160
53	Matured	3	0	0.050	76.268	10.523	8.40	25.225	0.503
54	Young	1	0	0.062	75.836	9.197	11.125	32.445	2.710

^aThe run number order was randomized using DX13 software.

TABLE 2: Results of ANOVA (full factorial model) and fit statistics.

Response parameter	<i>p</i> -value model	<i>p</i> -value Factor A	<i>p</i> -value Factor B	<i>p</i> -value inter. AB	Adj- <i>R</i> ² model	Pred- <i>R</i> ² model	Adeq precision
Thickness (mm)	< 0.0001****	< 0.0001****	< 0.0001****	0.0003***	0.918	0.875	17.748
Solubility (%)	< 0.0001****	0.0193*	0.0534	0.1649	0.724	0.578	11.953
WVTR (g/m ² /h)	< 0.0001****	< 0.0001****	< 0.0001****	0.1161	0.951	0.925	28.310
Opacity (A/mm)	< 0.0001****	< 0.0001****	< 0.0001****	< 0.0001****	0.945	0.915	21.029
Elongation at break (%)	< 0.0001****	< 0.0001****	< 0.0001****	0.0082**	0.922	0.881	19.672
Tensile strength (MPa)	< 0.0001****	< 0.0001****	< 0.0001****	< 0.0001****	0.985	0.977	41.428

Note: A = glycerol % (v/v). B = CMC grams (w/v).

Abbreviations: adeq = adequate, adj = adjusted, Inter. = interaction, pred = predicted.

* *p* < 0.05

** *p* < 0.01

*** *p* < 0.001

**** *p* < 0.0001

Values without * = not significant (*p* > 0.05).

sugar palm fruit with a crystalline structure exhibits denser properties and stronger molecular bonds, limiting its ability to absorb water or solvents. As a result, the film produced from mature sugar palm fruit is thinner, more rigid, and more resistant to moisture than the film produced from young sugar palm fruit.

The results in Figure 1 show that the edible films from both young and mature sugar palm fruit increased with increasing glycerol concentration. As a plasticizer, glycerol plays a crucial role in modifying the physical properties of edible films, particularly their thickness. Glycerol works by reducing the intermolecular forces between polymer chains, increasing mobility, and enhancing film flexibility. This effect is more pronounced in hydrophilic films, where the increase in water content due to the addition of glycerol directly increases film thickness. Previous research using young sugar palm fruit with added beeswax also reported a similar pattern, where the film thickness increased significantly with increasing glycerol concentration in the formulation [4, 6].

3.3. Main Factor and Interaction Effects on Solubility. The results of this study demonstrate that the effect of glycerol on the solubility of sugar palm fruit-based edible films is complex and depends on fruit maturity, as illustrated in Figure 2. In films derived from young fruits, the highest sol-

ubility was observed in the formulation containing 2% glycerol and 0.5% CMC. However, increasing glycerol concentration significantly reduced film solubility. This phenomenon contrasts with general literature reports stating that glycerol, as a hydrophilic plasticizer, typically increases water affinity and film solubility. The observed solubility reduction in young fruit films is presumably caused by the formation of a denser matrix structure resulting from synergistic interactions between glycerol, CMC, and specific polysaccharide components in young sugar palm fruit. This more compact matrix may inhibit water diffusion into the film, thereby reducing solubility. These findings are consistent with previous research by [6], who also reported decreased solubility at higher glycerol concentrations in films based on young sugar palm fruit. In contrast, films from mature fruits exhibited a different response to increasing glycerol concentration. Increasing glycerol concentration up to 3% significantly enhanced film solubility. This behavior aligns with general literature on the role of glycerol as a plasticizer that improves film flexibility and moisture retention. Higher glycerol concentrations also disrupt the crystalline structure of the film, resulting in a more hydrophilic matrix and increased water absorption.

The differential response between young and mature fruits to glycerol concentration indicates that plasticizer effects are highly dependent on the characteristics of the base

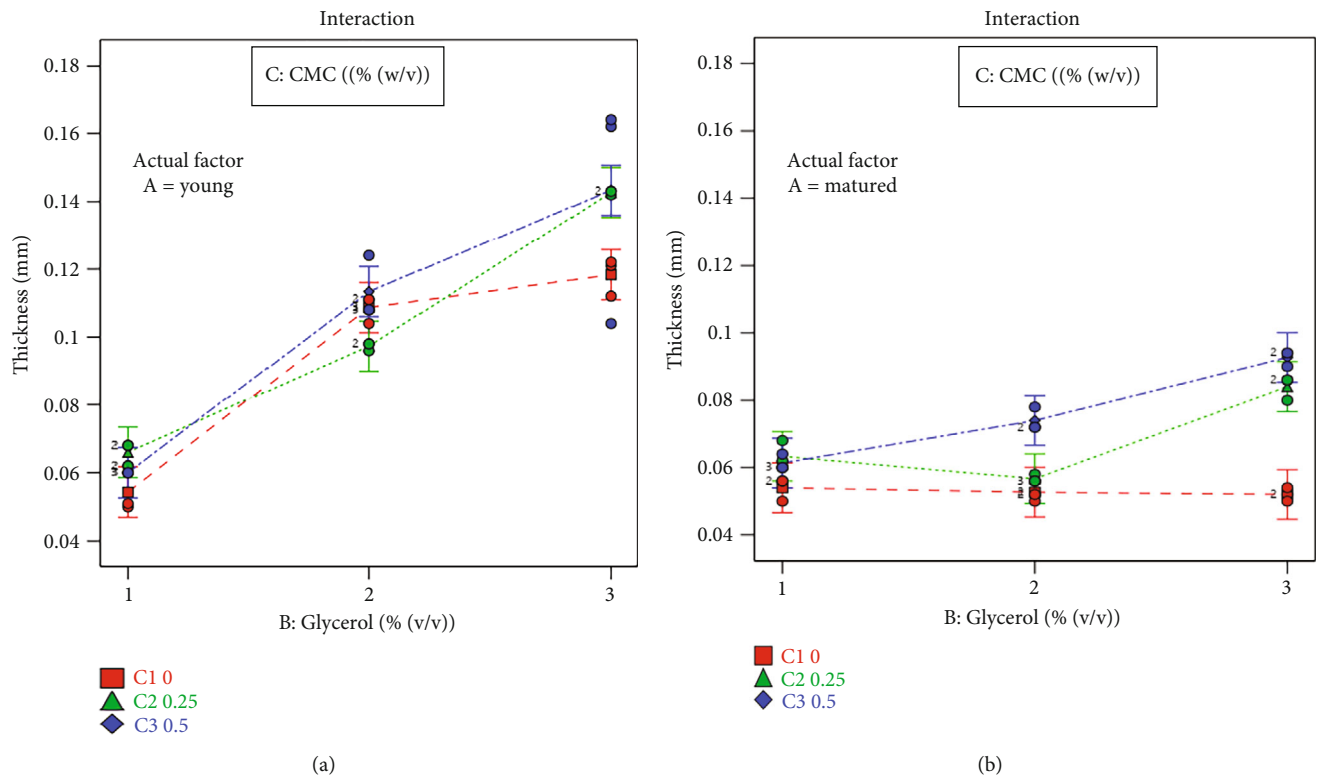


FIGURE 1: Interaction effects of glycerol (1%, 2%, and 3% [v/v]) and CMC (0%, 0.25%, and 0.5% [w/v]) on thickness edible films made from (a) young and (b) mature sugar palm fruit.

