2024 Т. 54 № 3 / Техника и технология пищевых производств / Food Processing: Techniques and Technology
ISSN 2074-9414 (Print)
ISSN 2313-1748 (Online)

https://doi.org/10.21603/2074-9414-2024-3-2527
https://elibrary.ru/MQDCLB

Original article
Available online at https://fptt.ru/en

Synthesis of Biodegradable Plastic from *Wak* Banana Peel Starch with Glycerol as Plasticizer

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Received: 13.02.2024
Revised: 26.02.2024
Accepted: 05.03.2024

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Abstract.
Biodegradable plastic from banana peel is durable and transparent. It breaks down naturally in the environment and can substitute traditional petroleum plastic, which is a source of pollution due to its slow degradation. This research is intended to improve the physical properties of biodegradable film obtained by the casting solution method from an Aceh variety of *wak* banana peel starch with glycerol as a plasticizer.

The authors relied on a factorial completely randomized design with two replications. The variables included the concentrations of *wak* banana peel starch (6, 8, and 10%) and glycerol (2, 5, and 8%). The data were subjected to the analysis of variance (ANOVA). The physical tests covered tensile strength, elongation, water absorption, and biodegradation. The functional groups of biodegradable films were analyzed using Fourier-transform infrared spectroscopy (FTIR). The morphological structure was studied by scanning electron microscopy (SEM).

The biodegradation test lasted for two and four days. The sample with less banana peel starch (6–8%) degraded faster. Higher glycerol concentrations (5–15%) affected the weight of the samples. The plastic samples with 15% glycerol degraded faster than the samples with minimal glycerol amount. A greater concentration of *wak* banana peel starch significantly affected tensile strength and elongation while the effect on water content and water absorption capacity was insignificant. Glycerol concentration affected water content and tensile strength, but had no significant effect on water absorption capacity and elongation. The ratio between the concentrations of *wak* banana peel starch and glycerol had a significant effect on tensile strength and water absorption capacity.

The best results belonged to the sample with 8% *wak* banana peel starch and 2% glycerol. The research provided new options for utilizing banana peels as biodegradable packaging and an alternative to traditional plastic. The commercialization and scalability of this ecologically friendly plastic require further research.

Keywords. Banana peel, starch, biodegradation, degradation process, permeability, plastic, extraction

For citation: Irmayanti, Anwar C. Synthesis of Biodegradable Plastic from *Wak* Banana Peel Starch with Glycerol as Plasticizer. Food Processing: Techniques and Technology. 2024;54(3):546–557. https://doi.org/10.21603/2074-9414-2024-3-2527

https://doi.org/10.21603/2074-9414-2024-3-2527
https://elibrary.ru/MQDCLB

Оригинальная статья
https://fptt.ru

Синтез биоразлагаемого пластика из банановой кожуры с глицерином в качестве пластификатора

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Поступила в редакцию: 13.02.2024
Принята после рецензирования: 26.02.2024
Принята к публикации: 05.03.2024

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Аннотация.
Из банановой кожуры получается биодеградируемый пластик высокой прочности и прозрачности. Он естественным образом разлагается в окружающей среде и может заменить традиционный пластик, который, в силу своего медленного разложения, является опасным источником загрязнения. Целью данного исследования являлось изучение физических свойств биоразлагаемой пленки, изготовленной из крахмала, полученной при помощи метода литьевого раствора из банановой кожуры с глицерином в качестве пластификатора.

В исследовании применялась факторная полностью рандомизированная модель с двумя повторениями. В качестве факторов выбраны: концентрация крахмала банановой кожуры (6, 8 и 10 %) и концентрация глицерина (2, 5 и 8 %). Данные были подвергнуты дисперсионному анализу (ANOVA). В ходе эксперимента изучены: прочность на разрыв, удлинение, поглощение воды и биодеградация. Функциональные группы образцов биоразлагаемых пленок анализировали при помощи инфракрасной спектроскопии с преобразованием Фурье. Морфологическую структуру экспериментального пластика изучали с помощью сканирующей электронной микроскопии.

По результатам теста на биоразлагаемость образец с меньшим содержанием крахмала (6–8 %) разлагался быстрее. Более высокие концентрации глицерина (5–15 %) привели к утяжелению образцов. Образцы пластика с 15 % глицерина разлагались быстрее, чем образцы с минимальным содержанием глицерина. Высокая концентрация крахмала из банановой кожуры существенно влияла на прочность и удлинение, а влияние на содержание воды и водопоглощающую способность оказалось незначительным. Концентрация глицерина оказала значительное влияние на содержание воды и прочность, при этом эффект на водопоглощающую способность и удлинение был незначительным. Соотношение между концентрацией крахмала из банановой кожуры и глицерина существенно влияло на прочность и водопоглощающую способность экспериментального образца биоразлагаемого пластика.

Наилучшие результаты продемонстрировал образец с 8 % крахмала из банановой кожуры и 2 % глицерина. Исследование выявило новые возможности использования банановой кожуры в качестве сырья для производства биоразлагаемой упаковки и альтернативы традиционному пластику. Коммерциализация и масштабируемость проекта требуют дальнейших исследований.

Ключевые слова. Банановая кожура, крахмал, биодеградация, процесс разложения, проницаемость, пластик, экстракция

Для цитирования: Ирмаянти, Анвар Ч. Синтез биоразлагаемого пластика из банановой кожуры с глицерином в качестве пластификатора // Техника и технология пищевых производств. 2024. Т. 54. № 3. С. 546–557. (На англ.) https://doi.org/10.21603/2074-9414-2024-3-2527

Introduction

Plastic has a wide range of forms, including sheets, panels, and films, each of which has its own advantages. Depending on the application, plastic may be made more flexible, which is an industrial benefit. Plastic is more affordable than any other packaging. It is strong, aesthetically pleasing, and lightweight; in addition, it comes in a variety of sizes and shapes. However, excessive use of plastic has made it a major pollutant. It takes plastic 500 years to deteriorate, and when it finally does, it becomes toxic. Plastic pollution of soil and water may have disastrous consequences. It affects people, e.g., by upsetting hormone balance or thyroid hormone axis. As a result, biodegradable plastic emerges as a viable remedy for every issue [1].

Starch is elastic and resembles petroleum-based polymers, which makes it a key ingredient in the production of biodegradable plastics. Starch comes from tuberous plants, e.g., potatoes, sweet potatoes, jicama, cassava, and arrowroot. The amount of starch in the mix defines the mechanical and physical properties of the biodegradable plastic produced. The synthesis of biodegradable plastics from tuberous plants has been well investigated. New alternatives for plastic synthesis are required to obtain more variety. Banana peel is a novel and prospective source of biodegradable plastic.

Banana peel is an easily obtained byproduct of food production that is discarded as waste and has no market value. However, banana peel is rich in starch and may be utilized as a raw material for such creative food wrapper as edible film, its main advantages being rapid degradation and edibility [2].

