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BIOPLASTICS MADE FROM STARCH FROM SAGO WASTE (METROXYLON SAGOO) WITH GLYCEROL VARIATION USING MELT INTERCALATION METHOD

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ABSTRACT

Sago waste, known locally in Maluku as ela sagu has great potential as a natural material for making bioplastics. This study aims to examine and analyse the effects of variations in glycerol volume on the physical and biological qualities of bioplastics made from sago waste through laboratory experiments. The process begins with the extraction of starch from sago waste, followed by bioplastic production, and concludes with tests for thickness, tensile strength, elongation at break, Young's modulus, water absorption, and degradation ability. The results reveal that variations in glycerol volume significantly affect the quality of the bioplastics (Sig. value < 0.05). P1 (1 ml of glycerol) demonstrates the best performance in terms of thickness (0.137 mm), elongation (13.367%), and Young's modulus (0.146 MPa). Notably, P1 is the best choice for applications requiring light thickness, high flexibility, and elasticity. Meanwhile, P4 (4 ml of glycerol) has the best water resistance (53.333%), although its tensile strength and Young's modulus are higher than the standard, making P4 more suitable for applications that require water resistance. Note that all treatments were 100% degraded within seven days, indicating that this bioplastic is highly environmentally friendly and meets the biodegradability criteria. Overall, this suggests that bioplastics derived from sago waste can be further developed into environmentally friendly alternatives.

Introduction

Plastic is a type of waste that is highly resistant to natural decomposition. Globally, plastic takes between 100 years and 500 years to fully degrade, depending on its type. Each year, approximately 430 million tonnes of plastic are produced, with two-thirds of it being used only once. Consequently, this significantly contributes to the growing issue of plastic pollution. Of this amount, around 350 million tons of plastic waste are generated each year and only 9% of it is successfully recycled (Silolongan & Apriyono, 2019). Meanwhile, the remaining 70% of plastic waste is not properly collected and pollutes the environment, including the oceans, which become the largest repository of plastic waste (Utami & Ningrum, 2020).

In response to this problem, countries worldwide are working to reduce plastic use, especially single-use plastics. Various efforts and innovations have been made to reduce the impact of plastic waste, in addition to the recycling process such as producing environmentally friendly plastics using raw materials from plant residues. This makes it easier for microorganisms to decompose in a relatively short period. Remarkably, bioplastics can be renewed and easily degraded since they are composed of polysaccharides (such as starch, cellulose, and chitin), proteins (including casein, whey, and collagen), and fats from animal sources (Hayati *et al*., 2020).

Previous research has developed bioplastics from various starches found in plants. This includes the use of taro tuber starch as a raw material for bioplastic production (Sinaga *et al*., 2014), the production of corn starch-based bioplastics with the addition of chitosan and glycerol (Coniwanti *et al*., 2014), bioplastics made from starch from various type of tubers (Nisah, 2017), bioplastics made from durian seed starch and cassava starch with MCC filler from cocoa peel (Nur *et al*., 2020) and bioplastics made from cassava starch and carrageenan with variations in gelatinisation duration and plasticiser type (Dewi *et al*., 2023). However, the use of these natural materials is less effective, despite their high starch content, since they are still used by society as staple foods. Therefore, bioplastic development requires natural materials containing starch that are not utilised as food ingredients.

One material currently being researched is sago waste, which is rich in starch and has great potential as a raw material for bioplastics. Sago waste is known as *ela sagu* in Maluku. *Ela sagu* is the pulp residue in the form of hard fibres obtained from the grating and pressing of sago stems into flour. In the sago processing process, the bark waste accounts for approximately 17% to 25% while the sago pulp accounts for about 75% to 78%, with a very high starch content. In particular, the high fibre content of sago makes it a promising material for developing bioplastics. Since bioplastics made from starch tend to be rigid and brittle, reinforcements and plasticisers are needed. A plasticiser is an additive material that increases the flexibility and durability of a material (Utami *et al*., 2014; Sismaini *et al*., 2022).