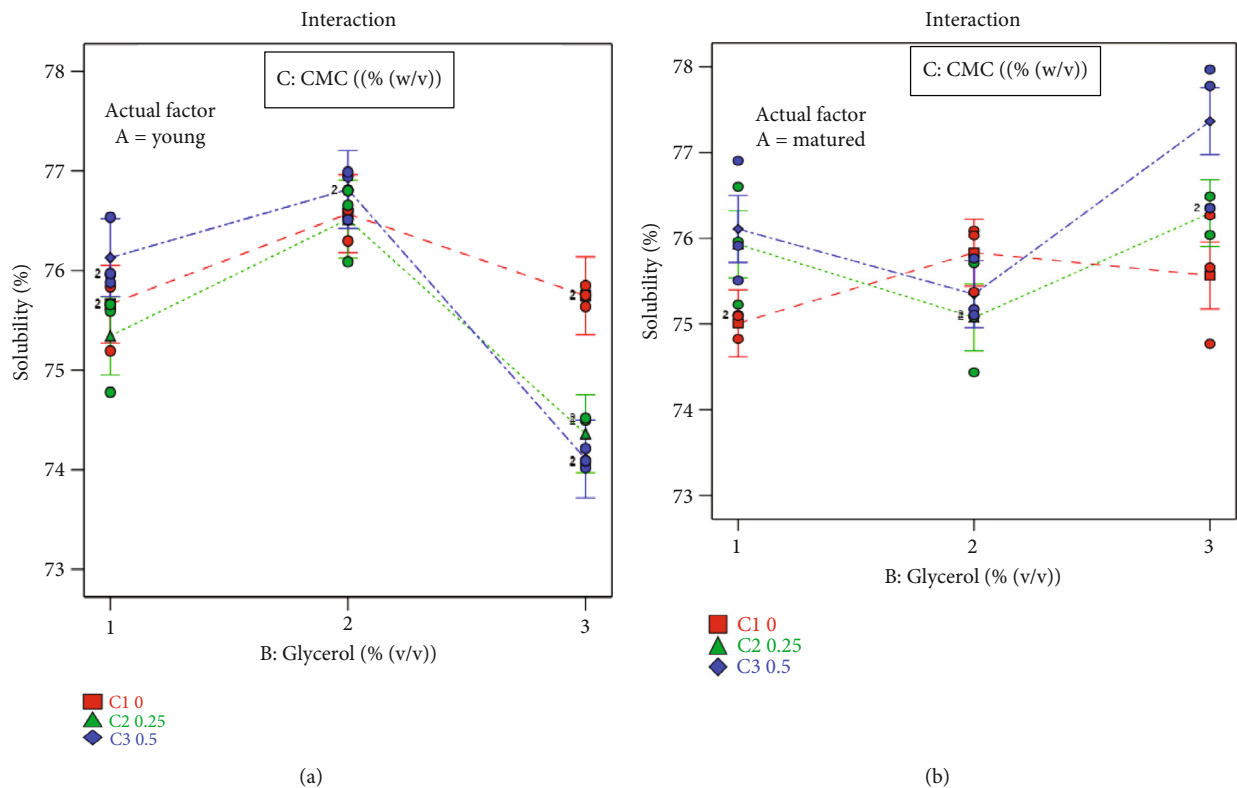


FIGURE 2: Interaction effects of glycerol (1%, 2%, and 3% [v/v]) and CMC (0%, 0.25%, and 0.5% [w/v]) on solubility edible films made from (a) young and (b) mature sugar palm fruit.

material and its interactions with other components in the film system. Fruit maturity affects polysaccharide composition and physicochemical properties, which ultimately determine the response to plasticizers. These findings highlight the importance of considering the specific properties of raw materials in designing edible film formulations, as the effects of additives such as glycerol may vary depending on the intrinsic characteristics of the base material.

In the case of young sugar palm fruit, the interaction between glycerol and CMC plays an important role in determining the mechanical properties of the edible film. As a hygroscopic compound, glycerol disrupts the compactness of the polymer matrix, increasing the film flexibility but reducing its TS [21]. Previous research has shown that an optimal amount of glycerol can improve film extensibility, while excessive glycerol can lead to a decrease in mechanical strength. These findings were also supported by a study conducted by [6], who studied edible films made from young sugar palm fruits. Additionally, the presence of CMC in the film formulation also influences its solubility and mechanical performance. As a thickening agent, CMC can enhance the structural integrity of a film when combined with an appropriate amount of glycerol [11]. However, when the glycerol concentration was too high, the hydrophilic properties of glycerol and CMC caused an increase in water absorption, which weakened the film and reduced its solubility [22]. Similar results were obtained in a study by [3], who developed an edible film from young sugar palm fruit.

3.4. Main Factor and the Interaction Effects on WVTR. The formulation containing 1% (v/v) glycerol and 0.5% (w/v) CMC showed the lowest WVTR values Figure 3. This difference in WVTR is attributed to variations in film structure, where the semicrystalline nature of the young fruit-based film facilitated greater water vapor transmission compared to the more densely packed crystalline structure of the mature fruit-based film.

Variations in WVTR were not only influenced by film structure, as previously reported, but also by the presence of glycerol as a hydrophilic plasticizer. Glycerol interacts with polymer chains in the film matrix, increasing molecular mobility and creating pathways that facilitate water vapor diffusion [23]. In sugar palm fruit-based edible films, optimizing glycerol concentration is essential to balance flexibility and moisture barrier properties. A study by [6] on young sugar palm fruit-based edible films also demonstrated that increasing glycerol concentration up to 3% resulted in a proportional increase in WVTR.

CMC plays a regulatory role in WVTR values for both young and mature fruit-based edible films. As a cellulose derivative, CMC exhibits water retention capacity and forms films with superior moisture barrier characteristics. The results indicate that the addition of CMC up to 0.5% reduced WVTR by enhancing the structural integrity of the film (Figure 3). Similar findings were reported in studies using sugar palm fruit-based edible films, where water vapor permeability varied depending on film composition, and the incorporation of polysaccharides such as CMC improved moisture barrier properties [5]. Furthermore, research [24]

confirmed that film matrix composition significantly influences physical characteristics. The addition of CMC contributed to reduced WVTR values due to its hydrophilic properties, which help minimize water vapor diffusion within the film.