Wak banana, or king banana, is a popular name for *Musa* (ABB Group) Pisang Awak, or *Musa paradisiaca* var.awak. Its peel contains more carbohydrates (31.8 g) than other banana cultivars, which makes it a viable alternative material for new biodegradable plastic. Its high carbohydrate content means good prospects as a plasticizer. Unfortunately, bioplastics derived from starch are of non-waterproof (hydrophilic) nature. Hydrophobic substances, e.g., chitosan and glycerol, can be added to starch-based bioplastics in order to enhance their mechanical characteristics [3].

Biodegradable film needs a plasticizer, i.e., a nonvolatile substance with a high boiling point that, when added to another material, can make it more plastic. Plasticizers reduce film brittleness, enhance permeability to gases, water vapor, and solutes, as well as improve plasticity. The list of popular plasticizers used in biodegradable films includes glycerol, beeswax, polyvinyl alcohol, and sorbitol [4]. Top of Form.

Kadam and Datta proved that biodegradable film derived from banana peel was more optimal than synthetic polymers and controls [1]. Saleh and Utami, who studied *mulu bebe* banana peel starch and biodegradable plastic with chitosan and glycerol, reported a water content of 13.389–19.621%, density of 0.047–0.112 g/cm^3, tensile strength of 0.983–4.790 MPa, elongation of 1.402–13.317%, and water absorption of 12.407–82.194% [3]. This research aims at improving the physical properties of biodegradable film made from starch obtained by the casting solution method from *wak* banana grown in the Province of Aceh, Sumatra, Indonesia, and glycerol as a plasticizer.

Study objects and methods

The tools used in this research included a small bucket, a knife, a blender, a small sieve, filter paper or thin cloth, a small pot, measuring glass, a stove, a spoon, an oven, a clock or stopwatch, and a digital scale. The analytical tools involved a Kao strength-testing device, a micrometer screw, an oven, an analytical balance, a tensile tester, a scanning electron microscope (SEM), and a Fourier-transform infrared (FTIR) spectrometer. The materials included green *wak* banana peel obtained from Lambaro Market, Aceh Besar, glycerol, water, and 70% alcohol.

Making banana peel starch. The starch extraction was carried out following the method described by Saleh and Utami (3), with slight modifications. The procedural steps involved washing and peeling the bananas in running water, followed by grinding the peels in a blender. After that, we added distilled water to facilitate crushing with a banana peel-to-distilled water ratio of 200 g to 250 mL. Then, we filtered the banana peel paste through cheesecloth and placed it in a 1,000 mL beaker. The banana peel filtrate settled there for 24 h until sediment, which was separated from supernatant. The obtained sediment was then reconstituted with an additional 250 mL of distilled water and left for another 24 h until sediment formed again and was separated from supernatant. Subsequently, we dried the sediment in an oven at 70°C for 24 h and sieved it through a no.100 mesh sieve.

Making biodegradable plastic. Forming biodegradable plastic from banana peels followed a modified procedure developed by Kadam and Datta [1]. We dissolved banana peel starch at concentrations of 6, 8, and 10% in 6% acetic acid by stirring at 70°C. Once all the solutions were dissolved, the banana peel starch solution was stirred for 15 min until the mix became homogeneous. After that, we added glycerol at concentrations of 2, 5, and 8%, stirred it, and heated for 15 min until the temperature reached 70°C. Subsequently, we poured the biodegradable plastic solution into molds pre-cleaned with 96% alcohol. The molds remained in the oven at 70°C for 7 h. Upon leaving the oven, they were left to cool down to room temperature (28°C). The physical tests included such parameters as tensile strength, elongation, water absorption, and biodegradation. The functional groups of biodegradable films were analyzed using a Fourier-transform infrared (FTIR) spectrometer. The morphological structure underwent scanning electron microscopy (SEM).

Water content test. We placed 2 g of fine-ground material into a pre-weighed crucible to be dried in the oven at 100–105ºC for 3–5 h, followed by cooling it in a desiccator for 15 min and re-weighing. After that, we calculated the moisture content using the formula introduced by Irmayanti *et al.* [5]:

$$\text{Moisture content} = (W_1 - W_2) / W_1 \times 100$$

where W_1 was the initial weight and W_2 stood for the sample weight after drying, i.e., the final weight.

Water absorption test. To test the water absorption, we placed 5 g of each sample in 100 mL of boiling water and heated them until complete gelatinization for 5 min. Once completely gelatinized, the plastic was weighed, and the water absorption was measured as the change before and after heating [6].

Tensile strength test. The samples remained in a room with standard temperature and humidity 23 ± 2°C, 52% for 24 h. Then, they were cut into standard size pieces of 2 × 8 cm. The initial length before adding load was recorded, and the testing was carried out by clamping both ends of the sample.

Elongation test. Elongation measurements followed the same procedure as the tensile strength test and was expressed as a percentage.

Morphological structure analysis (SEM). The cross-sectional morphological structure of the new biodegradable film was observed using a scanning electron microscope (SEM) analyzer (ZEOL, Germany). Before testing, the samples were placed in a desiccator with 54% humidity at room temperature. The biodegradable film was prepared by breaking it down in liquid nitrogen and then observing it according to standard procedures.

Fourier transform infrared (FTIR) test. The infrared spectra of the biodegradable film samples were measured using potassium bromide (KBr) pellets with a FTIR Prestige-21 Shimadzu spectrophotometer at wave lengths between 4,000 cm^{-1} and 400 cm^{-1}. The sample was placed into the set holder and searched with an appropriate spectrum. The result was obtained in the form of spectra of the relationship between the wave length and the intensity. The FTIR spectrum was recorded with the spectrometer at room temperature [7].

Statistical evaluation. Every experiment was conducted in triplicate, with a mean ± SD. All experimental data went through SPSS 26.0 for Microsoft. The significant changes in the physicochemical and sensory properties were defined using the Duncan's Multiple Range Test, with $p \leq 0.05$.

Results and discussion

The biodegradable plastic made from the Aceh variety of *wak* banana peelstarch was similar to biodegradable plastics made from other starch raw materials. It had a clear, slightly yellowish color and a smooth soft surface. It was non-porous and did not crack.

Figure 1. Biodegradable plastic from 10% banana peel starch and 5% glycerol

Рисунок 1. Образец биоразлагаемого пластика с 10 % крахмала банановой кожуры и 5 % глицерина

Water content test. The average water content of the biodegradable plastic from banana peel starch with glycerol ranged from 47.33 to 49.00%, with an average of 80.39%. The highest water content was 49.00% and belonged to the sample with 10% banana peel starch and glycerol concentrations of 2, 5, and 8% (Samples P_3G_1, P_3G_2, P_3G_3, see Table 1). The lowest water content of 47.33% was detected in the sample with 6 and 8% banana peel starch and 2 and 8% glycerol (Samples P_1G_2 and P_2G_3, see Table 1). Table 1 demonstrates the average water content in different biodegradable plastic samples.

