

Effects of Glycerol Content and Drying Temperatures on the Properties of Durian Rind Film

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Abstract

This research aimed to study the effects of glycerol as a plasticizer and the effects of drying temperatures on the physical, mechanical, and chemical properties of durian rind powder films. The glycerol content was studied at three levels, specifically; 0.75, 1.5, and 2.25% weight by volume (W/V), and the films were formed by drying at 35, 40, and 45°C. After drying, the obtained films were tested for physical, mechanical and chemical properties, including thickness, color value, moisture content, water vapor permeability, water solubility, tensile strength, water activity (a_w), and film degradation. The results found that, films had a thickness range of 0.14–0.17 mm, a brightness value (L^*) range of 72.3–76.8 and a moisture content range of 8.74–11.24%. The water vapor permeability and water solubility increased with increasing glycerol content. With respect to the mechanical properties, it was found that when the glycerol content increased, the tensile strength decreased. In contrast, the elongation of the films increased. Film degradation tests showed that increasing temperature and glycerol content resulted in a shorter degradation rate.

Keywords: Biodegradability, Durian rind, Drying

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Introduction

Currently, more than 460 Mt of plastic are produced worldwide. However, when plastic waste is improperly managed, it becomes an environmental pollutant. Approximately 1–2 Mt of plastic enter the oceans each year (Ritchie et al., 2023) causing adverse impacts on marine organisms and ecosystems. Therefore, improving global plastic waste management is critically important for addressing this issue.

Biomaterials have received increasing attention due to their environmentally friendly nature. These materials do not cause environmental toxicity during use or after disposal. In addition, the production processes of biomaterials can reduce greenhouse gas emissions compared with the manufacture of petroleum-based plastics. Moreover, agricultural or industrial waste materials can be utilized as raw materials, thereby adding value to waste resources.

Biodegradable films used for packaging various types of products are gaining popularity as substitutes for synthetic plastic-based packaging. These films can be used for food packaging or other consumer goods. Conventional plastics, after use, pose serious disposal problems, either being difficult to destroy or causing environmental pollution when discarded. Even when left to degrade naturally, they require a long period to decompose.

Currently, research and development efforts are focusing on materials that can replace plastics, known as biodegradable films. These films are being improved to possess properties similar to those of synthetic plastics, while also being more easily degradable in natural environments. Generally, the production of biodegradable films involves either synthetic-based polymers or bio-based polymers. In the case of bio-based polymers, film formation involves the use of components such as synthesized proteins, polysaccharides, fats, or a combination of various polymers to form composite films (Sothornvit & Krochta, 2005).

Most films are produced using starch-based polymers due to their abundance and low cost. However, using only starch as a single polymer results in brittle films that tear easily and are unsuitable for practical

applications. Thus, plasticizers must be added to improve various film properties (Sothornvit & Krochta, 2000). To obtain appropriate film characteristics for specific applications, plasticizers such as glycerol, polyethylene glycol, sorbitol, or others must be incorporated into the production process (Sukkasem et al., 2017). It has been reported that glycerol-plasticized films show better formability and greater flexibility than those using sorbitol.

Glycerol is highly compatible with hydrophilic polymers. It contains multiple hydroxyl ($-OH$) groups that can form hydrogen bonds with polymer chains such as starch, cellulose, and pectin. This interaction reduces intermolecular forces and enhances chain mobility, thereby increasing the flexibility of the films (Tarique et al., 2021). However, drying temperature has a significant influence on the distribution of glycerol within the polymer matrix, which in turn affects film density, free volume, and certain mechanical properties (Lina et al., 2025).