The plasticiser commonly utilised in bioplastic production is glycerol, while chitosan is used as a reinforcing material. The use of these two materials offers advantageous properties such as antibacterial, biocompatibility, biodegradability, and hydrophilicity (Coniwanti *et al*., 2014; Fatnasari *et al*., 2018). Accordingly, the quality of bioplastics can be assessed based on their mechanical properties, which are influenced by several factors. This includes the concentration of dissolved solids in the film solution, temperature, the addition of plasticisers, and the type of polymer. The plasticiser used is glycerol, which is flexible and reduces rigidity. With the right variations, bioplastics can be employed as conventional packaging plastics with similar advantages. However, they will break down and degrade through the activity of microorganisms.

The melt intercalation method is selected in the production of bioplastics due to its several advantages that support production efficiency and material quality. This process involves mixing polymer materials with fillers at high temperatures, resulting in composites with improved mechanical and thermal properties. One of the main benefits of this method is its simplicity and cost-efficiency, as it does not require solvents or complex drying processes (Lee *et al*., 2020). This method also enables bioplastic production at a lower cost compared to other methods such as solvent casting.

Furthermore, melt intercalation enhances the physical properties of bioplastics, including tensile strength and resistance to deformation. Following this, the addition of fillers such as nanoparticles or glycerol can reinforce the bioplastic structure and improve its thermal stability (Zhang *et al*., 2019). This makes bioplastics stronger and more durable, rendering them suitable for various industrial applications. This method also supports sustainability by utilising renewable materials such as starch or organic waste, reducing dependence on petroleum-based plastics that are difficult to degrade (Reddy *et al*., 2017). Additionally, it enables the utilisation of organic waste such as sago waste, which has significant potential as a bioplastic feedstock. Thus, melt intercalation becomes an environmentally friendly and cost-effective choice in the development of bioplastics.

Materials and Methods

This study employed a quantitative experimental laboratory design, in which sago starch-based bioplastics were produced with varying glycerol concentrations and evaluated for physical and biological properties. The independent variable was glycerol volume, with treatments: P1 (1 mL), P2 (2 mL), P3 (3 mL), and P4 (4 mL). The dependent variables were bioplastic properties: Thickness, tensile strength, elongation, Young's modulus, water absorption, and biodegradation rate. Raw material preparation: Sago waste (*ela sagu*) was collected from traditional sago processing factories in Tulehu Village, Central Maluku, Indonesia. The waste was washed, dried at 35°C for three days, ground, and sieved (120 mesh) to obtain fine powder. Following this, the powder was soaked in water for 24 hours to facilitate sedimentation, after which the supernatant was discarded. Subsequently, the sediment was oven-dried at 40°C for 60 minutes, ground again, and stored as starch.

Bioplastic fabrication: Bioplastics were prepared using the melt intercalation method with solvent evaporation. For each treatment, 2.5 g of chitosan was dissolved in glycerol (1-4 mL), 50 mL of distilled water, and 1.5 mL of 3% acetic acid. Then, 5 g of sago starch was added and the mixture was heated at 60°C with constant stirring for 30 minutes. The hot mixture was cooled for 3 minutes, poured into glass moulds, and dried at 30°C for 9 hours. Dried films were carefully removed for testing.

The physical and biological characterisation was conducted to assess the quality of the produced bioplastics. Thickness was measured at four points using a micrometre screw with a precision of 0.01 mm and the average value was recorded. Meanwhile, mechanical properties, including tensile strength, elongation at break, and Young's modulus were measured using a Universal Testing Machine, following ASTM E8-13a and ASTM D882-12 standards. At the same time, water absorption was assessed by performing a swelling test, where the samples were immersed in distilled water at room temperature and the percentage weight gain was calculated based on the change in sample weight after swelling.