The analysis of variance showed that the concentration of banana peel had a significant effect ($p \leq 0.05$) on water content while the concentration of glycerol and the ratio between the concentrations of banana peel and glycerol had none ($p > 0.05$). Figure 1 illustrates the effect of the concentration of banana peel starch on the water content in the experimental biodegradable plastic.

Figure 2 shows quite clearly that a higher concentration of banana peel starch correlated with a greater water content. The phenomenon could be explained by the fact that banana peel starch possesses hydrophilic properties and easily binds water. Amalia *et al.* explained the increase in water content by the hydrophilic nature of starch, which attracts and forms hydrogen bonds with

Table 1. Average values of water content in biodegradable plastic from banana peel starch with glycerol as plasticizer

Таблица 1. Средние значения содержания воды в биоразлагаемом пластике, полученного из крахмала банановой кожуры с добавлением глицерина в качестве пластификатора

Concentration of *wak* banana peel starch (P)	Concentration of glycerol (G)		
	$G_1 = 2\%$	$G_2 = 5\%$	$G_3 = 8\%$
$P_1 = 6\%$	47.33	48.00	48.00
$P_2 = 8\%$	48.67	48.67	47.33
$P_3 = 10\%$	49.00	49.00	49.00

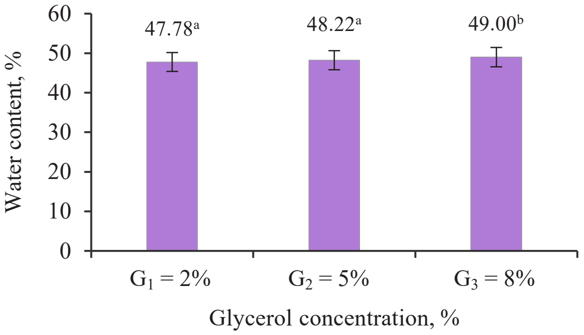


Figure 2. Effect of concentration of *wak* banana peel on water content in biodegradable plastic

Рисунок 2. Зависимость содержания воды в биоразлагаемом пластике от концентрации крахмала банановой кожуры water molecules [8]. Fitrianti *et al.* studied biodegradable plastic made from *walur* tuber starch and reported the optimal water content of 9.45% for the combination of 78% *walur* starch and 22% glycerol [9]. The bioplastic samples containing glycerol exhibited the greatest moisture content values. This effect was described by Cerqueira *et al*., who found that glycerol was made up of hydroxyl groups that had an attraction for water molecules, allowing the molecules to form hydrogen bonds and incorporate water in their structure [10]. According to Galietta and Di Gioia and Guilbert *et al.*, the hydrophilic nature of glycerol enables it to bind water during the polymerization process, thus increasing the water content of the polymer material as glycerol mass is employed [11, 12]. Furthermore, Amatullah *et al.* reported that the capacity of glycerol to bind water during the polymerization process also helped in the production of biodegradable plastics because it made the polymer material less brittle over time, eventually forming more flexible properties [13]. The fact that we used glycerol to modify the water content was consistent with the findings reported by Praseptiangga *et al.* [14].

Water absorption test. The water absorption analysis was conducted to determine the ability of the experimental plastic to absorb water after soaking. It was intended to show whether the novel bioplastic had properties close to those of synthetic plastic because plastic consumers prefer materials that meet specific requirements, e.g., water resistance [15].

The average water absorption of biodegradable plastic from banana peel starch with different glycerol concentrations ranged from 142.700 to 387.00%, with an average of 241.667%. The highest water absorption (387.00%) was in the sample with 6% banana peel starch and 5% glycerol (Sample P_1G_2, see Table 2). The lowest water absorption (142.70%) was recorded in the sample with 8% banana peel and 5% glycerol (Sample P_2G_2, see Table 2). Table 2 shows the average water absorption of biodegradable plastic [15].

The variance analysis indicated that the concentration of banana peel and glycerol had no significant effect ($p > 0.05$) on water absorption while the ratio between the concentrations of banana peel and glycerol did ($p < 0.05$) (Fig. 2).

According to Figure 3, a higher concentration of banana peel starch and glycerol corresponded with a more powerful water absorption. Probably, the intermolecular mobility reduced the regularity of biodegradable plastic [16]. As the concentration of banana peel starch increased, the water absorption tended to rise. This phenomenon was evident in the samples with 2% glycerol (G_1) at 6, 8, and 10% banana peel starch, 5% glycerol (G_2) at 8 and 10% banana peel starch, and 8% glycerol (G_3)

Table 2. Average water absorption, %, values of biodegradable plastic from banana peel with glycerol as plasticizer

Таблица 2. Средние значения водопоглощения, %, биоразлагаемого пластика из крахмала банановой кожуры с добавлением глицерина в качестве пластификатора

Concentration of *wak* banana peel starch (P)	Concentration of glycerol (G)		
	$G_1 = 2\%$	$G_2 = 5\%$	$G_3 = 8\%$
$P_1 = 6\%$	218.933	387.000	232.700
$P_2 = 8\%$	231.500	142.700	258.133
$P_3 = 10\%$	277.767	195.000	231.267

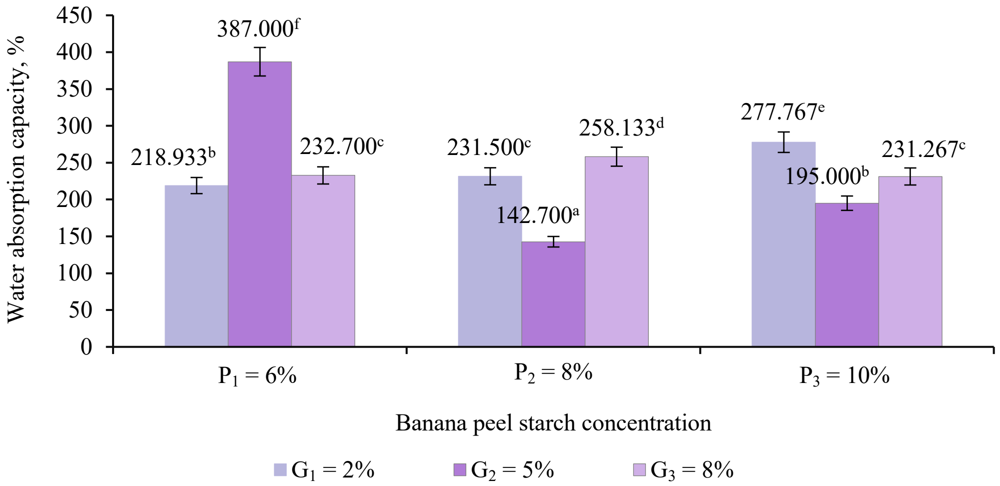


Figure 3. Effect of concentration ratio between banana peel starch and glycerol on water absorption capacity of biodegradable plastic

Рисунок 3. Зависимость водопоглощающей способности биоразлагаемого пластика от соотношения между концентрациями крахмала банановой кожуры и глицерина at 6 and 8% banana peel starch. Higher glycerol concentrations tended to increase the water absorption, probably, because starch tends to have more hydroxyl (OH) groups, allowing it to absorb more water. According to Ermawati, Rahmadhia, high glycerol concentrations could enhance the water absorption of biodegradable plastic due to the properties of glycerol as a plasticizer [17]. Yuxia *et al.* wrote that glycerol did not bind to starch molecules at high concentrations but interacted with water molecules through hydrogen bonds, reducing the compactness of the starch matrix [18]. It happened because glycerol is a hygroscopic substance that can absorb water well. Additionally, glycerol has hydrophilic properties, indicating that a material with hydrophilic groups interacts with water quite easily [19].