Durian, a major economic crop of Thailand, is widely consumed both domestically and internationally. In 2024, Thailand exported 1,546,218 tons of fresh durian, with a total export value exceeding 208 million baht. Domestic consumption amounted to 366,160 tons including both fresh durian and processed durian products. The durian consumption process produces a large volume of durian rind waste. Durian rind is primarily composed of carbohydrates, with composition similar to that of rice (Rachtanapun et al., 2012). It has been reported to contain approximately 60.45% cellulose, 15.45% lignin, 13.09% hemicellulose, 4.20% ash and pectin (2.27–9.35%) (Lee et al., 2020; Wai et al., 2009). Jariyapamornkoon et al. (2024) reported that pectin is widely used in food products due to its versatile functional properties, such as its ability to act as a gelling agent, thickener, and flexibility-enhancing agent. Zhao et al. (2019) isolated cellulose from durian rind to produce high-tensile-strength films for packaging applications, which were fully biodegradable in soil within four weeks. Uppasen et al. (2023) studied biocomposite films derived from durian rind and pineapple leaves and found that the films dissolved in the presence of soil moisture and were completely degraded within 24 h. This demonstrates the suitability of using durian rind to produce polymers for use in forming biodegradable films.

Therefore, this study aims to investigate the feasibility of processing Monthong durian rind for use as a polymer in biodegradable film production. The films were prepared with varying glycerol contents and dried at different temperatures. Furthermore, this approach may contribute to reducing durian rind waste and add value to agricultural by-products.

Materials and methods

1. Preparation of durian rind powder

Monthong durian from Chanthaburi Province, harvested within two weeks prior to the experiment, was used. Durian rind were prepared by removing the thorny and hard outer layers, retaining only the white inner pulp. The selected pulp was washed, cut into small pieces, and air-dried. It was then dried in a hot-air oven at 80°C until the moisture content was reduced to approximately 12–14% (dry basis). After cooling, the dried material was ground using a flour food grinder (JY-800, Henan Jiuyong Machinery Equipment Co., Ltd., China) and sieved through a 250 μ m mesh screen. and was stored in a vacuum-sealed container at room temperature (25 $\pm$ 1°C) for further analysis.

2. Film preparation

The film preparation was adapted from Bagheri et al. (2019). Durian rind powder (3% w/v) was dissolved in distilled water at 80°C and continuously stirred using a hotplate stirrer at a stirring speed of 150 rpm for 3 h. Then, 3 g of sodium alginate were added, and the solution was allowed to cool while stirring at room temperature for 1 h. Glycerol (Premium Glycerine, Srithongtaveep Chemical Co., Ltd., Thailand) was added at 3 concentrations 0.75, 1.5, and 2.25% (w/v) and the solution was stirred for another 30 min. A control formulation without glycerol was excluded because films prepared in the absence of glycerol as a plasticizer became hard and brittle after drying, fractured easily and could not be peeled intact from the casting plate. A 60-g portion of the film-forming solution was poured onto a smooth acrylic tray (16 $\times$ 24 $\times$ 3 cm) and dried in a hot-air oven at 35, 40, and 45°C until a final moisture content of 8–12% (dry basis) was achieved. The dried film was then peeled off and stored in a desiccator with a relative humidity of 10–20% RH for subsequent property testing.

3. Film property testing

3.1 Thickness

Film thickness was measured using a digital vernier caliper (500-712-20, Mitutoyo Thailand Co., Ltd., Thailand) with 2 decimal precisions. Measurements were taken at three different points and averaged.

3.2 Color

Film color was measured using a HunterLab colorimeter (ColorFlex EZ 45/0 (LAV), Hunter

Associates Laboratory, Inc., USA). Measurements were taken at 3 different points and averaged.

3.3 Moisture content

Moisture content was determined using a moisture analyzer (MX-50, A&D Company Limited, Japan). Film samples were cut into small pieces. The test was performed according to the operating requirements of the moisture analyzer. Moisture values were recorded.

3.4 Mechanical properties

Mechanical properties were tested according to ASTM D882 using a Texture analyzer (TA-XT2, Stable Micro Systems Ltd., UK). Film samples were cut to 25×100 mm and tested at a speed of 50 mm/min with a gauge length of 60 mm. Tensile strength and percent elongation at breaking point were recorded.