For biodegradation, bioplastics (1 × 1 cm) were weighed, buried in soil at a depth of 2 cm, and reweighed after seven days, according to ASTM D6002 standards. Each treatment was replicated three times (n = 12 per parameter), with tests performed in triplicate. The collected data were analysed using one-way Analysis of Variance (ANOVA) ($p < 0.05$), followed by Tukey's Honest Significant Difference (HSD) test using Statistical Package of Social Sciences (SPSS) version 22. Comparative reference values were obtained from JIS-Z-1707 (Nor *et al.*, 2020), SNI 7818:2014 (Nurhayati *et al.*, 2019), ASTM E8-13a, ASTM D882-12 (Ayu *et al.*, 2023), and ASTM D-6002 (Prima & Hesmita, 2015), as summarised in Table 1.

Table 1: Plastic quality standards

Characteristics	Standard	Value
Thickness (mm)	JIS-Z-1707	≤ 0.25
Tensile strength (MPa)	ASTM E8-13a	1.35-2.32
Elongation (%)	ASTM D882-12	≥ 10
Young's modulus (MPa)	JIS-Z-1707	≥ 0.35
Water resistance (%)	SNI 7818:2014	≥ 99
Biodegradation (day's)	ASTM D-6002	60

Results and Discussion

Bioplastic Synthesis

Biodegradable plastic is a type of environmentally friendly plastic whose components are derived from nature and can be renewed and easily decomposed in a relatively short time by soil microorganisms. The basic material used in the study was sago waste (*ela sagu*) with glycerol variation (1 ml, 2 ml, 3 ml, 4 ml). The morphology of bioplastics from each treatment is illustrated in Figure 1.

Figure 1 illustrates that the bioplastics derived from each treatment exhibit a uniform colour, which is blackish brown. This is attributed to the consistent main ingredient, namely starch derived from sago waste. Note that the utilisation of glycerol volume variation does not significantly impact the colour gradation observed in each treatment, as the disparity in treatment range is not substantial. Furthermore, the bioplastics derived from each treatment exhibit a rather rough texture, with an uneven surface and a transparent appearance on the opposite side. In addition, the bioplastics produced in the P1 treatment exhibited a greater degree of stiffness while those produced in P2, P3, and P4 were more flexible and exhibited a degree of stickiness.

Environmentally friendly plastic is a type of plastic whose constituent components originate from natural sources and are readily renewable, with the potential for degradation by microorganisms in a relatively short period. The primary material under investigation is sago waste, also known in the local Maluku language as *ela sagu*. *Ela sagu* is derived from the processing of sago stems into flour, which is sourced from Tulehu village in Central Maluku Regency. Sago waste is initially cleaned to separate dirt and fibres. Accordingly, the waste is dried for three days in direct sunlight to reduce the water content. After drying, the material is mashed using a blender and the resulting powder is soaked in water for 5 hours. The resulting starch sediment is then dried again.

All bioplastic sheets produced exhibited a rough, uneven texture on one side and a smooth, evenly textured surface on the other. This difference in texture is attributed to the moulding process, whereby one side is in direct contact with the air and the other is not (Krisnadi *et al.*, 2019). In particular, the surface of the bioplastic in direct contact with the air has a rougher texture than the surface not in contact with the air. This is due to the fact that during the drying process, the solids that are left behind make the plastic rough. Moreover, the bioplastics produced from each treatment have a blackish brown colour and are clear and transparent. They also have a slightly sour aroma that is caused by the use of acetic acid as a chitosan diluent.

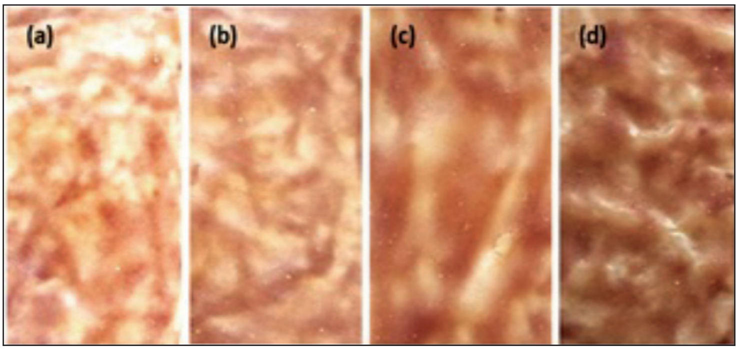

Figure 1: (a) Bioplastics with the addition of 1 ml glycerol, (b) bioplastics with the addition of 2 ml glycerol, (c) bioplastics with the addition of 3 ml glycerol, and (d) bioplastics with the addition of 4 ml glycerol