An edible film is usually a mix of glycerol with a greater water vapor permeability: the thicker the edible film, the more hydrophilicity it affects, depending on the concentration [20]. In our research, the weight of the edible film rose every hour as the amount of glycerol grew. It happened because glycerol is hydrophilic and can bind water. By increasing the hydrophilic component of the membrane, producers let water vapor seep into it, speeding up the transmission of water vapor. Similarly, Musavi and Bagheripoor reported that the glycerol combination used to create edible film had a greater capacity for absorbing water [21]. Vapor transmission membrane and water barrier control water evaporation and function well as an oxygen, carbon dioxide, and lipid barrier.

Tensile strength test. Tensile strength is an important mechanical property of plastic because it is related to its ability to protect the products it covers. Plastic with high tensile strength serves as food packaging that protects food items during handling, transportation, and marketing [22].

In our research, the average tensile strength of biodegradable plastic made from banana peels with glycerol concentration ranged from 0.40 to 3.00 MPa, with an average of 1.16 MPa. The highest tensile strength of 3.00 MPa belonged to the sample with 8% banana peel starch and 1% glycerol (Sample P_2G_1, see Table 3). The lowest tensile strength of 0.40 MPa was observed in the sample with 10% banana peel starch and 8% glycerol (Sample P_3G_3, see Table 3). Table 3 demonstrates the average tensile strength of the experimental biodegradable plastic.

The variance analysis showed that glycerol concentration had a highly significant effect ($p \leq 0.01$) on the tensile strength while the banana peel starch concentration and the ratio between banana peel and glycerol concentrations had a significant effect ($p \leq 0.05$). Figure 3 illustrates the effect of the ratio between banana peel starch and glycerol concentrations on the tensile strength of the experimental biodegradable plastic.

Figure 4 shows that a higher concentration of banana peel starch corresponded with a higher tensile strength while a higher concentration of glycerol correlated with a lower tensile strength. The dependance could be explained by the fact that excessive plasticizer concentrations made the material more elastic, which lowered its tensile

Table 3. Average tensile strength values, MPa, of biodegradable plastic from banana peel starch with glycerol as plasticizer

Таблица 3. Средние значения прочности, МПа, биоразлагаемого пластика из крахмала банановой кожуры с добавлением глицерина в качестве пластификатора

Concentration of *wak* banana peel starch (P)	Concentration of glycerol (G)		
	$G_1 = 2\%$	$G_2 = 5\%$	$G_3 = 8\%$
$P_1 = 6\%$	0.45	0.72	0.48
$P_2 = 8\%$	3.00	0.60	0.96
$P_3 = 10\%$	2.76	1.06	0.40

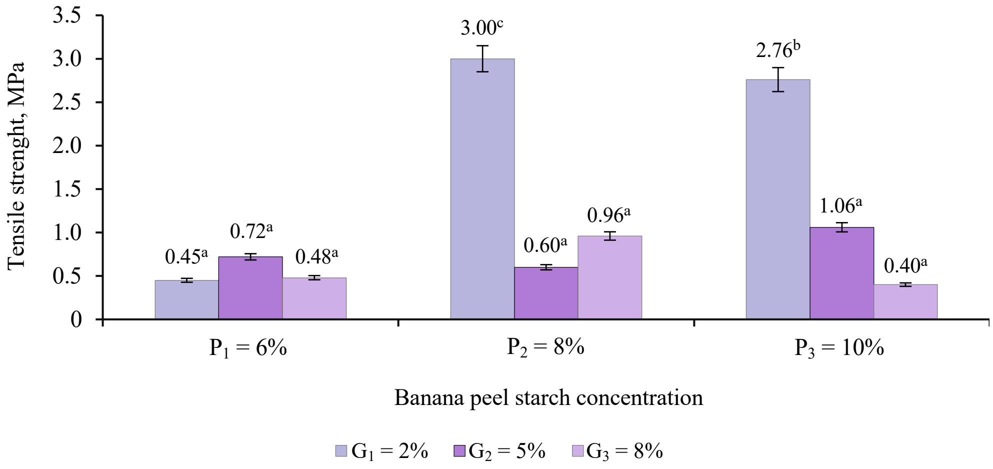


Figure 4. Effect of concentration ratio between banana peel starch and glycerol on tensile strength of biodegradable plastic

Рисунок 4. Зависимость прочности биоразлагаемого пластика от соотношения концентраций крахмала банановой кожуры и глицерина strength [7]. The decline also occurred due to the addition of more starch, which resulted in a greater matrix formation, causing the film matrix structure to become more robust, thus providing greater strength to support external loads. As the glycerol and starch composition reached its maximum, excessive glycerol did not mix completely. This change in mechanical properties was related to the ratio between starch and glycerol. According to Echeverria *et al.* the melting temperature, tensile strength, and Young's modulus decrease as the glycerol content grows, i.e., the tensile strength decreases as the glycerol volume increases [23].

The tensile strength was highest in the samples with 2% glycerol: because the amount of glycerol added was still very small, the plastic with a high tensile strength did not break readily. It happened because stronger chemical connections that need a lot of energy to break appear when plastic contains a greater number of hydrogen bonds. In this study, the tensile strength values of the bioplastic met the specified standards. The increasing amount of glycerol without balancing the starch composition prevented some components to mix perfectly, leading to an increase and subsequent decrease in tensile strength values. Dalimunthe reported that the tensile strength values went down as the glycerol concentration increased [24]. It happened because when glycerol mixed with polymer solutions, it formed hydrogen bonds between molecules, thus reducing the interaction between polymer molecules and making polymer molecule movement easier. McHugh and Krochta reduced hydrogen bonds in the film by increasing plasticizer content [25]. As a result, it increased flexibility, causing the film to be more flexible, thus reducing tensile strength values. Sanyang *et al.* explained that the phenomenon of decreasing tensile strength due to the effect of increasing plasticizer concentration could be described through the behavior of the plasticizer, which reduces the attractive forces between starch molecules and promotes the formation of hydrogen bonds between starch and plasticizer molecules [26].