3.5. Main Factor and Interaction Effects on Opacity. The differences between edible films made from mature and young sugar palm fruits, as well as the interaction between glycerol and CMC in relation to various responses to opacity, are illustrated in Figure 4.

Opacity indicates the level of transparency of a film, with higher opacity values corresponding to lower transparency [25]. The results presented in Figure 4 demonstrate that edible films based on mature sugar palm fruit exhibited lower opacity values than those based on young sugar palm fruit.

This difference was attributed to variations in the crystalline structures of the two types of sugar palm fruits. Mature sugar palm fruit possessed a more ordered crystalline structure, whereas young sugar palm fruit tended to have a semi-crystalline structure [15]. The denser crystalline structure in mature sugar palm fruit-based edible films hinders light penetration, thereby reducing transparency. In contrast, edible films made from young sugar palm fruit, which have a semi-crystalline structure with lower molecular regularity, allow light to pass through the film, increasing its transparency.

In addition to the crystalline structure, the transparency of edible films based on mature and young sugar palm fruit was influenced by the concentrations of glycerol and CMC. An increase in glycerol concentration contributed to a reduction in the transparency of edible films. This phenomenon occurred because of the difference in the refractive indices between glycerol and the film matrix, which increased the opacity values [26]. Higher glycerol concentrations induced changes in the microstructure of the film, affecting the light transmission properties and increasing light scattering. Furthermore, the addition of CMC also modified the physical properties of the edible films, including their transparency. As a hydrophilic polymer, CMC interacts with glycerol, enhancing the mechanical properties of the film while simultaneously reducing its transparency. The synergistic effect of glycerol and CMC led to the formation of a more complex film structure, thereby reducing the ability of the film to transmit light as the concentrations of both components increased [11, 27].

Moreover, the relationship between glycerol and CMC concentrations and film transparency can be explained by light scattering and absorption mechanisms. The increase in the concentration of both materials contributed to changes in the density and structural integrity of the film, ultimately increasing light scattering and reducing transparency [24]. A study conducted [6] on young sugar palm fruit-based edible films also reported similar findings, where an increase in glycerol concentration was inversely proportional to the transparency of the resulting film.

3.6. Main Factor and Interaction Effects on Elongation. The differences between edible films made from mature and

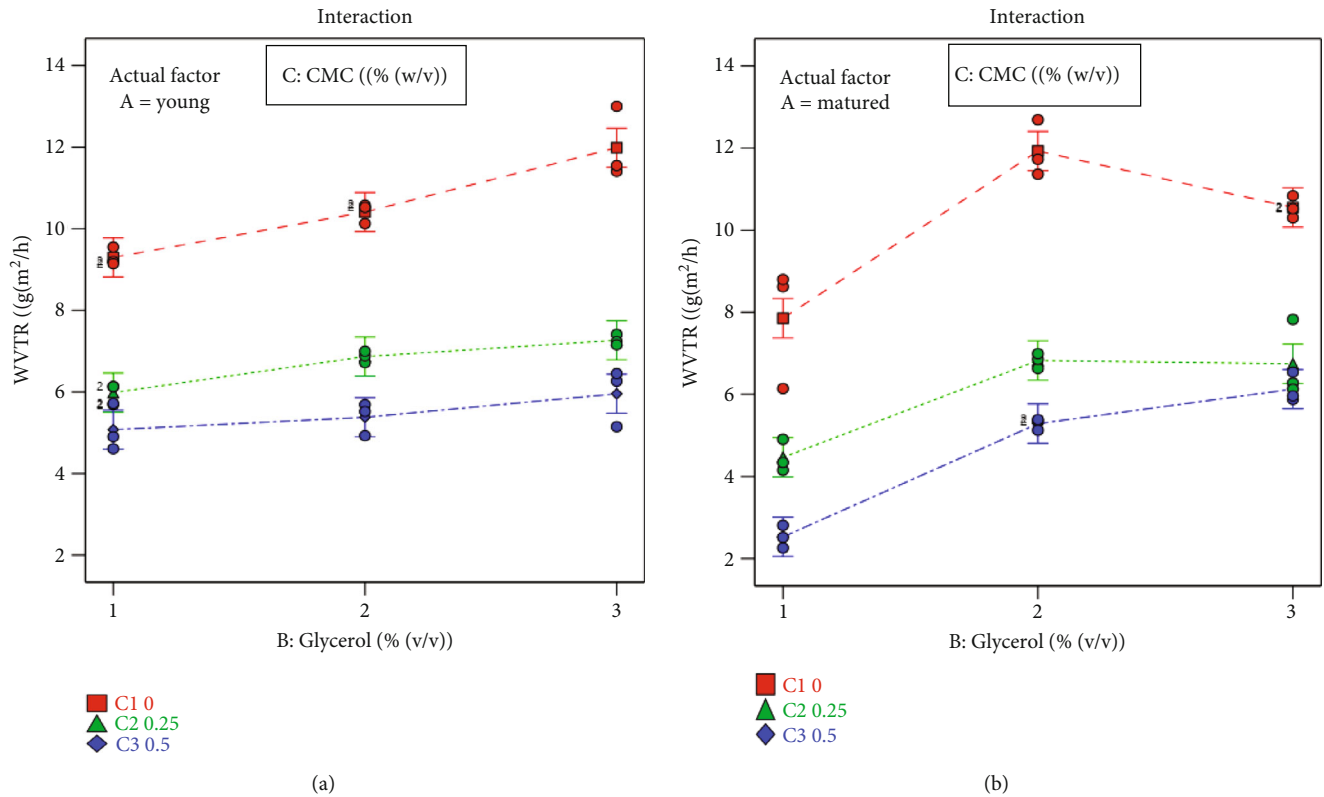


FIGURE 3: Interaction effects of glycerol (1%, 2%, and 3% [v/v]) and CMC (0%, 0.25%, and 0.5% [w/v]) on WVTR edible films made from (a) young and (b) mature sugar palm fruit.