The synthesised bioplastics were then subjected to a series of tests, including assessments of their thickness, elongation, tensile strength, elasticity, water absorption, and biodegradability. The objective of this test was to determine the optimal mass ratio of *ela sagu* starch to glycerol, which would result in the production of bioplastics with the most desirable characteristics. The test results are described in the following section.

Thickness of Bioplastics

A thickness test was conducted to determine the thickness of bioplastics after drying from the glass plate mould. The thickness of the bioplastic was measured by measuring four parts of the bioplastic film using a screw micrometre. The significance value for the homogeneity test is 0.054 > 0.05, indicating that the variability (dispersion) in each of the compared groups is similar or homogeneous.

Similarly, the significance value for the normality test is 0.085 > 0.05, indicating that the data follows a normal distribution, allowing for further analysis (ANOVA). In line with this, the ANOVA test results reveal a significance value of 0.020 < 0.05, indicating a significant effect of glycerol volume variation on the thickness of the bioplastics. Conversely, the Tukey's HSD test results suggest that there is no significant difference between P1, P2, and P3 while P1 and P4 differ significantly. Essentially, P1 has the lowest thickness (0.137 mm) while P4 has the highest thickness (0.207 mm), with all treatments featuring bioplastics that meet the standard of ≤ 0.25 mm (JIS-Z-1707).

One of the key parameters influencing the quality of bioplastics in the production of packaging products is thickness (Aripin *et al*., 2017). Note that the thickness of bioplastics produced through each treatment varies due to the manual moulding process on glass plates, which utilises basic equipment. Furthermore, it is postulated that the gelatinisation of sago waste starch results in a thickened, sticky consistency, which, in turn, affects the pressure applied during moulding and consequently the thickness of each bioplastics produced.

Table 2: Homogeneity test, normality, ANOVA, and Tukey's HSD

Parameter	**Test of Homogeneity**	**Tests of Normality**	**ANOVA**	**HSD Tukey's Treatment**				**Standard**
				P1	**P2**	**P3**	**P4**	
Thickness	0.054	0.085	0.020	0.137^{a}	0.157^{ab}	0.160^{ab}	0.207^{b}	≤ 0.25 mm (JIS-Z-1707)
Tensile strength	0.087	0.138	0.030	1.858^{a}	3.025^{a}	3.561^{a}	7.302^{b}	1.35-2.32 MPa (ASTM E8-13a)
Elongation	0.054	0.200	0.000	13.367^{a}	11.095^{ab}	9.383^{b}	6.170^{c}	≥ 10% (ASTM D882-12)
Young's modulus	0.087	0.052	0.002	0.146^{a}	0.304^{a}	0.381^{a}	1.190^{b}	0.35 MPa (JIS-2-1707)
Water absorption	0.226	0.200	0.000	211.000^{a}	175.667^{b}	128.333^{c}	53.333^{d}	≥ 99% (SNI 7818:2014)
Biodegradation	-	-	-	100	100	100	100	60 Days Decomposed 100% (ASTM-D-6002)

Explanation:

1. If the Sig. value > 0.05, the data is homogeneous and normally distributed.
2. If the Sig. value < 0.05, there is a significant effect of the treatment on the parameter (ANOVA).
3. Numbers followed by different letters in Tukey's HSD indicate a significant difference.