3.5 Water vapor transmission rate (WVTR)

WVTR was tested based on ASTM E96-95, modified from the method of Gontard et al. (1993). Circular film samples (7 cm diameter) were sealed over the mouths of cups (4.8 cm diameter, 5.8 cm height) containing 30 mL of distilled water. The cups were sealed with adhesive tape, weighed, and stored in a desiccator containing silica gel. Weight changes were recorded after 24 h, and the experiment was performed in triplicate. WVTR was calculated as;

$$\text{WVTR} = \text{Slope} / \text{Film area} \quad (1)$$

Where: WVTR is the water vapor transmission rate ($\text{g}/\text{m}^2 \cdot \text{day}$), slope is the weight loss/day (g/day) and film area is the surface area through which vapor permeates (m^2)

3.6 Water solubility

Water solubility was adapted from Jouki et al. (2013) film samples (40×100 mm) were dried at 105°C for 24 h, weighed (w), and then immersed in 30 mL of distilled water. The mixture was stirred using a magnetic stirrer for 24 h. The remaining film was filtered through pre-weighed Whatman No.1 filter paper (a_1), dried again at 105°C for 24 h, and reweighed (a_2). Water solubility was calculated as;

$$\% \text{Water solubility} = [(w - (a_2 - a_1)) / w] \times 100 \quad (2)$$

Where: W is the initial film weight (g), a_1 is the initial weight of filter paper (g), and a_2 is the final weight of filter paper (g).

3.7 Water activity (a_w)

Water activity (a_w) represents the proportion of free water molecules available in a food system and is a critical factor in the control and prevention of food spoilage. The a_w values in this study were measured using an Aqualab water activity meter (Series 4, Decagon Devices Inc., USA).

3.8 Biodegradation test

Biodegradation test was adapted from Theamdee and Sooksamran (2020). Film samples (2×5 cm) were weighed and buried in loamy soil (20–25% moisture by weight) at a depth of 8–10 cm in a shaded area without irrigation for 4 weeks. Subsequently, the remaining film sheets were recorded. Biodegradation was calculated as;

$$\text{Biodegradation} = [(A - B) / A] \times 100 \quad (3)$$

Where; A is the initial film weight (g), B is the film weight after degradation (g).

3.9 Microstructural analysis

Microstructural properties of the film surface and cross-sections were analyzed using a scanning electron microscope (SEM) (JSM-IT300, JEOL Ltd., Japan), low-vacuum microscopy to observe the correlation with other test results. The specimens used for testing had dimensions of 5×5 mm. Conductive tape was placed on the specimen stub, and the specimen was then attached to the stub.

3.10 Statistical analysis.

The data obtained from this research were analyzed using analysis of variance (ANOVA) to determine the statistical significance of differences among variables. Duncan's New Multiple Range Test (DMRT) was applied to compare the means at a confidence level of $\alpha=0.05$. All statistical analyses were performed using the SPSS Statistics 22 software. All film property tests were performed in triplicate

Results and discussion

The results of the drying process indicated that drying at 35, 40, and 45°C required 9, 6, and 4 h, respectively. The biodegradable film made from durian peel exhibited a brown color, resembling the color of durian peel flour. This coloration may be due to the non-enz browning reaction occurring during the drying process. The film was flexible. The surface of the film that was exposed to air during drying appeared relatively rough, possibly due to the coarse particle size of the durian peel flour and the evaporation of moisture into the atmosphere. In contrast, the side of the film in contact with the acrylic sheet had a smooth, glossy surface.

1. Thickness

When measuring the thickness of the film sheets, it was found that increasing the drying temperature significantly reduced the film thickness ($p < 0.05$). This reduction is attributed to more efficient water evaporation from the film-forming solution at higher temperatures, leading to greater shrinkage of the film due to water loss. This result is consistent with the findings of Perez-Gago & Krochta (2000) who reported that higher drying temperatures promote better alignment and bonding of polymer chains within the film matrix, resulting in a denser structure and consequently thinner films. In contrast, when comparing films with varying amounts of glycerol, it was observed that an increase in glycerol content significantly increased the film thickness ($p < 0.05$). This is due to glycerol's hygroscopic nature (Tapia-Blácido et al., 2013). Higher glycerol concentrations enhance the interaction between glycerol and the polymer, which slows down the evaporation of water during the drying process. These findings align with the report by Petersson and Stading (2005) who demonstrated that the addition of a plasticizer (acetylated monoglyceride) to cassava starch-based films resulted in increased film thickness. The measured film thickness values are illustrated in Fig. 1.

