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Effect of Temperature Treatment on the Mechanical Properties of Bioplastics Edible Film Seaweed Gracilaria SPP (DOI:10.54380/IJRDET0426_160)

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Abstract - *This study examines the effect of temperature treatment on the mechanical properties of seaweed-based edible film Gracilaria Spp. Combined with glycerol as a plasticizer and chitosan as a structural strengthener. The film was prepared from 10 g of seaweed, 80 mL of aqua, 5 mL of vinegar, 1 mL of glycerin, and 10 mL of chitosan, then tested under two treatment conditions. room temperature and high temperature (80-100°C). Mechanical properties testing was carried out using ASTM D638-V standards including tensile strength, elongation at break, and elastic modulus. The results showed a very large increase in all mechanical parameters due to high temperature treatment. The average tensile strength increased from 0.142 N/mm² (room temperature) to 26.542 N/mm² (temperature 80-100°C), representing an increase of approximately 187 times. The average modulus of elasticity also increased from 0.417 to 45.766 N/mm², while the average strain increased from 0.372 to 0.667. The high-temperature treatment led to the formation of tighter cross-bonds between polymer chains as well as substantial homogenization of the film matrix. All formulations in the high-temperature treatment met the minimum tensile strength standard of JIS Z 1707 (0.392 MPa), while the average elongation value (66.7%) was close to the minimum limit of 70%. These findings confirm the potential of Gracilaria spp.-based bioplastics as a sustainable eco-friendly packaging alternative.*

Keywords - *Bioplastics. Edible Film. Gracilaria spp, Mechanical Properties. Temperature Treatment. Chitosan. Glycerol.*

I. INTRODUCTION

The problem of synthetic plastic waste has put the world at an environmental crisis point that requires a serious scientific and policy response.

Global data shows that more than 380 million tons of plastic are produced each year, and only about 9% are successfully recycled [1],[2]. Indonesia itself is recorded as one of the largest contributors of plastic waste to the ocean, with an estimated reach of 0.48-1.29 million tons per year [3],[4]. This problem is increasingly complex considering that synthetic polymer materials such as polyethylene (PE), polypropylene (PP), and polyethylene terephthalate (PET) require a natural degradation time of up to hundreds of years, so their accumulation in aquatic and terrestrial ecosystems continues to increase exponentially [5],[6],[7].

In response to these challenges, the development of biodegradable materials based on biological resources, especially from marine organisms, which has become a research arena has grown rapidly in the last decade [8],[9]. One of the most promising candidates is edible film or bioplastic based on seaweed polysaccharides, which naturally have the ability to form a film matrix through the gelatin process [10],[11]. Seaweed of the genus Gracilaria spp, belongs to the division of Rhodophyta (red algae), which is known as one of the main sources that contain high amounts of gelatinous polysaccharides reaching 20-40% dry weight which serves as a polymer forming film matrix. Its abundant availability in Indonesia's tropical waters makes it an economically competitive strategic raw material [12],[13].

However, pure hydrocolloid-based films often have suboptimal mechanical properties, especially in terms of tensile strength and flexibility to compete directly with conventional plastics as packaging materials [14],[15].

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To overcome these limitations, the addition of plasticizers such as glycerol or sorbitol has been shown to reduce film brittleness by lowering the glass transition temperature (Tg) of the polymer matrix, while the addition of polycationic and semi-hydrophobic chitosan can strengthen the cross-links between polymer chains and increase the film's resistance to the penetration of water vapor and microorganisms [16]. In addition to chemical modifications, the conditions of the thermal process during film fabrication are also known to have a very significant influence on the final quality of the matrix, although this aspect is relatively underappreciated in the available literature [5],[17],[2].

This study focuses on exploring the effect of temperature treatment, room temperature as a control and high temperature 80-100°C as an experimental treatment of the mechanical properties-of Gracilaria spp-based edible film, which is strengthened with chitosan and glycerol. The mechanical parameters studied include maximum tensile strength, strain at breaking point, and modulus of elasticity. Through systematic and comparative analysis, this study is expected to make a concrete scientific contribution in an effort to develop marine resource-based bioplastics that meet technical feasibility standards as well as be environmentally friendly.

II. RESEARCH METHODS

A. Film Material and Composition

The edible film in this study was fabricated using a basic formula consisting of: 10 g dried Gracilaria spp seaweed, 80 mL of aquaade, 5 mL of vinegar solution (acetic acid), 1 mL of glycerin as a plasticizer, and 10 mL of chitosan solution as a structural strengthener. Glycerol doubles as a plasticizing agent that reduces the brittleness of the film by inserting between the gelatinous polymer chains, thereby reducing the density of intermolecular bonds. Chitosan is added to strengthen the polymer matrix network through electrostatic interactions between the protonation amino group ($-NH_3^+$) of chitosan and the negatively charged sulfate group on the gelatinous polymer.