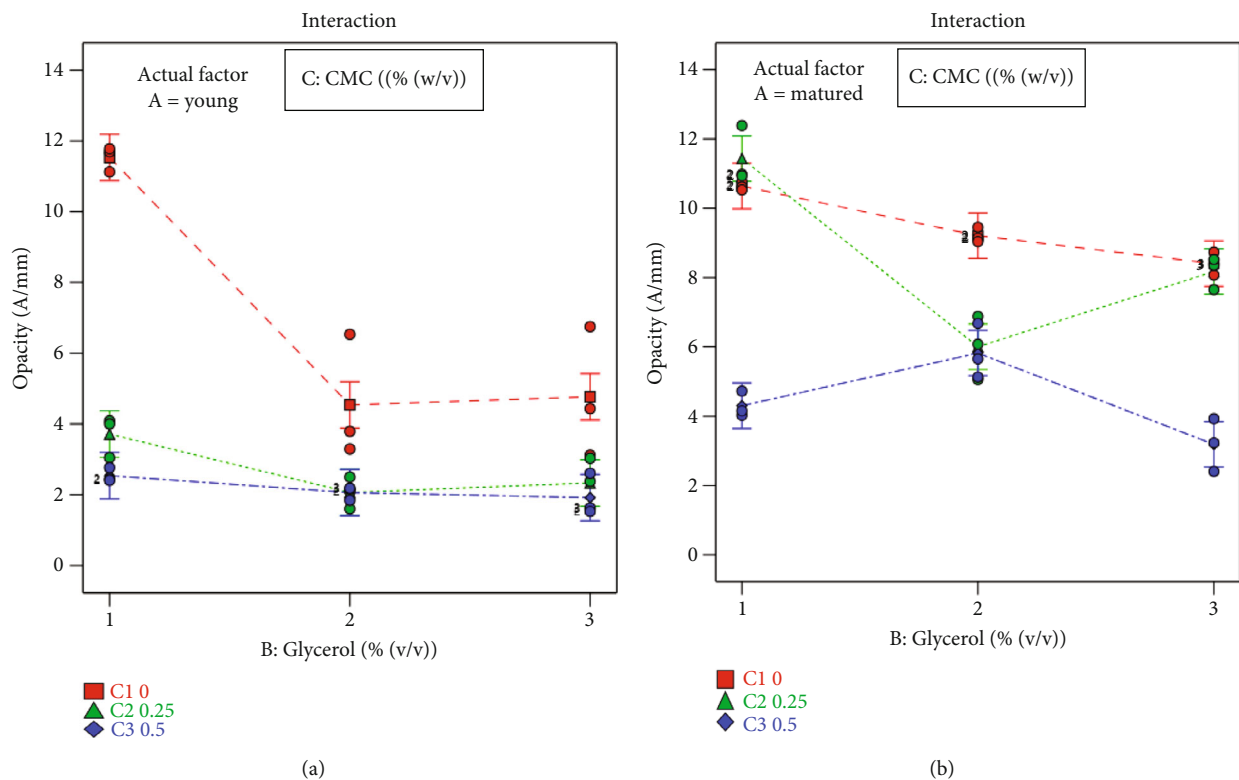


FIGURE 4: Interaction effects of glycerol (1%, 2%, and 3% [v/v]) and CMC (0%, 0.25%, and 0.5% [w/v]) on opacity edible films made from (a) young and (b) mature sugar palm fruit.

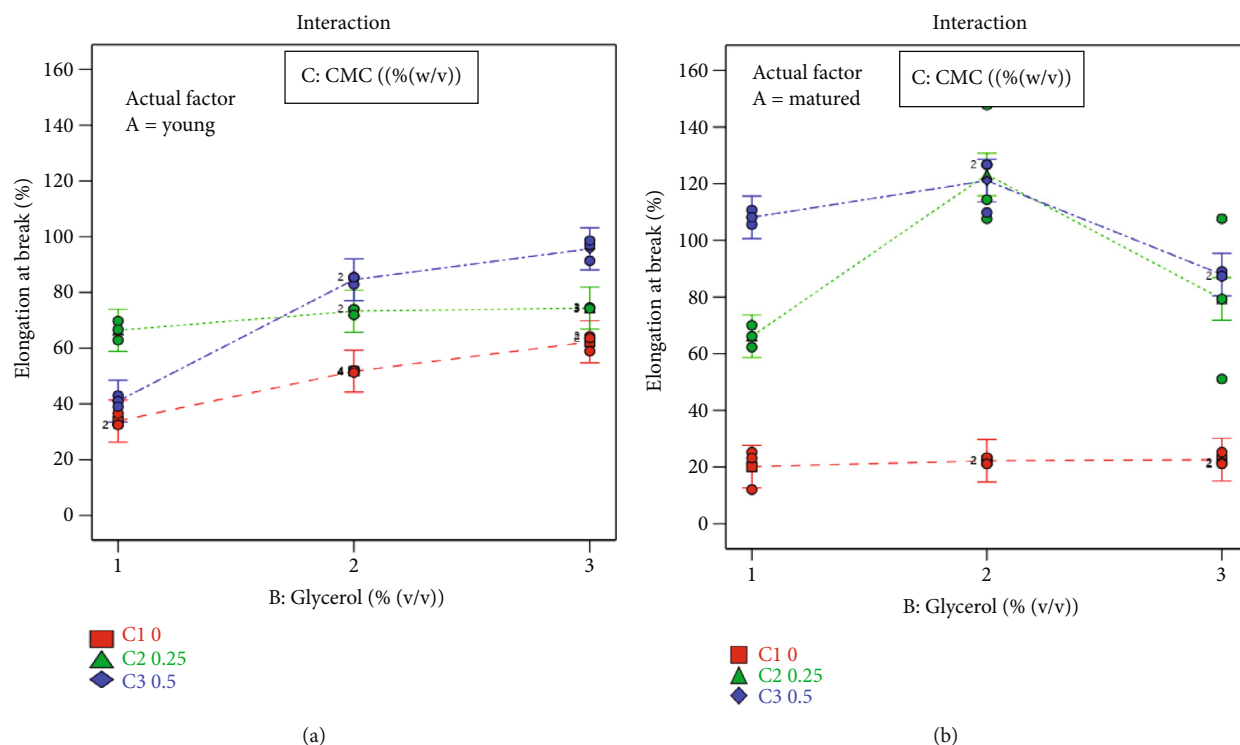


FIGURE 5: Interaction effects of glycerol (1%, 2%, and 3% [v/v]) and CMC (0%, 0.25%, and 0.5% [w/v]) on elongation edible films made from (a) young and (b) mature sugar palm fruit.