Additionally, the thickness of bioplastics is also influenced by the amount of soluble solids, despite the use of a mould of the same size. The thickness of bioplastics is expected to increase in conjunction with the increase in the amount of soluble solids resulting from the addition of varying volumes of glycerol (Ikhsan *et al*., 2021). That is, the higher the volume of glycerol added, the higher the amount of soluble solids will be, which affects the thickness of bioplastics. Correspondingly, the thicker the bioplastic formed, the more water-resistant it will be. Consistent with this, a higher bioplastics thickness value indicates greater permeability to oxygen, Carbon Dioxide (CO_2) and water vapour, which in turn results in a longer shelf life for the resulting product (Muhammad *et al*., 2020; Khotimah *et al*., 2022).

JIS Z 1707:2014 is a Japanese industrial standard that sets technical requirements for bioplastics, including a maximum thickness of ≤ 0.25 mm. This standard ensures that bioplastics meet the quality and performance requirements suitable for specific applications such as food packaging and other consumer products. All of the thickness values are below the maximum limit set by the JIS Z 1707:2014 standard, which is ≤ 0.25 mm. This indicates that the produced bioplastics meet the thickness requirements of the standard.

The addition of glycerol as a plasticiser in the production of bioplastics can influence the film's thickness. In a study by Saputra and Supriyo (2022), the addition of glycerol to corn starch-based bioplastics resulted in films with varying thicknesses, depending on the concentration of glycerol used.

In another study by Jannah (2024), the addition of glycerol to sago starch-based bioplastics also affected the film thickness. However, this study did not specify the exact thickness values obtained. Generally, while the addition of glycerol can enhance the flexibility and elasticity of bioplastics, it can also affect the film thickness. Therefore, it is essential to optimise the glycerol concentration to maintain the desired bioplastic thickness. The addition of glycerol affects the bioplastics thickness and needs to be optimised to achieve the desired thickness. Although the thickness meets the standard, further testing is required to assess the mechanical properties, water resistance, and biodegradability of the bioplastic to ensure its practical application.

Tensile Strength of Bioplastics

Tensile strength is the maximum stress a material can withstand before breaking, measured using a universal testing machine. The significance value for the homogeneity test is $0.087 > 0.05$, indicating that the variability within each of the compared groups is similar or homogeneous. Similarly, the significance value for the normality test is $0.138 > 0.05$, indicating that the data follows a normal distribution, allowing for further analysis (ANOVA). The ANOVA test results yield a significance value of $0.030 < 0.05$, indicating that glycerol volume variation affects the tensile strength of the bioplastics. By contrast, Tukey's HSD test results report no significant difference between P1, P2, and P3, yet they differ significantly from P4. Specifically, P1 has the lowest tensile strength (1.858 MPa) and P4 has the highest (7.302 MPa). Only the P1 treatment resulted in bioplastics with tensile strength that meets the standard of 1.35 MPa to 2.32 MPa (ASTM E8-13a).

The tensile strength of bioplastics represents the maximum level of strength or pull that bioplastics can achieve prior to breaking or tearing (Saputra & Supriyo, 2020). The results of the study revealed that the addition of glycerol led to an increase in tensile strength properties. However, insufficient glycerol addition caused the bioplastics to exhibit cracking or reduced elasticity. This phenomenon is believed to be caused by the addition of small amounts of glycerol, which results in the layer becoming thin, soft, and sticky, making it difficult to lift from the mould. Glycerol has a greater affinity for water, which softens the surface.

ASTM E8-13a is an international standard that measures the tensile strength of metal and plastic materials. This standard specifies that the tensile strength of a particular material must fall within the range of 1.35 MPa to 2.32 MPa to meet quality criteria. Thus, bioplastics with tensile strength values outside this range may not meet the standard and may require modifications to improve their performance. From the data above (Table 2), it can be observed that the tensile strength values for all treatments exceed the upper limit of the ASTM E8-13a standard (2.32 MPa), with P4 presenting the highest value. This suggests that increasing the glycerol volume in bioplastics production can enhance the material's tensile strength.

The addition of glycerol as a plasticiser functions to improve the flexibility and reduce the brittleness of the bioplastic. However, a study by Dewi *et al*. (2023) reported that the addition of glycerol can increase the tensile strength of sago starch-based bioplastics. This may be due to the increased interaction between molecules, leading to a denser and stronger structure.