Elongation test. Elongation indicates the state of plastic after it changes in length during stretching [27]. In our research, the average elongation values of biodegradable plastic from banana peel starch with different glycerol concentrations ranged from 49.92 to 115.43%, with an average of 80.39%. The highest elongation value of 115.43% was found in the sample with 10% banana peel and 3% glycerol (Sample P_3G_1, see Table 4). The lowest elongation value of 49.942% occurred in the sample with 6% banana peel and 8% glycerol (Sample P_1G_3, see Table 4). Table 4 shows the average elongation values of the experimental biodegradable plastic.

The variance analysis showed that the concentration of *wak* banana peel starch significantly affected the elongation values ($p \leq 0.05$) while the concentration of glycerol and the ratio between the concentrations of banana peel starch and glycerol had no significant effect ($p > 0.05$). Figure 5 illustrates the effect of the concentration of banana peel starch on the elongation values of the experimental biodegradable plastic.

Figure 5 shows that a higher concentration of banana peel starch resulted in higher elongation values. It happened due to the increased fiber content. According to Hoque and Janaswamy, banana peels are abundant in total dietary fibers (43–50%), starch (3%), and lignocellulosic fiber [28, 29].

The high starch concentration in banana peel increased the elongation. The highest elongation was in the sample with 10% banana peel starch: at this concentration, the amount of dissolved solids in the plastic could stretch the polymer bonds in the starch, resulting in a more flexible biodegradable plastic. The stretching of starch polymer bonds as affected by glycerol and starch increased elongation. When combined with glycerol, starch with its high amylose content increased plastic elongation [30].

In our research, the elongation values were higher than those obtained by Oluwasina *et al.* [31]. In their study, the elongation values ranged from 10.85 to 24.55% while in this research it was 80.39%.

Biodegradation tests. Biodegradation tests determined how quickly the experimental plastic could degrade under the action of various microorganisms. We used soil as medium because it contains various types of decomposing microorganisms, i.e., fungi and bacteria, which fuel the degradation process [32]. In our study, the bio-

Table 4. Average elongation values, %, of biodegradable plastic from banana peel starch with glycerol as plasticizer

Таблица 4. Средние значения удлинения, %, биоразлагаемого пластика из крахмала банановой кожуры с глицерином

Concentration of *wak* banana peel (P)	Concentration of glycerol (G)		
	$G_1 = 2\%$	$G_2 = 5\%$	$G_3 = 8\%$
$P_1 = 6\%$	85.59	50.40	49.92
$P_2 = 8\%$	78.25	88.07	61.01
$P_3 = 10\%$	115.43	103.94	90.90

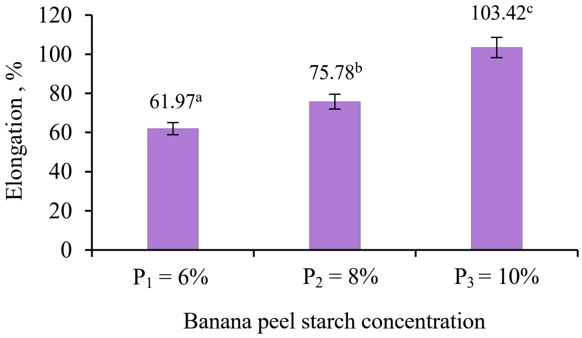


Figure 5. Effect of concentration of banana peel starch on elongation of biodegradable plastic

Рисунок 5. Зависимость удлинения биоразлагаемого пластика от концентрации крахмала банановой кожуры degradable plastic was made from starch, which is an organic component, easily decomposed by soil microorganisms. *Aspergillus niger* is a fungus that plays a significant role in plastic degradation. It contains α-amylase that breaks glycosidic bonds in starch into shorter polymers, e.g., glucose [33]. This is what makes organic plastic environmentally friendly.

The samples of biodegradable plastic stayed in soil for 2 and 4 days. Table 5 shows the alterations that occurred during the storage of biodegradable plastic in soil.

Table 5 clearly demonstrates that samples P_3G_1, P_3G_2, and P_3G_3 remained on day 2. On days 2 and 4, all other samples degraded completely. The two-day storage proved that a combination of low starch addition (6–8%) led to faster degradation. Higher concentrations of glycerol (5–15%) affected the weight of the degraded samples. The plastic samples with 15% glycerol underwent a faster degradation process compared to the samples with a lower glycerol content.

The phenomenon could be explained by the hydrophilic nature of glycerol. It accelerates water absorption, allowing microorganisms to degrade plastic samples more quickly. Additionally, the OH groups in glycerol and starch can initiate hydrolysis reactions after absorbing water from the soil. As a result, starch degrades into small pieces until it eventually disappears in the soil. Polymers degrade due to the process of damage or a decrease in quality caused by the breaking of chain bonds in the polymer. This process depends on the ability of plastic to absorb water: more water makes it easier for the material to degrade because water serves as a medium for most microbes and bacteria. In addition, the natural degradability of the constituent components, as well as assistance from decomposing bacteria and organisms such as earthworms, can accelerate the rate of plastic degradation.

The breakdown of plastic in the soil could already be observed after the first day of planting, with a weight reduction of 40–50% from the average initial weight of 0.17 g. On day 2, the weight reduction percentage reached 40%. By day 4, the biodegradable plastic had completely degraded.

Mueller, who also studied the degradation ability of plastic in a soil burial test, concluded that the degradation capability of synthesized plastic was affected by various factors, e.g., soil type, microbial type, and humidity [34]. A study by Rusdianto *et al.* managed to degrade plastic completely within a month using the same method but with maleic acid as a plasticizer [35]. In biodegradability tests, water should be able to penetrate the structure of the material to facilitate biological (microbial) activity [36]. This finding was further supported by Song *et al.*, in

Table 5. Plastic biodegradation test

Таблица 5. Результаты теста на биодеградацию пластика

	G_1	G_2	G_3	Total
P_1	0	0	0	0
P_2	0	0	0	0
P_3	40	50	52	142
	40	50	52	Mean = 47.3

Table 6. Functional group analysis by Fourier-transform infrared (FTIR) spectrometry

Таблица 6. Анализ функциональных групп по результатам инфракрасной спектроскопии с преобразованием Фурье

Vibration type	Wave length, cm^{-1}
	Banana peel starch + glycerol
-OH hydroxyl	3,655–3,584
CH_3 methyl	–
C=C alkene	2,000–2,200
C=O carbonyl	–
C-O ester	–