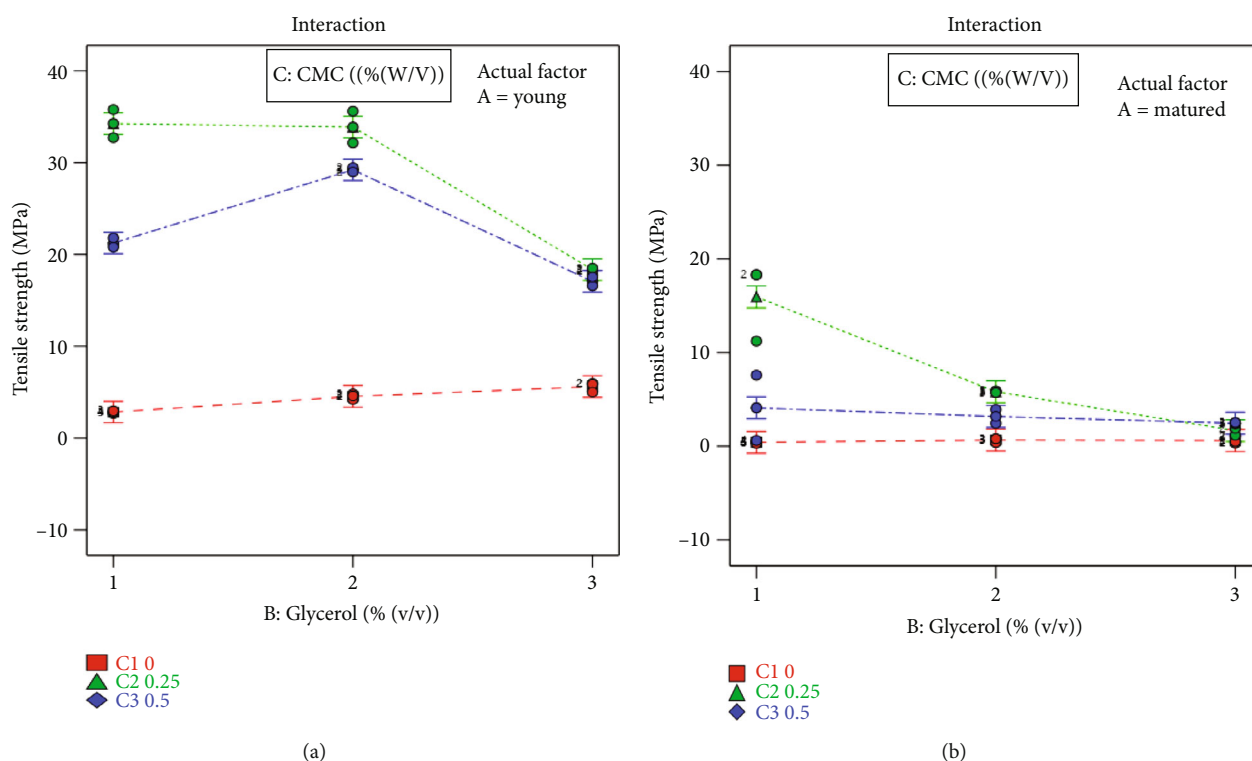


FIGURE 6: Interaction effects of glycerol (1%, 2%, and 3% [v/v]) and CMC (0%, 0.25%, and 0.5% [w/v]) on tensile strength edible films made from (a) young and (b) mature sugar palm fruit.

TABLE 3: Constraints for the optimization process.

Variable name	Goal	Lower limit	Upper limit	Importance
A: sugar palm fruits (%) (<i>w/v</i>)	Is in range	Young	Matured	3
B: glycerol (%) (<i>v/v</i>)	Is in range	1	3	3
C: CMC (%) (<i>w/v</i>)	Is in range	0	0.5	3
Thickness (mm)	Minimize	0.05	0.164	3
Solubility (%)	Minimize	74.023	77.969	3
WVTR (g(m ² /h))	Minimize	2.261	12.999	3
Transparency (A/mm)	Is in range	1.528	12.387	3
Elongation at break (EAB) (%)	Maximize	12.003	147.713	3
Tensile strength (TS) (MPa)	Is in range	0.324	35.787	3

TABLE 4: Solution of the optimized formula given by DX-13.

No.	Sugar palm fruits (%) (<i>w/v</i>)	Glycerol (%) (<i>v/v</i>)	CMC (%) (<i>w/v</i>)	Thickness (mm)	Solubility (%)	WVTR (g(m ² /h))	Transparency (A/mm)	EAB (%)	TS (MPa)	Desirability
1	Matured	2	0.25	0.057	75.076	6.826	6.002	123.241	5.818	0.755
2	Matured	2	0.5	0.074	75.348	5.289	5.819	121.097	3.180	0.742
3	Matured	1	0.5	0.061	76.109	2.531	4.299	108.146	4.100	0.736
4	Young	1	0.25	0.066	75.343	5.981	3.711	66.412	34.260	0.622
5	Matured	1	0.25	0.063	75.930	4.469	11.434	66.172	15.947	0.617
6	Matured	3	0.25	0.084	76.293	6.744	8.175	79.358	1.666	0.542
7	Young	3	0.5	0.143	74.108	5.953	1.919	95.647	17.070	0.518
8	Young	1	0.5	0.060	76.129	5.074	2.538	41.000	21.248	0.509
9	Young	2	0.25	0.097	76.515	6.865	2.063	73.253	33.881	0.485
10	Young	2	0.5	0.113	76.814	5.377	2.060	84.562	29.225	0.471
11	Young	3	0.25	0.143	74.363	7.267	2.334	74.356	18.359	0.453
12	Matured	3	0.5	0.093	77.366	6.129	3.185	87.947	2.455	0.430
13	Young	1	0	0.054	75.663	9.296	11.533	33.816	2.837	0.420
14	Matured	1	0	0.054	75.008	7.854	10.640	20.128	0.416	0.380
15	Young	2	0	0.109	76.570	10.409	4.537	51.714	4.540	0.332
16	Matured	3	0	0.052	75.566	10.555	8.402	22.609	0.612	0.321
17	Young	3	0	0.118	75.747	11.985	4.766	62.253	5.605	0.298
18	Matured	2	0	0.053	75.832	11.927	9.210	22.208	0.658	0.251

TABLE 5: Confirmation of results: actual versus predicted values.

Analysis	Predicted mean	<i>n</i>	95% PI low	Data mean	95% PI high
Thickness (mm)	0.056	5	0.043	0.058	0.069
Solubility (%)	75.076	5	74.377	74.387	75.775
WVTR (g(m ² /h))	6.826	5	5.969	7.370	7.682
Opacity (A/mm)	6	5	4.830	5.373	7.175
Elongation at break (EAB) (%)	123.241	5	109.794	128.932	136.687
Tensile strength (TS) (MPa)	5.818	5	3.722	5.510	7.914

young sugar palm fruits, as well as the interaction between glycerol and CMC in relation to various responses to elongation, are illustrated in Figure 5.

The results presented in Figure 5 show that the edible film based on young sugar palm fruit had lower elongation

values compared to that based on mature sugar palm fruit. This difference is based on XRD analysis from previous studies [15]. Mature sugar palm fruit has a more ordered crystalline structure (66.16%), allowing even stress distribution when the film is stretched. This regularity strengthens

TABLE 6: Contact angle on the surface of edible film from young and mature sugar palm fruit.

Parameter	Edible film from young sugar palm fruit	Edible film from mature sugar palm fruit
Contact angle	72.576 ± 4.655 ^a	109.348 ± 2.609 ^b

Note: Values are presented as the mean ± standard deviation ($n = 3$). Superscripts with different letters indicate significant differences between sample temperatures, as determined by independent t -test ($p \leq 0.05$).

intermolecular interactions (hydrogen bonds and van der Waals forces) that are homogeneously distributed, thereby enhancing resistance to deformation. In contrast, young sugar palm fruit with a semiamorphous structure (49.0%) has irregular amorphous regions, creating weak points that cause stress concentration and premature failure during elongation [15].