Additionally, research by Dewi *et al*. (2024) demonstrated that the addition of glycerol to sago starch-based bioplastics could enhance tensile strength. It is essential to note that excessive glycerol addition can reduce tensile strength by weakening molecular bonds. Bioplastics with high tensile strength such as P4 (7.302 MPa), demonstrate the potential for use in applications requiring materials with high mechanical strength. Nonetheless, it should be remembered that excessively high tensile strength could also lead to brittleness, which may be undesirable in certain applications. Therefore, it is crucial to adjust the bioplastic formulation to meet the specific needs of the intended application.

Elongation of Bioplastics

Breaking length or elongation refers to the maximum change in length that occurs during stretching until the film sample is cut off. The significance value for the homogeneity test is 0.054 > 0.05, indicating that the variability within each of the compared groups is similar or homogeneous. Similarly, the significance value for the normality test is 0.200 > 0.05, indicating that the data follows a normal distribution, allowing for further analysis (ANOVA). The ANOVA test results present a significance value of 0.000 < 0.05, indicating that there is an effect of glycerol volume variation on elongation. Although the Tukey's HSD test results indicate that there is no significant difference between P1 and P2, a significant difference is observed between P3 and P4. In addition, while there is no significant difference between P2 and P3, a significant difference is observed for P4. As a result, P1 has the highest elongation (13.367%) and P4 has the lowest (6.170%). Meanwhile, P1 and P2 have bioplastics with elongation that meet the standard of ≥ 10% (ASTM D882-12).

Elongation is defined as the percentage increase in film length, measured from the initial length to the final length obtained after testing. The results demonstrated that the addition of glycerol resulted in a corresponding increase in elongation. This phenomenon can be attributed to the plasticiser reducing the intermolecular bonds between amylose and amylopectin in starch, as well as to hydrogen bonding between starch molecules and the plasticiser.

ASTM D882-12 is an international standard for measuring the mechanical properties of plastic films, including elongation. This standard specifies that the minimum elongation value for plastic films is 10%, indicating that the material has adequate flexibility for certain applications. From the data above (Table 2), it is evident that all treatments have elongation values that meet the ASTM D882-12 standard, which is ≥ 10%, though there is a decrease in elongation values as the glycerol volume increases.

The addition of glycerol as a plasticiser enhances the flexibility and elasticity of bioplastics. However, a study by Ayu (2023) highlighted that the addition of glycerol can reduce the elongation value of sago starch-based bioplastics. This is due to the increased molecular interactions that result in a denser and stronger structure, thereby reducing the material's ability to stretch. A decrease in elongation values was also observed in a study by Nasution (2024), which revealed that adding glycerol to sago starch-based bioplastics could increase tensile strength while reducing elongation. In other words, this indicates a trade-off between the strength and flexibility of the material.

Bioplastics with elongation values that meet the ASTM D882-12 standard demonstrate potential for use in applications requiring flexibility such as food packaging and other consumer products. Nevertheless, it is noteworthy that excessively high elongation values can make the material overly elastic and unstable. Conversely, exceptionally low elongation values can make the material brittle and prone to breaking. Therefore, it is crucial to adjust the bioplastic formulation to achieve a balance between strength and flexibility according to the specific needs of the intended application.

Young's Modulus of Bioplastics

Young's modulus test was conducted to determine the elasticity of bioplastics made from sago waste. Young's modulus is obtained from the ratio between tensile strength and elongation. The significance value for the homogeneity test is 0.087 > 0.05, indicating that the variability within each of the compared groups is similar or homogeneous. Similarly, the significance value for the normality test is 0.052 > 0.05, indicating that the data follows a normal distribution, allowing for further analysis (ANOVA).

The ANOVA test results present a significance value of 0.002 < 0.05, indicating that there is an effect of glycerol volume variation on Young's modulus. Meanwhile, Tukey's HSD test results indicate that there is no significant difference between P1, P2, and P3, yet they differ significantly from P4. Therefore, P1 has the lowest Young's modulus (0.146 MPa) and P4 has the highest (1.190 MPa). In addition, P1 and P2 have bioplastics with Young's modulus below the standard while P3 and P4 exceed the standard of 0.35 MPa (JIS-Z-1707).