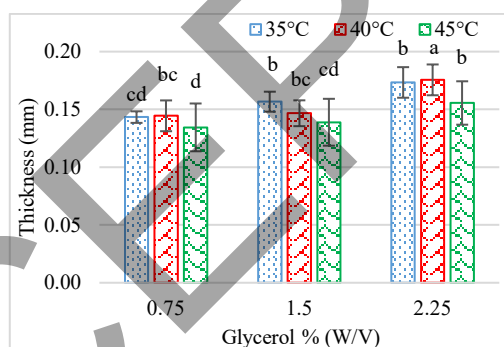


Fig. 1 Thickness of film

Remark: Different letters (a–d) representing statistically significant differences ($p < 0.05$).

2. Color

Due to the light brown color of durian rind powder, the films produced from durian rind powder exhibited a color corresponding to the natural hue of the starch used as the base material. Al-Harrasi et al. (2022) reported that films dried at lower temperatures showed lower transparency than those dried at higher temperatures. This reduction in transparency at lower drying temperatures can be attributed to the relatively higher moisture content retained in the films, which enhances light scattering within the film matrix. With respect to color parameters, higher b^* values were generally observed in films dried at higher temperatures, indicating increased yellowness. In contrast, films dried at lower temperatures tended to exhibit lower b^* values, which may be associated with non-uniform drying, where moisture evaporation occurs initially at the film surface while heat gradually penetrates into the inner layers. In addition, increased yellowness at elevated drying temperatures may also be related to the formation of Maillard reaction products during the drying process. The lightness value (L^*) ranged from 68.7 to 74.2, the a^* value ranged from 6.2 to 7.7, and the b^* value ranged from 16.2 to 21.9. Glycerol is a transparent, colorless compound and therefore does not directly contribute to the intrinsic color of the films. None of the increases in glycerol content had any significant effect on the color of the films. The color values of the films are shown in Table 1.

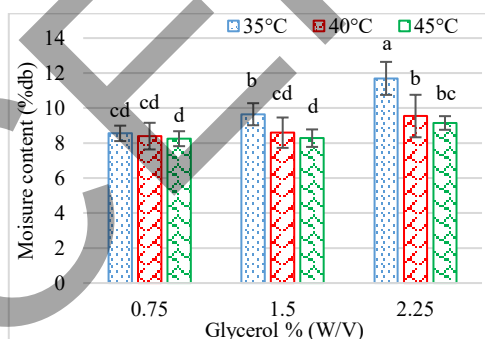
Table 1 Color of durian peel

Drying temperature	% glycerol (W/V)	Color			ΔE	WI
		L*	a*	b*		
35°C	0.75	72.8 ^a	6.4 ^{ab}	18.6 ^{bc}	7.6 ^b	33.6 ^b
	1.5	74.2 ^a	6.5 ^{ab}	16.2 ^c	9.7 ^a	31.1 ^c
	2.25	73.2 ^a	6.2 ^b	19.2 ^{ab}	7.8 ^b	33.5 ^b
40°C	0.75	69.6 ^d	7.2 ^{ab}	19.2 ^{ab}	4.5 ^{cd}	36.7 ^{ab}
	1.5	68.7 ^c	7.0 ^{ab}	19.4 ^{ab}	3.6 ^d	37.5 ^a
	2.25	69.2 ^{bc}	7.7 ^a	21.9 ^a	4.5 ^{cd}	38.5 ^a
45°C	0.75	70.3 ^{bc}	7.5 ^{ab}	19.2 ^{ab}	5.3 ^c	36.1 ^{ab}
	1.5	69.4 ^{bc}	7.2 ^{ab}	19.8 ^{ab}	4.3 ^{cd}	37.1 ^a
	2.25	70.9 ^b	7.4 ^{ab}	21.3 ^{ab}	5.7 ^c	36.8 ^a

Remark: Different lowercase superscripts (a–d) within the same column indicate statistically significant differences ($p < 0.05$).