Rheological analysis results show that mature sugar palm fruit exhibits Newtonian flow behavior, indicating structural stability and uniform distribution of components (polysaccharides, glycerol, and CMC). This produces homogeneous films without defects, supporting optimal elongation. Conversely, the pseudoplastic behavior of young sugar palm fruit indicates molecular irregularity, causing component agglomeration and film inhomogeneity. These structural imperfections reduce the film's ability to distribute stress evenly, resulting in lower elongation [15].

In mature fruit, glycerol (3%) interacts optimally with the ordered crystalline matrix, softening the amorphous regions without disrupting the integrity of the crystalline domains. This homogeneously enhances the flexibility of the polymer chains. In young fruit, glycerol (2%) cannot fully compensate for the structural irregularities. Its uneven distribution in the amorphous regions reduces its effectiveness in improving elongation.

The differences in the results between mature and young sugar palm fruit were caused by variations in the molecular structure (crystalline vs. semicrystalline) and their responses to CMC and glycerol. Mature sugar palm fruit required a higher glycerol concentration (3%) to achieve optimal flexibility because of its dense structure, whereas young sugar palm fruit only needed 2% glycerol because its structure was naturally more flexible. Furthermore, the addition of 0.25% CMC provided optimal effects for both types of sugar palm fruit, but its interaction with the polymer matrix differed because of variations in the molecular structure. These findings are consistent with the research conducted by [4], who also used sugar palm fruit as a raw material for edible film production.

3.7. Main Factor and Interaction Effects on TS. The differences between edible films made from mature and young sugar palm fruits, as well as the interaction between glycerol and CMC in relation to various responses to TS, are illustrated in Figure 6.

The results presented in Figure 6 demonstrate that films derived from young sugar palm fruit exhibited higher TS than those prepared from mature sugar palm fruit. This finding appears unusual since materials with higher crystal-

linity (such as mature fruit-based films) would typically be expected to show greater mechanical strength. However, this discrepancy can be explained by examining the structural composition of the respective films.

The difference in mechanical strength primarily stems from chemical composition changes occurring during fruit maturation. Although mature fruit-based films possess a more ordered crystalline structure (66.16%), these crystals tend to form large, rigid domains that act as stress concentration points under tensile loading. Conversely, young fruit-based films display lower crystallinity (49.0%) [15] but feature smaller, uniformly distributed crystalline regions within an amorphous matrix. This configuration creates a natural composite structure where the crystalline domains provide reinforcement while the amorphous regions contribute flexibility.

The higher galactose content in young fruit (mannose:galactose ratio of 3:1 vs. 5:1 in mature fruit) [26] induces greater molecular branching. This branching pattern inhibits the formation of excessively large crystalline structures while promoting stronger interpolymer chain entanglement.

The tightly entangled polymer network in young fruit-based films confers superior mechanical strength. During tensile deformation, the applied stress distributes evenly throughout this interconnected network, requiring greater energy to fracture the material.

Furthermore, the combination of sugar palm-based edible films, derived from both young and mature fruits, with CMC and glycerol significantly enhanced the TS. Research conducted by [4], which utilized young sugar palm fruit as the raw material for edible film production, demonstrated that the incorporation of CMC and glycerol improved the mechanical properties, stability, and functionality of films as food packaging materials. Specifically, the formulation containing 0.25% CMC and 1% glycerol yielded the highest TS, which was attributed to the effective interaction between CMC and glycerol in enhancing the structural integrity of the film [28].

Glycerol acted as a plasticizer, reducing the intermolecular forces within the polymer chains, thereby increasing the mobility and flexibility of the film. This plasticizing effect is crucial for achieving the optimal mechanical properties in edible films. However, the study indicated that increasing the glycerol concentration beyond a certain threshold could lead to antiplasticization effects, which reduced the TS of the film. Therefore, the specific combination of 1% glycerol and 0.25% CMC was considered the optimal formulation to maximize TS while maintaining flexibility [23]. The interaction between CMC and glycerol during the film-forming process is also thought to play a significant role in determining the mechanical properties of edible films. It has been suggested that the hydroxyl groups in glycerol could interact with the CMC matrix through hydrogen bonding, which may contribute to the enhancement of the film's TS and structural stability [29]. This proposed synergistic effect could not only improve the mechanical durability of the edible films for food packaging applications but also contribute to maintaining product quality by reducing moisture loss [26].

3.7.1. Optimized Process. In the optimization process, the independent variables were set within specific ranges, and

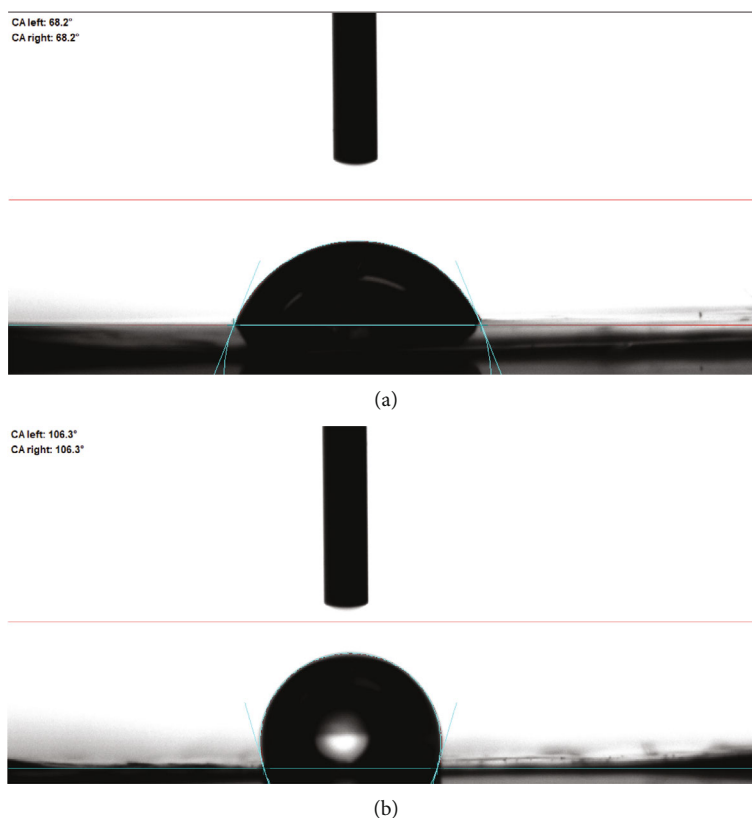


FIGURE 7: Contact angle on the surface of the edible film: (a) young and (b) mature sugar palm fruit.

their importance levels were adjusted to a default value of 3. The objectives for each response were determined based on the research goals presented in Table 3. To obtain edible films with optimal durability, parameters such as thickness, solubility, and WVTR were minimized. This was aimed at ensuring that the produced edible films were not easily soluble and possessed maximum water vapor barrier capacity while maintaining a low thickness. Meanwhile, transparency and TS were set within specific ranges (in the range), while elongation was maximized to enhance the elasticity of edible films. The increase in elongation was aimed at preventing cracking during application. The TS parameter was maintained within a specific range (in range), as the application of edible films did not require excessively rigid properties but required sufficient flexibility to support their function as effective packaging materials.