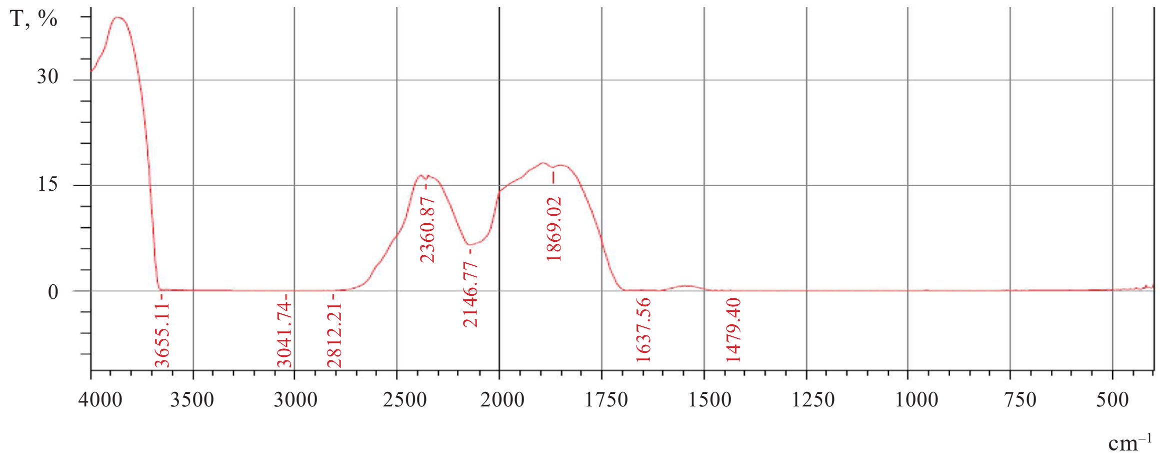
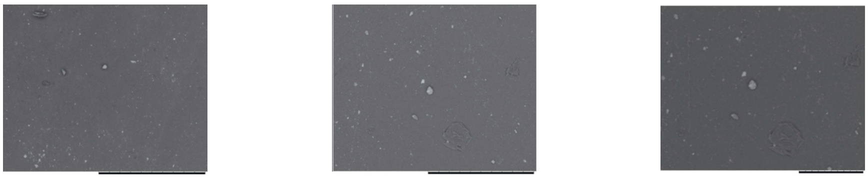


Figure 6. Effect of banana peel starch and glycerol on functional groups in biodegradable plastic

Рисунок 6. Влияние крахмала банановой кожуры и глицерина на функциональные группы биоразлагаемого пластика



a
Biodegradable plastic display
with 100× magnification

b
Biodegradable plastic display
with 1.000× magnification

c
Biodegradable plastic display
of starch with 1.200× magnification

Figure 7. Morphology of biodegradable plastic from banana starch by scanning electron microscope (SEM)

Рисунок 7. Морфология биоразлагаемого пластика из бананового крахмала по результатам сканирующей электронной микроскопии

whose soil burial test the biodegradable plastic developed holes that would affect the polymer matrix and make the plastic brittle [37]. In our study, the plastic degraded more quickly because glycerol absorbed moisture from the air.

Functional group test. The functional group test involved Fourier-transform infrared (FTIR) equipment. FTIR spectrometry is widely employed to identify a compound because different (organic) compounds have different FTIR spectra. Vibrations of chemical bonds in a molecule cause absorption bands predominantly in the spectral range of 4000–400 cm^{-1} [38].

The synthesized biodegradable plastic was chemically characterized by analyzing the end groups using the FTIR method (Table 6).

Figure 6 illustrates the effect of concentrations of banana peel starch and glycerol containing two types of functional groups, namely hydroxyl groups (-OH) in the range of 3655–3584, classified as alcohols and phenols. The absorption of the alkene C=C was in the range of 2000–2200.

The FTIR spectra made it possible to analyze how monomers combine to generate polymers. The hydrogen-linked polymeric OH stretch vibrations of starch were represented by a large, strong band at 3655.11 m^{-1}, as seen in the FTIR spectra of banana peel starch [39, 40]. The prevalence of -CH_2 groups with C-H stretch peaked at 2812.21 cm^{-1} [41]. Between 600 and 1500 cm^{-1} was the starch fingerprint zone [42]. Within the fingerprint region, the distinctive starch peaks overlapped one another. As a result, bands appeared at 1637 and 1479.40 cm^{-1}, which corresponded to the C-C stretch and C-O-C glycoside linkages, respectively [39, 43]. According to Weligama Thuppahige *et al.* [42], the band at 1869.02 cm^{-1} corresponded to N-H primary amine bends of proteins linked to banana peel starch. The moisture (10–13.5%) and protein (3%) contents of starch are accepted by the codex criteria for their exceptional quality [42, 44].

Our plastic was hydrophilic because the functional groups were the same as its constituent component, i.e., starch. Thus, a physical blending process occurred. Plastic is biodegradable if the carbonyl C=O group is visible in the absorption region of the 1600s and the C-O ester appears in the range of the 1100s. The results of the functional group analysis indicated a low transmission of infrared rays, which means that few bonds or functional groups were well-identified, resulting in a very dark sample color.

Scanning electron microscopy (SEM). Scanning electron microscopy is a method used to create images of microscopic surfaces. An electron beam with a diameter between 5 and 10 nm is passed along the sample. The interactions between them result in such phenomena as high-energy electron reflection, low-energy secondary electron formation, electron absorption, X-ray formation, or visible light formation (cathodoluminescence) [45].

Figure 7 indicates that the surface of the biodegradable plastic was smooth. However, white spots were visible in the images at all three levels of magnification. Probably, they were starch granules that did not mix homogeneously with other materials.

In the image, each particle is bound to another one, indicating excellent density and resulting in a relatively low water absorption compared to other biodegradable plastics. Almalik *et al.* conveyed a similar notion, attributing imperfect mixing and non-homogeneous morphological structure of the film to incomplete stirring and the presence of chitosan, which is insoluble in organic solvents [46].

The surface was not free from air bubbles. The formation of air cavities was caused by stirring and molding, which affected the surface structure of the biodegradable plastic. The better the molding process, the faster the evaporation of water vapor contained in the material. As a result, particles moved upwards during the water evaporation process, thus making intercellular layers merge.

Conclusion

Banana peel starch significantly affected tensile strength and elongation while having no significant effect on water content and water absorption in the experimental biodegradable plastic. Glycerol concentration had a significant effect on water content and tensile strength but none on water absorption and elongation.

The ratio between the concentrations of *wak* banana peel starch and glycerol concentrations significantly affected tensile strength and water absorption. The best results belonged to the sample with 8% banana peel starch and 2% glycerol: its water content was 48.00%, water absorption was 231.5%, tensile strength was 3 MPa, and elongation was 78.25%. The surface of the biodegradable plastic was smooth. It had two types of functional groups, namely hydroxyl groups (OH) in the range of 3655–3584 cm^{-1}, classified as alcohols and phenols. The absorption of the alkene C=C was in the range of 2000–2200 cm^{-1}. The new biodegradable plastic was hydrophilic because the functional groups were the same as in starch, which indicated physical blending. The car-bonyl C=O group in the absorption region of the 1600s and the C-O ester in the range of the 1100s proved that the alternative plastic obtained from *wak* banana peel was biodegradable.

Contribution

All the authors were equally involved in the research analysis and manuscript writing.

Conflict of interest

The authors declare no conflict of interests regarding the publication of this article.

Критерии авторства

Все авторы в равной степени принимали участие в исследовании и написании рукописи.

Конфликт интересов

Авторы заявляют об отсутствии потенциальных конфликтов интересов в отношении исследования, авторства и / или публикации данной статьи.