3. Moisture content

The residual moisture content in the film varied according to the amount of glycerol. An increase in glycerol content led to higher moisture levels in the film, as glycerol is a polar molecule with hydrophilic properties, the water retention of glycerol is associated with intermolecular linkages and the molecular structure of plasticizers that can improve the chance of plasticizers interacting with water molecules. This characteristic allows the film to retain more moisture even when dried at the same temperature (Jaderi et al., 2023). This characteristic allows the film to retain more moisture even when dried at the same temperature. In contrast, increasing the drying temperature resulted in a decrease in film moisture content, as water in the film-forming solution evaporates more efficiently at higher temperatures. The moisture content of the films is presented in Fig. 2.

**Fig. 2** Moisture content of films

Remark: Different letters (a–d) representing statistically significant differences ($p < 0.05$).

4. Mechanical property

Due to the presence of multiple hydroxyl (–OH) groups, glycerol readily forms hydrogen bonds with both polymer chains and water molecules. This interaction reduces the intermolecular forces between polymer chains, leading to increased chain mobility and greater intermolecular spacing. As a result, the polymer matrix becomes more loosely packed, which increases the free volume and decreases the structural density. Consequently, the mechanical properties of the material are altered. High glycerol content enhances plasticization through hydrogen bonding, leading to greater chain mobility and free volume and consequently reducing tensile strength while improving film flexibility. An increase in glycerol content from 0.75 to 2.25%W/V (as shown in Fig. 3 and 4) allowed glycerol to effectively insert itself between molecular chains, thereby increasing the intermolecular spacing and reducing the cohesive forces between starch molecules (Rachtanapun & Tongdeesootorn, 2009). This led to a decrease in the tensile strength of the films while increasing their flexibility.

Drying temperature significantly influences the arrangement of polymer chains and the distribution of glycerol within the film matrix. At higher drying temperatures, water evaporates more efficiently, promoting polymer chain rearrangement and a more uniform film structure during the drying process. In contrast,

insufficient drying temperature may lead to water retention within the film, which can hinder effective hydrogen bonding between glycerol and the polymer chains. This results in a heterogeneous film structure and deteriorated mechanical properties, particularly a reduction in elongation at breaks. Notably, films with 0.75% (W/V) glycerol exhibited the highest tensile strength across all drying temperatures tested. Simultaneously, increasing the drying temperature enhanced the mobility of starch molecules, allowing them to realign into a more compact structure (Andrade-Mahecha et al., 2012; Bagheri et al., 2019; Ghaderi et al. 2019). As a result, the tensile strength of the films increased with temperature. The highest tensile strength was observed in films containing 0.75% (W/V) glycerol and dried at 45°C. Moreover, the high cellulose content and the presence of lignin in durian rind contribute to films that exhibit both mechanical strength and flexibility.

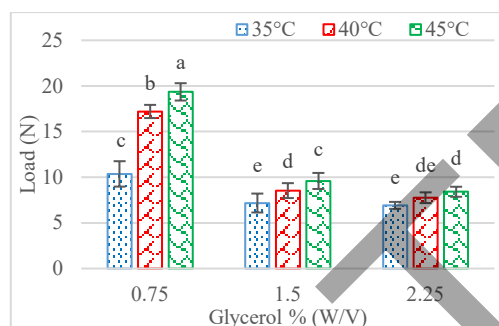


Fig. 3 Force resistance of film

Remark: Different letters (a–e) representing statistically significant differences ($p < 0.05$).

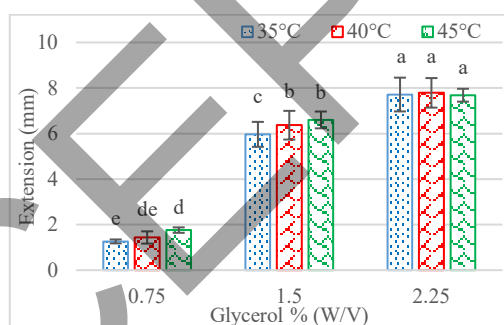


Fig. 4 Elongations of film

Remark: Different letters (a–e) representing statistically significant differences ($p < 0.05$).