3.8. Optimized Formula. Eighteen solutions were obtained using the Design-Expert software, as shown in Table 4. The desirability values ranged from zero to one, and the solution with the highest desirability value was selected as the optimal formula. Solution 1 achieves the highest desirability value (0.755). Therefore, the resulting formula, which utilized mature sugar palm fruit combined with 2% glycerol and CMC (0.25 g of CMC), was considered optimal.

3.8.1. Optimum Formula Confirmation. To confirm the optimal formula suggested by DX-13, edible films made from mature sugar palm fruit with 2% (v/v) glycerol and 0.25 g (w/v) CMC were produced five times. The results are pre-

sented in Table 5. The average measurements were then compared with the predicted values from the DX-13, as shown in Table 5. All response data fell within the range of the 95% low prediction interval (PI) and the 95% high PI, indicating that the optimal formula was achieved using the formulation of 2% (v/v) glycerol and 0.25 g (w/v) CMC. This confirmed that the research objectives were successfully met.

3.9. CA of Edible Film Young and Mature Sugar Palm Fruit. CA measurements (θ) were performed to assess the wettability of the edible films. As shown in Table 6 and Figure 7, films from mature fruit exhibited significantly higher CAs than those from young fruit, indicating a clear progression towards greater hydrophobicity with fruit maturity. This divergence in wettability is a direct consequence of the distinct structural compositions at different maturity stages. The semicrystalline structure of young fruit is characterized by a larger amorphous phase, which facilitates water penetration and interaction, leading to the observed lower CAs and higher hydrophilicity [26]. Conversely, the mature fruit-based films possess a higher degree of crystallinity where the tightly packed and ordered molecular structure acts as a barrier, effectively repelling water molecules and resulting in higher CAs and increased hydrophobicity [30, 31].

4. Conclusion

In this study, we developed edible films from both mature and young sugar palm fruits by incorporating CMC and

glycerol. We employed a $2 \times 3 \times 3$ full factorial expert design, comprising three replicates, to determine the optimal formula. The results showed that the addition of glycerol and CMC increased the thickness and elongation of the films but decreased the solubility, opacity, and TS. The addition of glycerol increased the water transmission rate (WVTR), whereas the addition of CMC decreased it. In the hydrophobicity test, measured by CA, the edible film made from mature sugar palm fruit exhibited hydrophobic properties, while the edible film made from young fruit showed hydrophilic properties. The best formula was obtained from edible films made from mature sugar palm fruit with 2% glycerol and 0.25% CMC, which demonstrated good packaging performance.

Data Availability Statement

Data will be made available on request.

Disclosure

All authors participated in editing the article and agreed with the published version of the manuscript.

Conflicts of Interest

The authors declare no conflicts of interest.

Author Contributions

Conceptualization: Eko Hari Purnomo, Yermia, Winiati Pudji Rahayu, Nugraha Edhi Suyatma, and Tjahja Muhandri. Methodology: Eko Hari Purnomo, Yermia, Winiati Pudji Rahayu, Nugraha Edhi Suyatma, and Tjahja Muhandri. Investigation: Yermia. Data curation: Yermia. Formal analysis: Yermia, Winiati Pudji Rahayu, Nugraha Edhi Suyatma, Tjahja Muhandri, and Eko Hari Purnomo. Visualization: Yermia. Resources: Yermia (*Arenga pinnata* fruits), Winiati Pudji Rahayu, Nugraha Edhi Suyatma, Tjahja Muhandri, and Eko Hari Purnomo (laboratory access). Writing—original draft: Yermia. Writing—review and editing: Winiati Pudji Rahayu, Nugraha Edhi Suyatma, Tjahja Muhandri, and Eko Hari Purnomo.

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References

- [1] O. L. Pop, C. R. Pop, M. Dufrechou, et al., "Edible Films and Coatings Functionalization by Probiotic Incorporation: A Review," *Polymers* 12, no. 1 (2020): 12, <https://doi.org/10.3390/polym12010012>.
- [2] A. Kocira, K. Kozłowicz, K. Panasiewicz, M. Staniak, E. Szpunar-Krok, and P. Hortyńska, "Polysaccharides as Edible films and Coatings: Characteristics and Influence on Fruit and Vegetable Quality—A Review," *Agronomy* 11, no. 5 (2021): 813, <https://doi.org/10.3390/agronomy11050813>.
- [3] B. Santoso, "Characterization of Composite Edible Film Derived From Palm Fruit (*Arenga pinnata*) and Beeswax," *Journal of Technology and the Food Industry* 17, no. 2 (2006): 125–135.
- [4] O. M. Sandi, T. Muhandri, and N. E. Suyatma, "Optimization of the Production of Heat Sealable Film From Kolang-Kaling as Packaging Material," *Journal of Food Technology and Industry* 35, no. 1 (2024): 79–91, <https://doi.org/10.6066/jtip.2024.35.1.79>.
- [5] J. B. Tarigan, I. Nainggolan, and J. Kaban, "The Physiochemical and Antibacterial Properties of Galactomannan Edible Film of *Arenga Pinnata* Incorporated With *Zingiber officinale* Essential Oil," *Asian Journal of Pharmaceutical and Clinical Research* 11, no. 12 (2018): 138–142, <https://doi.org/10.22159/ajpcr.2018.v11i12.28061>.
- [6] S. Sitompul and E. Zubaidah, "Effects of Plasticizer Type and Concentration on the Physical Properties of Edible Chicken Dregs Film (*Arenga pinnata*)," *Journal of Food and Agroindustry* 5, no. 1 (2017): 13–25.
- [7] N. Kumar, "Polysaccharide-Based Component and Their Relevance in Edible Film/Coating: A Review," *Nutrition & Food Science* 49, no. 5 (2019): 793–823, <https://doi.org/10.1108/NFS-10-2018-0294>.
- [8] ASTM International, *ASTM D882-02: Standard Test Method for Tensile Properties of Thin Plastic Sheeting* (ASTM International, 2002).
- [9] ASTM International, *ASTM E96-95: Standard Test Methods for Water Vapor Transmission of Materials* (ASTM International, 1995).
- [10] Japanese Standards Association, *JIS Z 1707: General Rules for Plastic Films for Food Packaging* (Japanese Standards Association, 1995).
- [11] N. A. Yanti, S. W. Ahmad, L. O. A. N. Ramadhan, A. Ardiansyah, and I. Indrawati, "Characteristics of Biocellulose-Based Edible Film From Sago Wastewater (*Metroxylon sago* ROTTB.) on Various Glycerol Concentration," *agriTECH* 44, no. 1 (2024): 9–16, <https://doi.org/10.22146/agritech.75154>.
- [12] N. A. Yanti, S. W. Ahmad, O. A. N. Ramadhan, M. Jamili, T. Walhidayah, and J. Mamangkey, "Properties and Application of Edible Modified Bacterial Cellulose Film-Based Sago Liquid Waste as Food Packaging," *Polymers* 13, no. 20 (2021): <https://doi.org/10.3390/polym13203570>.
- [13] W. Warkoyo, A. I. Dzirikika, V. A. Wahyudi, D. D. Siskawardani, and M. Zahoor, "Study of Physical, Mechanical, and Barrier Edible Film Based on Yellow Sweet Potato with Additional Glycerol and Palm Oil," in *E3S Web of Conferences* (EDP Sciences, 2023), <https://doi.org/10.1051/e3sconf/202343200037>.
- [14] R. Rosmawati, S. F. Sari, A. Asnani, et al., "Influence of Sorbitol and Glycerol on Physical and Tensile Properties of Biodegradable-Edible Film From Snakehead Gelatin and κ -Carrageenan," *International Journal of Food Science* 2025 (2025): 7568352, <https://doi.org/10.1155/ijfo/7568352>.
- [15] Y. Yermia, W. P. Rahayu, N. E. Suyatma, T. Muhandri, and E. H. Purnomo, "Rheological Characterization of Sugar Palm Fruits (*Arenga pinnata*) at Different Maturity Levels and Concentrations," *Indonesian Food Science and Technology Journal* 8, no. 1 (2024): 68–77, <https://doi.org/10.22437/iftst.v8i1.37940>.
- [16] Y. Yermia, W. P. Rahayu, N. E. Suyatma, T. Muhandri, and E. H. Purnomo, "Chemical and Thermal Properties of Sugar Palm Fruits (*Arenga pinnata*) at Different Maturity Levels,"