References

1. Kadam P, Datta S. Production of Biodegradable Plastic from Banana Peel. International Journal of Innovative Research in Science. Engineering and Technology. 2020;9(7):6177–6185. https://www.ijirset.com/upload/2020/july/141_PRODUCTION_NC.PDF

2. Lilis K, Wahyu S, Sapta Hadi K. Characteristic of ascorbic acid in crosslinked chitosan edible film as drug delivery system membrane. MATEC Web of Conferences. 2018;154:01027. https://doi.org/10.1051/matecconf/201815401027

3. Saleh ERM, Utami S. Characteristics of biodegradable plastic from mulu bebe banana peel starch with the addition of chitosan and glycerol plasticizer. Conference Series: Earth and Environmental Science. 2023;1177:012047. https://doi.org/10.1088/1755-1315/1177/1/012047

4. Dalimunthe NF, Al Fath MT, Taslim, Samosir ML, Sianipar DJ. The effect of additional kepok banana blossom (Musa paradisiaca normalis) on mechanical properties of pectin-edible film as packaging. Conference Series: Earth and Environmental Science. 2024;1352:012008. https://doi.org/10.1088/1755-1315/1352/1/012008

5. Irmayanti I, Juliani J, Anwar C, Irhami I, Aprita IR. Pengaruh penambahan tepung melinjo (Gnetum Gnemon linn.) dan lama pengukusan terhadap sifat fisik dan uji hedonik flakes. Serambi Journal of Agricultural Technology. 2023;5(1):36–46. https://doi.org/10.32672/sjat.v5i1.6168

6. Irmayanti I, Sunartaty R, Anwar C. Rich in fiber biscuits formulation with katuk leaf flour fortification (Sauropus androgynus) and roasting time variation. Serambi Journal of Agricultural Technology. 2019;1(2):66–73. https://doi.org/10.32672/sjat.v1i2.1599

7. Darni Y, Utami H. Development of Environmentally Friendly Bioplastic from Sorghum Starch: Study on Manufacturing and Characterization of Mechanical Properties. Jurnal Teknik Kimia Universitas Diponegoro. 2021;9(2):87–95. https://jurnal.usk.ac.id/RKL/article/view/79/73

8. Amalia D, Saleh D, Djonaedi E. Synthesis of biodegradable plastics using corn starch and corn husk as the fillers as well as chitosan and sorbitol. Journal of Physics: Conference Series. 2020;1442:012007. https://doi.org/ 10.1088/1742-6596/1442/1/012007

9. Fitrianti Y, Azzahra RT, Kusumawati E, Keryanti. Pengaruh Penambahan Polyvinyl Alcohol (PVOH) pada Biofoam dari Tepung Biji Nangka dan Ampok Jagung dengan Metode Thermopressing. Jurnal Teknik Kimia USU. 2023;12(2):100–107. https://doi.org/10.32734/jtk.v12i2.9228

10. Cerqueira MA, Souza BWS, Teixeira JA, VicenteAA. Effect of glycerol and corn oil on physicochemical properties of polysaccharide films – A comparative study. Food Hydrocolloids. 2023;27(1):175–184. https://doi.org/10.1016/j.foodhyd.2011.07.007

11. Galietta G, Di Gioia L, Guilbert S, Cuq B. Mechanical and Thermomechanical Properties of Films Based on Whey Proteins as Affected by Plasticizer and Crosslinking Agents. Journal of Dairy Science.1998;81(12):3121–3130. https://doi.org/10.3168/jds.S0022-0302(98)75877-1

12. Abdillahi H, Chabrat E, Rouilly A, Rigal L. Influence of citric acid on thermoplastic wheat flour/poly (lactic acid) blends. II. Barrier properties and water vapor sorption isotherms. 2013;50:104–111. https://doi.org/10.1016/j.indcrop.2013.06.028

13. Amatullah AN, Kemala T, Irawadi TT. The Heat Resistant Capabilities of Bioplastic Composites on Sago Hampas Starch-Al2O3. Jurnal Rekayasa Kimia dan Lingkungan. 2022;17(2):97–103. https://doi.org/10.23955/rkl.v17i2.25520

14. Praseptiangga D, Maimuni BH, Manuhara GJ, Muhammad DRA. Mechanical and Barrier Properties of Semi Refined Kappa Carrageenan-based Composite Edible Film and Its Application on Minimally Processed Chicken Breast Fillet. Conference Series: Materials Science and Engineering. 2018;333:012086. https://doi.org/10.1088/1757-899X/333/1/012086

15. Arifin HR, Indiarto R, Ciptaningtiyas D. Physical characteristics of edible film from modified breadfruit starch (*Artocarpus atilis* F.) with glycerol. Conference Series: Earth and Environmental Science.2020;443:012028. https://doi.org/10.1088/1755-1315/443/1/012028

16. Ginting MHS, Hasibuan R, Lubis M, Tanjung DS, Iqbal N. Effect of Hydrochloric Acid Concentration as Chitosan Solvent on Mechanical Properties of Bioplastics from Durian Seed Starch (Durio Zibethinus) with Filler Chitosan and Plasticizer Sorbitol. Conference Series: Materials Science and Engineering. 2017;180:012126. https://doi.org/10.1088/1757-899X/180/1/012126

17. Ermawati TA, Rahmadhia SN. Physico-chemical characteristics of edible film from breadfruit starch (*Artocarpus altilis*) and beeswax. Advances in Food Science, Sustainable Agriculture and Agroindustrial Engineering. 2023;6(4):325–337. https://doi.org/10.21776/ub.afssaae.2023.006.04.1

18. Li Y, Duan Q, Yue S, Alee M, Liu H. Enhancing mechanical and water barrier properties of starch film using chia mucilage. International Journal of Biological Macromolecules. 2024;274:133288. https://doi.org/10.1016/j.ijbiomac.2024.133288

19. Vijayakumar V, Nam SY. A Review of Recent Chitosan Anion Exchange Membranes for Polymer Electrolyte Membrane Fuel Cells. Membranes. 2022;12(12):1265. https://doi.org/10.3390/membranes12121265

20. Ratna R, Hari M, Syafriandi S. Pemanfaatan Pektin Kulit Pisang Kepok (*Musa paradisiaca* L.) Untuk Pembuatan Kemasan Edible film Dengan Penambahan Gliserol Sebagai Plasticizer. Rona Teknik Pertanian. 2022;15(1):97–107. https://doi.org/10.17969/rtp.v15i1.23820

21. Fahrullah F, Kisworo D, Noersidiq A. Edible Film Based on Whey-Chia Seed: Physical Characterization with Addition of Different Plasticizers. Jurnal Penelitian Pendidikan IPA. 2023;9(10):8554–8565. https://doi.org/10.29303/jppipa.v9i10.4978

22. Pitak N, Rakshit SK. Physical and antimicrobial properties of banana flour/chitosan biodegradable and self sealing films used for preserving Fresh-cut vegetables. LWT - Food Science and Technology. 2011;44(10):2310-2315. https://doi.org/10.1016/j.lwt.2011.05.024