5. Water vapor transmission rate (WVTR)

An increase in glycerol content led to a higher water vapor transmission rate, as shown in Fig. 5. This is because glycerol is a hydrophilic material that can easily insert itself into the gaps between durian rind powder molecules, thereby reducing the cohesive forces between polymer chains. As a result, more voids are formed within the polymer matrix after drying, allowing water vapor to permeate through the film more easily. Conversely, increasing the drying temperature enhanced the cohesive forces between molecules and improved the alignment and tightness of polymer chains, resulting in a denser structure. Higher drying temperatures enhance the mobility of both polymer chains and glycerol molecules, allowing glycerol to more effectively penetrate the intermolecular spaces between polymer chains. The uniform distribution of glycerol and the efficient formation of hydrogen bonds between glycerol and the polymer result in a film structure with an optimal free volume and improved structural continuity. This reduces the number of voids available for water vapor to pass through, thereby lowering the water vapor transmission rate. These findings are consistent with those reported by Miller and Krochta (1997) and Chiou et al. (2009).

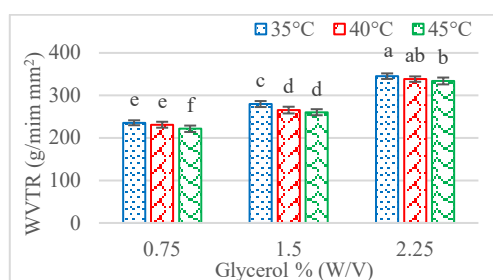


Fig. 5 Water vapor transmission rate

Remark: Different letters (a–f) representing statistically significant differences ($p < 0.05$).

6. Water solubility

An increase in the amount of glycerol resulted in higher water solubility of the film, as shown in Fig. 6. This is consistent with the findings of Jouki et al. (2013) and Jaderi et al. (2023). Plasticizers can effectively reduce the intermolecular interactions within biopolymers and enhance the water solubility of films because glycerol is a hydrophilic material. There are more (–OH) groups that form H-bonds with water. Therefore, glycerol incorporated into a film makes the film more easily soluble. This hydrophilic nature allows water molecules to penetrate into the polymer matrix more easily, thereby increasing the water solubility of the film as the glycerol content increases. Conversely, increasing the drying temperature leads to a decrease in the water solubility of the film, in alignment with the reports of Soazo et al. (2011) and Qin et al. (2023). High drying temperatures enhance the strength of the film, resulting in less water-soluble films. This observation is consistent with the experimental results on the mechanical properties and water vapor transmission rate of the film.

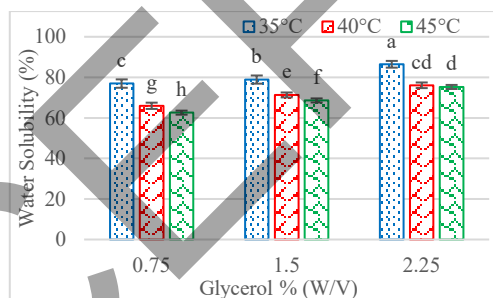


Fig. 6 Water solubility of film

Remark: Different letters (a–h) representing statistically significant differences ($p < 0.05$).

7. Water activity (a_w)

The a_w values ranged from 0.43 to 0.58, which falls within the range for dried foods (dried food typically has a_w not exceeding 0.6). These values are lower than the threshold required for the growth of bacteria, molds, and yeasts. Increasing the amount of glycerol did not affect the a_w value after drying. In contrast, drying at higher temperatures significantly reduced the a_w ($p < 0.05$). The higher drying temperatures facilitate the evaporation of free water in the product, which is directly related to the a_w value. As a result, a_w is lower compared to drying at lower temperatures. This is because higher temperatures enhance the evaporation of water from the film-forming solution. These findings are consistent with the report of Lombard et al. (2008), which indicated that high drying temperatures cause water in the product to rapidly migrate and evaporate through air gaps. The a_w indicates the minimum level of water that microorganisms can utilize for growth and participate in various chemical reactions. In general, most bacteria are unable to grow at a_w levels below 0.90, while the majority of molds cannot grow at a_w levels below 0.80. Nevertheless, certain xerophilic molds and osmophilic yeasts have been reported to survive and grow in food products with a_w values as low as 0.65 and 0.61, respectively (Srichayet, 2019). The water activity values are shown in Fig. 7.