Figure 1. Preparation Process of Glacilaria Spp into Bioplastics up to Testing Stage

B. Filming Procedure

The dried seaweed is cleaned and soaked in aqueducts for 1-2 hours for rehydration, then rinsed to remove impurities and surface salts. The rehydrated sample is then homogenized using a blender until a uniform porridge texture is obtained. The seaweed suspension is heated to 70-80°C for 30 minutes on a hot plate with continuous magnetic stirring to extract the gelatinous polysaccharides into the solution. The filtrate obtained from filtering with a strimin cloth is then mixed with a solution of chitosan and glycerol, stirred until homogeneous, and poured into a flat mold.

The film is printed to a thickness of 2 mm and dried. Two groups of treatments are applied:

- Room temperature (±27°C) as control.
- Temperature 80-100°C in an air circulation oven.

C. Mechanical Properties Testing

The mechanical properties of the film were tested using the ASTM D638-V standard procedure. Specimens were cut with dimensions of 2.54 x 12 cm with a thickness of 2 mm. The crosshead speed was set at 50 mm/min with an initial gauge length of 50 mm. From each treatment group four specimens were prepared (n= 4).

The measured parameters included: (1) maximum tensile strength (σ max, N/mm²). (2) strain at break point (ε). and (3) modulus of elasticity (E, N/mm²) calculated as the slope of the stress-strain curve in the initial elastic linear region.

1. Tensile Strength

Tensile strength is the maximum stress that a material is able to withstand when subjected to tensile force until it fails, while elongation at breaking describes the degree of flexibility of the material expressed as a percentage change in length to initial length. In this study, tests were performed on four independent specimens (n = 4) to ensure the reproducibility of the results. The calculation of tensile strength and elongation at breaking was carried out mathematically based on methods commonly used in the scientific literature, with the following equations. [18], [19], [20].[21].

$$\sigma \frac{F_{max}}{A} \quad (1)$$

2. Stretch/Elongation

Where σ shows tensile strength (MPa), Fmax is the maximum accepted tensile force of the material (N), and A is the initial cross-sectional area of the specimen (mm²). Meanwhile, the elongation value at breaking (ε) can be calculated mathematically using the corresponding equation

$$\varepsilon \frac{\Delta L}{L_0} \times 100\% \quad (2)$$

3. Modulus of Elasticity

Where ΔL is the change in the length of the specimen and L_0 is the initial length. The Young modulus (E) is used to describe the degree of stiffness of the material, i.e. the ratio between tensile stress (σ) and tensile strain (ε), which is calculated using the corresponding equation.

$$E \frac{\varepsilon}{\sigma} \times 100\% \quad (3)$$

III. RESULTS AND DISCUSSION

A. Data on the Mechanical Properties of the Film at Both Treatment Conditions

Complete data on the mechanical properties of all specimens under both temperature treatment conditions are presented in Table 1. The striking differences between the two treatment groups are seen directly from the range of values that do not overlap at all. The overall tensile strength values of high-temperature specimens (22.867-31.033 N/mm²) far exceed the highest values at room temperature (0.245 N/mm²), which is statistically descriptive enough to conclude that there is a very substantial effect of temperature treatment.

Figure 2. Spesimen Bioplastik Gracilaria Spp

Table 1. Data on Mechanical Properties of Gracilaria Spp. Edible Film at Room Temperature and Temperature Conditions (80-100°C)

Treatment	Spesimen	Tensile Strength (N/mm²)		Strenghth ε		Modulus of Elasticity (N/mm²)	
		Max	Average	Max	Average	For Spending	Average
Room Temperature	1	0,245	0,142	0,444	0,372	0,913	0,417
	2	0,151		0,311		0,346	
	3	0,109		0,422		0,221	
	4	0,064		0,311		0,188	
Temperature 80–100°C	1	27,767	26,542	0,956	0,667	25,997	45,766
	2	24,500		0,511		54,484	
	3	22,867		0,600		47,444	
	4	31,033		0,600		55,141	

B. Strong Analysis of Film Pull

Figure 3 presents a visualization of the tensile strength of each specimen in both treatment groups, along with the average values of each group.

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The graph clearly illustrates the enormous gap between the two treatment conditions, so much so that the room temperature data is almost invisible when depicted in the same Y-axis as the high-temperature data.