23. Echeverria L, da Silva C, Danesi EDG, Porciuncula BDA, Barros BCB. Characterization of okara and rice bran and their application as fat substitutes in chicken nugget formulations. LWT. 2022;161:113383. https://doi.org/10.1016/j.lwt.2022.113383

24. Dalimunthe NF, Al Fath MT, Taslim, Samosir ML, Sianipar DJ. The effect of additional kepok banana blossom (*Musa paradisiaca normalis*) on mechanical properties of pectin-edible film as packaging. Conference Series: Earth and Environmental Science. 2024;1352:012008. https://doi.org/10.1088/1755-1315/1352/1/012008

25. McHugh TH, Krochta JM. Sorbitol- vs glycerol-plasticized whey protein edible films: integrated oxygen permeability and tensile property evaluation. Journal of Agricultural and Food Chemistry. 1994;42(4):841–845. https://doi.org/10.1021/jf00040a001

26. Sanyang ML, Sapuan SM, Jawaid M, Ishak MR, Sahari J. Effect of Plasticizer Type and Concentration on Tensile, Thermal and Barrier Properties of Biodegradable Films Based on Sugar Palm (*Arenga pinnata*) Starch. Polymers. 2015;7(6):1106–1124. https://doi.org/10.3390/polym7061106

27. Mappamadeng AH, Amalia R. Optimization and Characterization of Physical–Mechanical Properties of Biodegradable Edible Films Based on Pectin from Breadfruit Peel for Food Packaging. Journal of Vocational Studies on Applied Research. 2022;4(1):1–6. https://doi.org/10.14710/jvsar.v4i1.14175

28. Hoque M, Janaswamy S. Biodegradable packaging films from banana peel fiber. Sustainable Chemistry and Pharmacy. 2024;37:101400. https://doi.org/10.1016/j.scp.2023.101400

29. Lai JCH, Mahesan D, Samat NASbA, Baini R. Characterization and optimization of extracted pectin from unripe banana and mango fruit peels. Materiakstoday: Proceedings. 2022;65:3020–3029. https://doi.org/10.1016/j.matpr.2022.03.580

30. Lilis K, Wahyu S, Kesuma SH. Characteristic of ascorbic acid in crosslinked chitosan edible film as drug delivery system membrane. MATEC Web of Conferences. 2018;154:01027. https://doi.org/10.1051/matecconf/201815401027

31. Oluwasina OO, Olaleye FK, Olusegun SJ, Oluwasina OO, Mohallem NDS. Influence of oxidized starch on physicomechanical, thermal properties, and atomic force micrographs of cassava starch bioplastic film. International Journal of Biological Macromolecules. 2019;135:282–293. https://doi.org/10.1016/j.ijbiomac.2019.05.150

32. Shiwei L, Yufei Li, Zhao S, Shao Z. Biodegradation of Typical Plastics: From Microbial Diversity to Metabolic Mechanisms. International Journal Molecular Sciences.2024;25(1):593. https://doi.org/10.3390/ijms25010593

33. Fibriarti BL, Feliatra, Amin B, Darwis. Biodegradation of LDPE plastic by local strain of *Bacillus* sp.isolated from dump soil of Pekanbaru, Indonesia. Biodiversitas Journal of Biological Diversity. 2021;22(12):5484–5490. https://doi.org/10.13057/biodiv/d221232

34. Mueller R-J. Biological degradation of synthetic polyesters—Enzymes as potential catalysts for polyester recycling. Process Biochemistry. 2006;41(10):2124–2128. https://doi.org/10.1016/j.procbio.2006.05.018

35. Rusdianto AS, Usman M, Lindriati T, Ruriani E, Mahardika NS. The Characterization of Biodegradable Plastics from Cassava Starch with Varried Addition of Robusta Coffee Skin (*Coffea canefora*) and Glycerol. International Journal on Food, Agriculture, and Natural Resources. 2022;3(3):34-38. https://doi.org/10.46676/ij-fanres.v3i3.68

36. McCrum NG, Buckley CP, Bucknal CB. Principles of Polymer Engineering. Oxford University Press, 2021. 464 p.

37. Song JH, Murphy RJ, Narayan R, Davies GBH. Biodegradable and compostable alternatives to conventional plastics. Philosophical Transactions of the Royal Society B: Biological Sciences. 2009;364(1526):2127–2139. https://doi.org/10.1098/rstb.2008.0289

38. Tanjung DA, Jamarun N, Lubis R. Optimization of malic anhydrate concentration in manufacturing PP-g-MA compatibilizer on test percent of grafting degree. Jurnal Natural. 2024;24(2):93–97. https://doi.org/10.24815/jn.v24i2.35317

39. Coates JP. Interpretation of infrared spectra: Recent advancements and applications. Applied Spectroscopy Reviews. 1996;31:179–192. https://doi.org/10.1080/05704929608000568

40. Czaikoski A, da Cunha RL, Menegalli FC. Rheological behavior of cellulose nanofibers from cassava peel obtained by combination of chemical and physical processes. Carbohydrate Polymers. 2020;248:116744. https://doi.org/10.1016/j.carbpol.2020.116744

41. Charoensopa K, Thangunpai K, Kong P, Enomae T, Enomae T, Ploysri W. Extraction of Nanocellulose from the Residue of Sugarcane Bagasse Fiber for Anti-Staphylococcus aureus (*S. aureus*) Application. Polymers. 2024;16(11);1612. https://doi.org/10.3390/polym16111612

42. Thuppahige VTW, Moghaddam L, Welsh ZG, Wang T, Xiao H-W, Karim A. Extraction and characterisation of starch from cassava (*Manihot esculenta*) agro-industrial wastes. LWT. 2023;182:114787. https://doi.org/10.1016/j.lwt.2023.114787

43. Ferreira DCM, Molina G, Pelissari FM. Biodegradable trays based on cassava starch blended with agroindustrial residues. Composites Part B: Engineering. 2020;183:107682. https://doi.org/10.1016/j.compositesb.2019.107682

44. Algar AFC, Umali AB, Tayobong RRP. Physicochemical and functional properties of starch from Philippine edible Canna (*Canna indica* L.) rhizomes. Journal of microbiology, biotechnology and food sciences. 2019;9(1):34–37. https://doi.org/10.15414/jmbfs.2019.9.1.34-37

45. Baidurah S. Methods of Analyses for Biodegradable Polymers: A Review. Polymers. 2022;14(22):4928. https://doi.org/10.3390/polym14224928

46. Almalik A, Donno R, Cadman CJ, Cellesi F, Day PJ, Tirelli N. Hyaluronic acid-coated chitosan nanoparticles: Molecular weight-dependent effects on morphology and hyaluronic acid presentation. Journal of Controlled Release. 2013;172(3):1142–1150. https://doi.org/10.1016/j.jconrel.2013.09.032