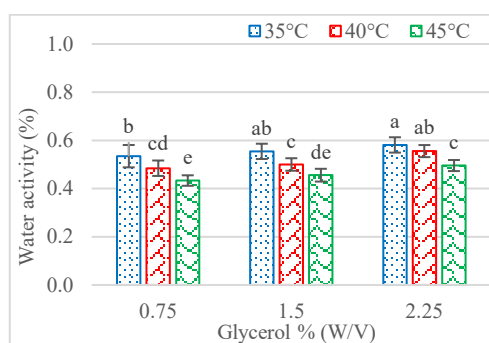


Fig. 7 Water activity of films (a_w)

Remark: Different letters (a–e) representing statistically significant differences ($p < 0.05$).

8. Biodegradation

After 4 weeks of biodegradation testing, it was observed that the film containing 2.25% (W/V) glycerol appeared noticeably thinner compared to the films with 0.75 and 1.5% (W/V) glycerol, respectively. The extent of film degradation is shown in Fig. 8.

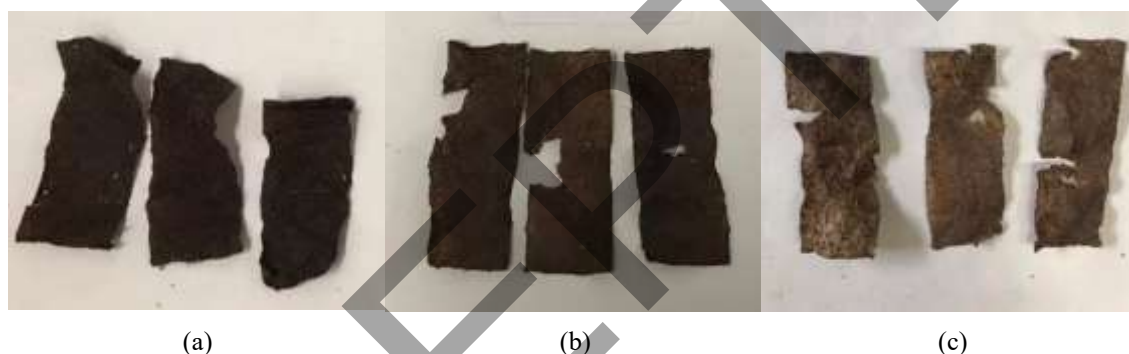


Fig. 8 Film degradation (a) Glycerol 0.75 % (W/V), (b) Glycerol 1.5 % (W/V) and (c) Glycerol 2.25 % (W/V)

According to the biodegradation test results, the films exhibited degradation rates ranging from 58.60% to 78.35%, as illustrated in Fig. 9, indicating their potential for environmental degradation. The drying temperature had no significant effect on the biodegradability of the films. However, an increase in glycerol content resulted in a significantly higher biodegradation rate ($p < 0.05$). This enhancement can be attributed to the intrinsic properties of durian rind powder, which, as a biopolymer, is readily biodegradable. Moreover, the incorporation of glycerol enhanced the hydrophilic characteristics of the films, thereby facilitating moisture absorption and stimulating microbial activity, which in turn accelerated the degradation process. These findings are consistent with the results reported by Babaei et al. (2015) and Theamdee and Pansaeng (2019) who observed that seedling bags made from tapioca starch with higher glycerol content demonstrated increased water absorption and solubility, consequently promoting faster biodegradation. It is important to note that biodegradation is influenced by various environmental factors, including soil moisture, temperature, microbial activity, and the presence of other biological agents, all of which can contribute to an increased degradation rate.

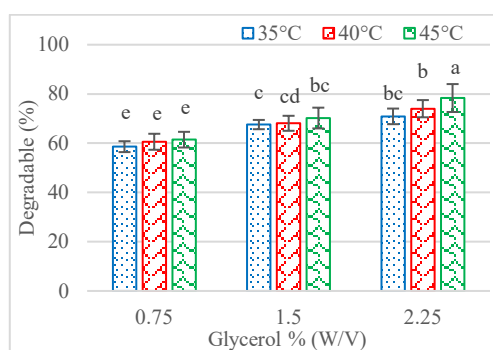


Fig. 9 Biodegradation rate of the film

Remark: Different letters (a–e) representing statistically significant differences ($p < 0.05$).