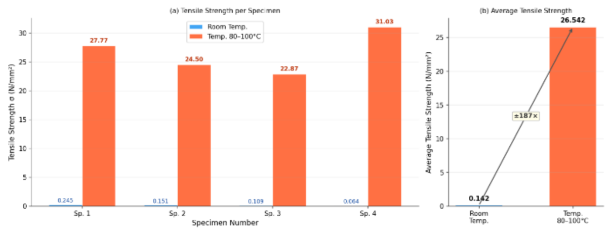

Figure 3. Tensile Strength of Gracilaria spp. Film Edible at Room Temperature and High Temperature Conditions (80-100°C). (a) Value per specimen, (b) Average value of the group with the increase ratio.

From Figure 3. (a) it can be seen that in the room temperature treatment, the individual tensile strength values ranged from 0.064 to 0.245 N/mm², with specimen 1 showing the highest value and specimen 4 showing the lowest. This variability reflects the heterogeneity of the distribution of components in the film matrix formed under low thermal conditions. In contrast, at temperature treatment of 80-100°C, all specimens showed a much higher tensile strength value with a range of 22.867-31.033 N/mm², and specimen 4 being the highest. On average (Figure 1 (b)), the high-temperature treatment yielded a tensile strength of 26,542 N/mm² compared to only 0.142 N/mm² at room temperature an increase of about 187 times represented by the arrow on the graph.

This dramatic increase can be explained by the physicochemical mechanism of the gelatinous polymer. At temperatures of 80-100°C, the agarose chains in the matrix undergo a much more perfect process, the agarose molecules form a more orderly and tightly arranged double helix through intensive intermolecular hydrogen bonding. This process results in a highly cohesive three-dimensional network (gel network), in contrast to the amorphous structures that form at room temperature. On the other hand, chitosan that is protonated at an acidic pH (due to the addition of vinegar) interacts electrostatically with the negative carboxyl/sulfate group of the gelatin, forming an interpolymer complex that is further strengthened by thermal energy. These results are consistent with the findings [16]. Which reported a significant increase in carrageenan-glycerol tensile strength at higher processing temperatures.

C. Regangan (Elongasi) Film Analysis

Figure 4 shows the strain value of each specimen compared between the two treatment conditions, accompanied by the JIS Z 1707 standard reference line which specifies an elongation of at least 70% (ε = 0.70) as a condition for the feasibility of the packaging film.

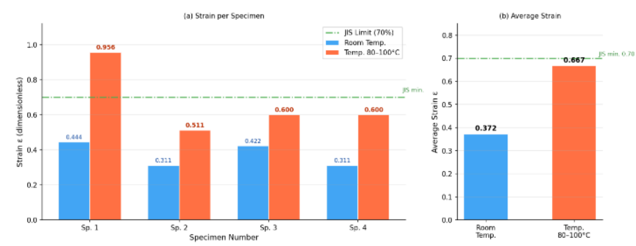

Figure 4. Stretch (Elongation) of Edible Film Gracilaria spp. at Room Temperature and High Temperature Conditions (80-100°C). (a) Value per specimen with JIS boundary line (b) Group average value.

From the graph, it can be seen that the increase in strain due to high temperature treatment is more moderate than the tensile strength. The average strain value increased from 0.372 (room temperature) to 0.667 (high temperature), or about 79%. An interesting pattern was seen in specimen 1 of the high temperature treatment which reached a maximum strain of 0.956 close to one time the length of the original specimen and was the only specimen to exceed the JIS limit of 0.70. On average for the group, the strain value at high temperatures (0.667) was still slightly below the JIS threshold.

Mechanically, the phenomenon of increased elongation along with the increase in tensile strength at high temperature treatment appears to be at odds with the classic trade-off of strength-tenacity (strength ductility trade off). However, this can be explained through the theory of stress redistribution in polymer tissues. At room temperature, heterogeneous and weak film matrices tend to experience local failure at the highest concentration stress points, resulting in premature rupture at smaller strains.

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In contrast, thermally consolidated matrices have a better stress redistribution capacity because the bond network is more evenly distributed, so the film is able to undergo greater deformation before final failure. These findings are in line with the principles of fracture mechanics in polymer materials put forward by Widodo, n.d. [22].

D. Modulus Analysis of Film Elasticity

Figure 5 shows the modulus values of elasticity per specimen and the group average. The modulus of elasticity represents the rigidity of the material the higher the value, the greater the stress required to produce the unit strain in the elastic domain.