JIS Z 1707 is an international standard used for food packaging plastics, which stipulates that the Young's modulus value for such plastics must be ≤ 0.35 MPa. Young's modulus is a measure of material stiffness, indicating how much a material can undergo elastic deformation when subjected to a load. Note that a low Young's modulus value signifies that the material is more flexible and elastic, which is desirable in food packaging applications. From the data above (Table 2), it can be noted that all Young's modulus values for P1 to P3 meet the JIS Z 1707 standard (≤ 0.35 MPa) while P4 exceeds this limit. This suggests that an increase in glycerol volume can affect the stiffness of the bioplastics.

The addition of glycerol as a plasticiser aims to enhance the flexibility and elasticity of the bioplastic. By contrast, a study by Rahmatullah *et al*. (2024) highlighted that the addition of glycerol could lower the Young's modulus value in starch and kapok fibre-based bioplastics. This is due to the increased molecular spacing caused by glycerol, which reduces the intermolecular bonding strength and enhances material flexibility. Moreover, a study by Devi *et al*. (2024) also presented that adding glycerol to sago starch-based bioplastics can increase elongation and reduce Young's modulus. Nonetheless, excessive glycerol addition can reduce the mechanical strength of the bioplastic.

Bioplastics with a Young's modulus value that meets the JIS Z 1707 standard demonstrate potential for use in food packaging applications, as they possess good flexibility and can withstand elastic deformation. Note that a Young's modulus value that is overly low can make the material excessively elastic and unstable. Conversely, a Young's modulus value that is exceptionally high can make the material brittle and prone to breakage. Hence, it is essential to adjust the bioplastic formulation to strike a balance between strength and flexibility, tailored to the specific application needs.

Water Resistance of Bioplastics

After the Young's modulus is measured, water resistance is assessed, which aims to determine the percentage of the bioplastic's ability to store water. The significance value for the homogeneity test is 0.226 > 0.05, indicating that the variability within each of the compared groups is similar or homogeneous. Similarly, the significance value for the normality test is 0.200 > 0.05, indicating that the data follows a normal distribution, allowing for further analysis (ANOVA). The ANOVA test results reveal a significance value of 0.000 < 0.05, indicating that there is an effect of glycerol volume variation on water resistance. On the other hand, the Tukey's HSD test results indicate that P1 differs from P2, P3, and P4, as well as P2 differing from P3 and P4, and P3 differing from P4. Accordingly, P1 has the highest water resistance (211.000%) and P4 has the lowest (53.333%). At the same time, P4 has a lower water resistance of ≥ 99% (SNI 7818:2014), compared to the standard (when compared to P1, P2, and P3).

SNI 7818:2014 stipulates that bioplastics must have a minimum water resistance of 99%, meaning the maximum water absorption should be 1%. Bioplastics with water absorption above 100% indicate that the material absorbs more water than its original mass, which suggests exceptionally low water resistance. From the data above (Table 2), it can be observed that all treatments have water absorption far exceeding the SNI 7818:2014 standard. Specifically, P4 exhibits the lowest water absorption among the treatments, yet it is still well above the standard limit.

The addition of glycerol as a plasticiser can affect the water resistance of bioplastics. According to a study by Shrestha (2022), adding glycerol at high concentrations can increase water absorption in starch-based bioplastics. This is due to the hygroscopic nature of glycerol, which attracts water into the bioplastic structure, thereby reducing overall water resistance. Additionally, in a study by Masahid *et al*. (2023), adding glycerol to cassava starch-based bioplastics increased water absorption. However, adding whey protein decreased water absorption, indicating that the composition of materials significantly affects the water resistance of bioplastics.