9. Microstructural analysis

Microstructural examination of the film cross-sections, as illustrated in Fig. 10, revealed that films with higher glycerol content exhibited a greater distribution of pores across the cross-sectional area compared to those with lower glycerol content. These pores, dispersed throughout the film matrix, are the result of glycerol molecules being incorporated into the intermolecular spaces of durian rind powder. Under high-temperature drying conditions, some of the glycerol molecules rapidly evaporated, resulting in the formation of voids throughout the film structure. This porous structure is directly related to a decrease in mechanical strength, an increase in water vapor transmission rate, enhanced water solubility, and a shorter biodegradation time. The findings suggest that both glycerol content and drying temperature play a significant role in influencing the film's structural and functional properties.

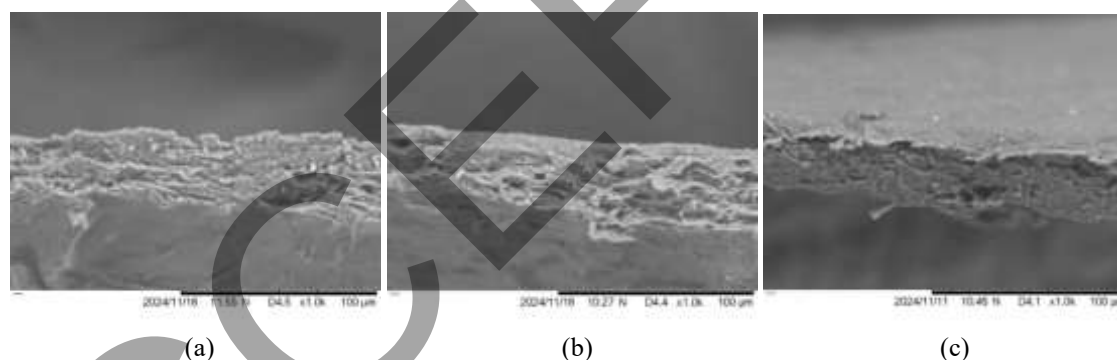


Fig. 10 SEM micrographs of the films cross-section (a) Glycerol 0.75 % (W/V), (b) Glycerol 1.5 % (W/V) and (c) Glycerol 2.25 % (W/V)

Conclusion

The results of this study demonstrate that biodegradable films can be successfully formed using thermal processing at various drying temperatures. The properties of the films were modified by incorporating different concentrations of plasticizers. A relationship was observed between the drying temperature and glycerol concentration used during film preparation. Due to its hydrophilic nature, glycerol can effectively interact with the polymer matrix. Increasing glycerol content led to an increase in film thickness, elongation at breaks, WVTR, water solubility, a_w and biodegradability. Moisture content was also highest in films with the highest glycerol concentration, while tensile strength decreased. In contrast, increasing the drying temperature resulted in enhanced film thickness, tensile strength, elongation, and biodegradability. This indicates that higher drying temperatures promote better molecular alignment and densification during the drying process. Meanwhile, WVTR, water solubility, moisture content, and water activity decreased with higher drying temperatures. Film formation from durian rind powder can be achieved using various glycerol concentrations and drying temperatures, depending on the desired functional properties for specific applications. Importantly, the films are environmentally friendly and naturally biodegradable. Durian rind powder-based films can be utilized in various packaging applications, including food packaging. The optimal conditions for film production were established at a glycerol concentration of 2.25% alongside drying

conditions of 45°C, as the resulting film demonstrated substantial flexibility and rapid biodegradation. Further study should investigate different types of plasticizers or alternative material combinations to enhance the durability, mechanical strength and color of bio-film, as well as to further explore their potential applications.

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Conflicts of interest

The authors declare no conflicts of interest.

Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this manuscript, the authors used ChatGPT to enhance language clarity and improve grammar. The final content was reviewed and edited by the corresponding authors, who take full responsibility for the accuracy and integrity of the publication.

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