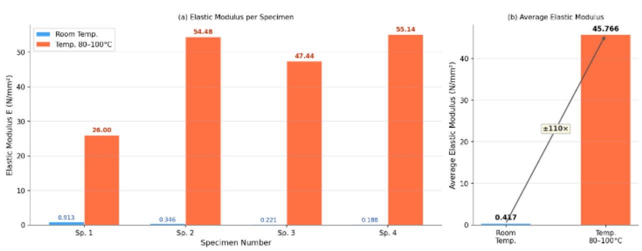

Figure 5. Modulus of Elasticity of Edible Film Gracilaria spp. at Room Temperature and High Temperature Conditions (80-100°C). (a) Value per specimen, (b) Average value of the group with the increase ratio.

The average modulus of elasticity increased from 0.417 N/mm² at room temperature to 45.766 N/mm² at 80-100°C. The increase was about 110 times. From Figure 5 (a) it can be seen that there was considerable variation between specimens at high temperature treatment (25.997-55.141 N/mm²), with specimens 2 and 4 showing the highest values. The interesting thing is that the order of modulus of elasticity does not always align with the order of tensile strength. Specimen 4 has the highest tensile strength (31.033 N/mm²) but not the highest modulus, while specimen 2 has the highest modulus (54.484 N/mm²) but the tensile strength is lower.

This partial inconsistency scientifically reflects the differences in the shape of the stress-strain curve between specimens - particularly at the initial slope of the curve (elastic domain) versus the fracture boundary. Specimens with high modulus have a steeper curve at the beginning (rigid in the elastic stage), but that does not mean that it is able to withstand greater stresses before breaking. This phenomenon is consistent with observations [8],[23] In the bioplastic Kappaphycus alvarezii, where variations in reinforcing concentrations disproportionately affect the slope of the elastic curve and fracture boundaries. A very significant increase in modulus of elasticity due to thermal treatment indicates that Gracilaria spp.-based films processed at high temperatures have structural rigidity relevant to food packaging applications that require protection against mechanical deformation.

E. Tension-strain Curve Analysis (σ–ε)

Figure 6 presents a reconstructed stress-strain curve based on the mechanical data points of the entire specimen under both treatment conditions. This curve provides a comprehensive picture of the material's behavior across the entire deformation range, from initial elastic deformation to breaking point

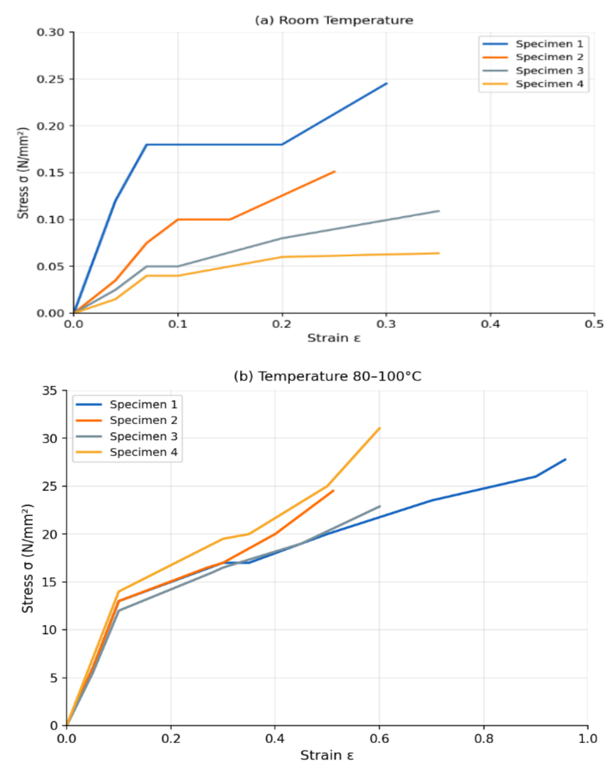

Figure 6. Tension-Strain Curve (σ-ε) Edible Film Gracilaria spp. (a) Room Temperature (b) Temperature (80-100°C). X-Axis. Strain ε. Y-Axis. Tension σ (N/mm²).

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From Figure 6 (a), the room temperature curve shows a very low stress pattern (maximum 0.245 N/mm²) with a behavior that tends to plasticize the curve relatively flat after passing the initial yield point. This is typical for hydrocolloid materials with low cross-bond density, where polymer chains can flow relatively freely against each other after the weak bond is broken. In contrast, the high-temperature curve in Figure 6 (b) shows a much different profile: the tension increases progressively and step-wise as the strain increases, with a maximum value of 31.033 N/mm². This step-wise pattern reflects a gradual strengthening mechanism, with each step on the curve representing a succession of weak bonds breaking, followed by load redistribution to the stronger bonds in the network, before a complete failure. This pattern was also reported by Fardhyanti and Julianur (2015) on carrageenan film processed at high temperatures. [24], [25].