Based on the research results, none of the treatments in this study meet the SNI 7818:2014 standard. Although P4 has the lowest water absorption, it is still far above the maximum limit set by the standard. In response, further modifications to the bioplastic formulation are necessary to achieve the desired water resistance as specified by the standard. To improve the water resistance of bioplastics made from sago solid waste, steps that can be considered include adding hydrophobic materials such as chitosan or acetic acid, which can enhance the hydrophobic properties of bioplastics and reduce water absorption. Furthermore, optimising the manufacturing process such as varying drying temperature and drying time can affect the structure and water resistance properties of bioplastics. By making these modifications, it is expected that bioplastics with water resistance meeting the SNI 7818:2014 standard can be obtained.

Biodegradation of Bioplastics

Biodegradation was conducted to determine the degradation rate of bioplastics in the soil. Table 2 above indicates that bioplastics made from starch derived from sago waste (P1, P2, P3, and P4) decompose completely after seven days of planting in the soil. The biodegradation of bioplastics from each treatment meets the standard of 60 Days Decomposed 100% (ASTM-D-6002).

ASTM D6002 is an international standard used to assess the biodegradation of environmentally degradable plastics. This standard requires materials to degrade 100% within 60 days. It measures the amount of carbon that is converted into CO_2 by microorganisms in aerobic conditions. If the bioplastic being assessed does not meet these criteria, the material is not considered fully biodegradable. In this case, the sago solid waste-based bioplastics assessed over seven days demonstrated very rapid degradation compared to the standard.

The data in Table 1 provided summarises that all treatments (P1, P2, P3, and P4) underwent 100% biodegradation within seven days. This result indicates that sago solid waste-based bioplastics have an extremely fast biodegradation rate, far exceeding the 60-day standard set by ASTM D6002. Compared to the ASTM D6002 standard, which requires 100% biodegradation within 60 days, the test results, which present 100% biodegradation within seven days, exceed the established standard. This indicates that the sago solid waste-based bioplastics assessed degrade much faster by microorganisms in the environment compared to the set standard.

This suggests that these bioplastics are highly environmentally friendly, as they break down quickly without leaving residues that could pollute the environment. However, this rapid biodegradation could pose a challenge in applications where environmental resistance is required such as food packaging that needs to last longer.

Glycerol functions as a plasticiser, which can affect the flexibility and mechanical strength of the bioplastic. In this case, while the addition of higher glycerol concentrations (as in P4) increases the flexibility of the bioplastics, it may also increase the material's porosity, thereby facilitating water penetration and microorganism activity. Research by Yuniardi *et al*. (2023) noted that glycerol, as a plasticiser can accelerate the biodegradation process by increasing fragility and the rate of microorganism penetration. Though excessive glycerol addition may alter the physical structure of the bioplastic, affecting its strength. The decrease in mechanical strength due to glycerol may impact the product's durability in certain applications, though it does not affect the biodegradation rate.

This rapid biodegradation result suggests that sago solid waste-based bioplastics can be utilised in environmental applications that require high biodegradability such as single-use packaging products designed to break down quickly after use. For example, they can be used in food packaging or plastic bags that are expected to degrade after disposal. Despite this, it is worth noting that for applications requiring longer durability such as electronic product packaging or medical equipment, this rapid biodegradation rate may not be ideal.

Conclusions

Starch from sago waste, known as *ela sagu* (in the traditional Maluku language) can be used as a material for bioplastics. Variations in glycerol volume affect thickness, tensile strength, elongation, Young's modulus, and water resistance, with P1 (1 ml glycerol) yielding the best performance in terms of thickness (0.137 mm), elongation (13.367%), and Young's modulus (0.146 MPa). Therefore, P1 is the best choice for applications requiring lightweight thickness, high flexibility, and elasticity. P4 (4 ml glycerol) has the best water resistance (53.333%), although its tensile strength and Young's modulus values are higher than the standard. This makes P4 more suitable for applications requiring water resistance. In line with this, all treatments were 100% degraded within seven days, indicating that this bioplastic is highly environmentally friendly and meets biodegradability criteria.

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Conflict of Interest Statement

The authors declare that they have no conflict of interest.

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