- BIO Web of Conferences* 169 (2025): 01012, <https://doi.org/10.1051/bioconf/202516901012>.
- [17] N. Khazaei, M. Esmaili, Z. E. Djomeh, M. Ghasemlou, and M. Jouki, "Characterization of New Biodegradable Edible Film Made From Basil Seed (*Ocimum basilicum* L.) Gum," *Carbohydrate Polymers* 102, no. 1 (2014): 199–206, <https://doi.org/10.1016/j.carbpol.2013.10.062>.
 - [18] N. E. Suyatma, S. Gunawan, R. Y. Putri, et al., "Active Biohybrid Nanocomposite Films Made from Chitosan, zno Nanoparticles, and Stearic Acid: Optimization Study to Develop Antibacterial Films for Food Packaging Application," *Materials* 16, no. 3 (2023): 926, <https://doi.org/10.3390/ma16030926>.
 - [19] W. A. Asfaw, K. D. Tafa, and N. Satheesh, "Optimization of Citron Peel Pectin and Glycerol Concentration in the Production of Edible Film Using Response Surface Methodology," *Heliyon* 9, no. 3 (2023): e13724, <https://doi.org/10.1016/j.heliyon.2023.e13724>.
 - [20] ASTM International, "ASTM D5946: Standard Test Method for Corona-Treated Polymer Films Using Water Contact Angle Measurements," *Annual Book of ASTM Standards* 08.03 (2017): 1–6, <https://doi.org/10.1520/D5946-17>.
 - [21] D. D. Siskawardani, W. Warkoyo, and A. A. Siwi, "The Effect of Aloe Vera and Glycerol Addition on Edible Film of Lesser Yam Starch (*Dioscorea esculenta* L. Burkill)," 2020: <https://doi.org/10.22219/fths.v3i1>.
 - [22] B. Qoeroti, A. Pangastuti, and A. Susilowati, "Application of Edible Film Incorporated With *Portulaca oleracea* Extract to Inhibit Microbiological and Oxidative Damage in Sausages," *Biodiversitas Journal of Biological Diversity* 22, no. 8 (2021): 3556–3561, <https://doi.org/10.13057/biodiv/d220856>.
 - [23] A. Farahnaky, B. Saberi, and M. Majzoobi, "Effect of Glycerol on Physical and Mechanical Properties of Wheat Starch Edible Films," *Journal of Texture Studies* 44, no. 3 (2013): 176–186, <https://doi.org/10.1111/jtxs.12007>.
 - [24] M. Dick, T. M. H. Costa, A. Gomaa, M. Subirade, A. D. O. Rios, and S. H. Flôres, "Edible Film Production From Chia Seed Mucilage: Effect of Glycerol Concentration on Its Physicochemical and Mechanical Properties," *Carbohydrate Polymers* 130 (2015): 198–205, <https://doi.org/10.1016/j.carbpol.2015.05.040>.
 - [25] M. Atef, M. Rezaei, and R. Behrooz, "Preparation and Characterization Agar-Based Nanocomposite Film Reinforced by Nanocrystalline Cellulose," *International Journal of Biological Macromolecules* 70 (2014): 537–544, <https://doi.org/10.1016/j.ijbiomac.2014.07.013>.
 - [26] M. A. O. Torio, J. Saez, and F. E. Merca, "Physicochemical Characterization of Galactomannan From Sugar Palm (*Arenga saccharifera* Labill.) Endosperm at Different Stages of Nut Maturity," *Philippine Journal of Science* 135 (2006): 19–30.
 - [27] W. Tongdeesoontorn, L. J. Mauer, S. Wongruong, P. Sriburi, and P. Rachtanapun, "Effect of Carboxymethyl Cellulose Concentration on Physical Properties of Biodegradable Cassava Starch-Based Films," *Chemistry Central Journal* 5, no. 1 (2011): 6, <https://doi.org/10.1186/1752-153X-5-6>.
 - [28] V. Venditto, M. Pellegrino, R. Califano, et al., "Monolithic Polymeric Aerogels With VOCs Sorbent Nanoporous Crystalline and Water Sorbent Amorphous Phases," *ACS Applied Materials & Interfaces* 7, no. 2 (2015): 1318–1326, <https://doi.org/10.1021/am507116e>.
 - [29] J. S. Yaradoddi, N. R. Banapurmath, S. V. Ganachari, et al., "Biodegradable Carboxymethyl Cellulose Based Material for Sustainable Packaging Application," *Scientific Reports* 10, no. 1 (2020): 21960, <https://doi.org/10.1038/s41598-020-78912-z>.
 - [30] A. Sedighiamiri, L. E. Govaert, M. J. W. Kanters, and J. A. W. Van Dommelen, "Micromechanics of Semicrystalline Polymers: Yield Kinetics and Long-Term Failure," *Journal of Polymer Science Part B: Polymer Physics* 50, no. 24 (2012): 1664–1679, <https://doi.org/10.1002/polb.23136>.
 - [31] T. Fujie, Y. Kawamoto, H. Haniuda, et al., "Selective Molecular Permeability Induced by Glass Transition Dynamics of Semicrystalline Polymer Ultrathin Films," *Macromolecules* 46, no. 2 (2013): 395–402, <https://doi.org/10.1021/ma302081e>.