F. Comprehensive Comparison of All Mechanical Parameters

Figure 7 presents a comprehensive visual summary of all the mechanical parameters studied, using two parallel representations. Logarithmic scale bar graphs to display actual values proportionally, and normalized radar graphs to visualize the relative mechanical profiles between treatments.

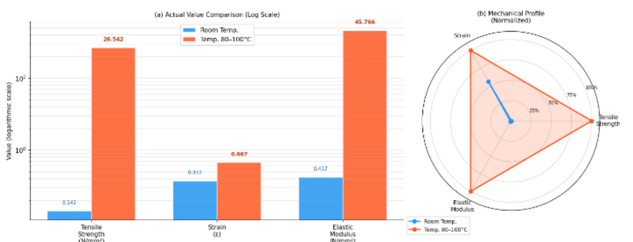

Figure 7. Comprehensive Comparison of Edible Properties of Gracilaria spp. (a) Actual value of logarithmic scale, (b) Normalized mechanical profile to maximum value per parameter.

From Figure 7 (a) The logarithmic scale is used because the difference in values between treatments is so large (up to 187 times for tensile strength) that it cannot be visualized informatively on a linear scale.

This graph intuitively shows the superiority of the high-temperature treatment on all three parameters simultaneously. Figure 7 (b) emphasizes this through radar graphs, the area covered by the red polygon (high temperature) is much larger than the blue polygon (room temperature), and the room temperature only reaches about 0.5-1.0% of the maximum value on the tensile strength and modulus of elasticity parameters. The only parameter where the relative difference is smaller is strain, where the room temperature reaches about 56% of the high temperature value confirms that the elongation response to temperature treatment is more moderate than the strength and stiffness response.

G. Conformity with Bioplastic Standards and Comparison with Previous Research

Based on the JIS Z 1707 standard, all specimens under high temperature treatment met the minimum tensile strength limit of 0.392 MPa by a very large margin. The mean elongation value in high temperature treatment (66.7%) approached but did not fully meet the minimum standard of 70% of JIS, although specimen 1 individually exceeded that standard (95.6%). Compared to the literature, the average tensile strength of 26.542 N/mm² in this study exceeded the reported value (Chalermthai et al., 2024; Naghera et al., 2025; Rusli et al., 2017) for edible carrageenan-glycerol film (14.03-21.55 N/mm²), as well as results and Julianur (2015) for carrageenan film Eucheuma cottonii (11.09-18.34 N/mm²). The contribution of chitosan as a structural reinforcer and the synergistic effect of thermal treatment were significant differentiating factors. In terms of elongation, the highest values in this study (95.6%) exceeded the reported range [8],[26]. for the bioplastic Kappaphycus alvarezii (28-62%), indicates that thermally processed chitosan gelatinous matrix has a dual advantage. superior tensile strength as well as competitive elongation.

IV. CONCLUSION

This study has empirically proven that temperature treatment exerts a very dominant and multidimensional influence on the mechanical properties of Gracilaria spp.-based edible films-reinforced with chitosan and glycerol.

Temperature treatment of 80-100°C increased the average tensile strength by 187 times (from 0.142 to 26.542 N/mm²), increased the average modulus of elasticity by more than 110 times (from 0.417 to 45.766 N/mm²), and increased the average strain by 79% (from 0.372 to 0.667). This increase is likely related to the formation of tighter polymer networks due to thermal treatment, which allows for stronger interactions between thermally strengthened agar, chitosan, and glycerol, and matrix consolidation due to partial evaporation of solvents. All specimens at high temperature treatment met the minimum tensile strength standard of JIS Z 1707, while the average elongation value (66.7%) almost met the 70% threshold. These findings confirm that thermal treatment is a technical prerequisite and not just optimization to produce Gracilaria spp.-based bioplastics that are viable as an environmentally friendly packaging alternative. However, the applicability of this film still needs to be validated through testing for moisture permeability, biodegradability, thermal stability, and food contact safety.

V. ADVICE

Plasticizer concentration optimization using the Response Surface Methodology approach needs to be performed to ensure that all specimens consistently meet JIS elongation standards. Testing of water vapor permeability (WVP), transparency, and film biodegradability under real environmental conditions is required as a validation of application feasibility. A scale-up study of fabrication processes is also important to assess energy efficiency at thermal treatment and quality consistency at larger production volumes Further research is also recommended to use variations in glycerol and chitosan concentrations to achieve a balance between tensile strength and elongation, given that the average elongation value in high-temperature treatment is still slightly below the JIS Z 1707 standard.

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