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Valorization of banana peel (*Musa paradisiaca*) as a raw material for biopolymer production

Valorización de la cáscara de banano (*Musa paradisiaca*) como materia prima para la producción de biopolímeros

Jimena Taco *, Ronald Jiménez and Maria Soto

Instituto Superior Tecnológico Tsáchila. [https://ror.org/03fnk5526]

*Corresponding author: jimenataco@tsachila.edu.ec

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Abstract

The use of plastic materials and their negative effects on society have increased studies on biomaterials as substitute materials. In the present research, a biofilm obtained from banana peel (PBCP) was developed, and subsequently, several properties were evaluated. By means of centrifugation, pulverized banana was extracted by varying the number of revolutions per minute (rpm): 900, 1500, and 3000. Glycerol was used for the formation of PBCP at concentrations of 30 % and 50 %; additionally, the heating temperatures were controlled at 70, 80, and 90 °C. The results showed that due to the low protein content of the pulverized banana, the treatments did not show thermal denaturation. The treatments subjected to 3000 rpm and 90 °C denoted higher viscosity values (57 570 Pa·s). On the other hand, in the analysis of moisture absorption kinetics, it was determined that the temperature and rpm variables did not influence the results obtained; however, the higher the percentage of glycerol in the film, the higher the rate of moisture absorption, going from 3.1×10^{-10} to 3.7×10^{-10} cm^2/s and 3.9×10^{-10} to 4.9×10^{-10} cm^2/s, respectively. Regarding water vapor permeability, a significant difference in the levels of glycerol was evidenced; the PVA values of the PBCP in the different conditions ranged between 2.8 and 5.0 g·mm/(kPa·h·m^2). From the above, it is determined that it is possible to produce PBCP, and to improve the viscosity results, it is recommended to use an emulsifier to avoid the reagglomeration of the molecules.

Keywords: Biodegradability, biopolymer, plasticizer, production, rheology.

Resumen

El uso de materiales plásticos y sus efectos negativos en la sociedad ha incrementado los estudios acerca de biomateriales como materiales sustitutos. Durante la presente investigación se desarrolló una biopelícula obtenida a partir de cáscara de plátano (PBCP) y posteriormente se evaluaron varias propiedades. Mediante centrifugado se extrajo pulverizado de plátano variando el número de revoluciones por minuto (rpm): 900, 1500 y 3000. Para la formación de la PBCP se utilizó glicerol en concentraciones de 30 % y 50 %; adicionalmente, se controlaron las temperaturas de calentamiento en 70, 80 y 90 °C. Los resultados mostraron que, debido a la baja cantidad proteica del pulverizado de plátano, los tratamientos no muestran desnaturalización térmica; los tratamientos sometidos a 3000 rpm y 90 °C mostraron mayores valores de viscosidad (57 570 Pa·s). Por el contrario, en el análisis de cinética de absorción de humedad se determinó que las variables de temperatura y de rpm no influyen en los resultados obtenidos. No obstante, mientras mayor es el porcentaje de glicerol en la película, mayor es la tasa de absorción de humedad, pasando de $3,1 \times 10^{-10}$ a $3,7 \times 10^{-10}$ cm^2/s y de $3,9 \times 10^{-10}$ a $4,9 \times 10^{-10}$ cm^2/s, respectivamente. En la permeabilidad de vapor de agua se evidencia una diferencia significativa en los niveles de glicerol. Los valores de PVA de las PBCP en las diferentes condiciones oscilaron entre 2,8 y 5,0 g·mm/(kPa·h·m^2). Por lo expuesto anteriormente, se determina que es posible elaborar PBCP y, para mejorar los resultados de viscosidad, se recomienda usar un emulsionante para evitar la reaglomeración de las moléculas.

Palabras clave: Biodegradabilidad, biopolímero, plastificante, producción, reología.

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Orcid IDs:

Jimena Taco: https://orcid.org/0000-0002-2700-2351
Ronald Jiménez : https://orcid.org/0000-0002-7853-7540
Maria Soto: https://orcid.org/0000-0002-6196-6920

1 Introduction

Globalized markets and consumer demands for products of not only hygienic-sanitary quality but also environmentally friendly traits have led the food industry to a paradigm shift in production in order to adapt to the needs of its clients (Ramos et al., 2020). One of the strategies used by the agro-industry to achieve this goal is cleaner production (CP), which allows the internal or external recycling of waste to increase process efficiency and reduce environmental risks (Hoof et al., 2018; Lucero-Murillo et al., 2026).

Another issue related to food production and consumption is the progressive use of disposable packaging, which—despite advantages such as low cost, resistance to oxidation, functional specificity, and versatility—causes a serious environmental impact (Mejía Osorio, 2020). Furthermore, according to Tuárez et al. (2022), additives incorporated to improve the functional properties of polymers used in packaging migrate into food, posing potential risks to human health. In this context, researchers are currently seeking substitutes for non-biodegradable packaging, and combined efforts have led to the development of biodegradable packaging produced from biopolymers (Ospina, 2015).

In the agricultural sector, the scale of waste is extensive, for example, crop residues and plant waste that remain in the field after harvesting (Mikus and Galus, 2022). Therefore, the main degradable biopolymers used for the development of edible films, coatings, containers, and food packaging are polysaccharides, with particular emphasis on derivatives of organic residues (Eixenberger et al., 2022).

For instance, Taghavi Kevij et al. (2021) developed functional edible films using gelatin and different concentrations (0, 3, 6, 9, 12, and 15 %) of powdered orange peel (POP). The thickness, moisture percentage, and water vapor permeability of the gelatin films increased as the POP content in the formulation increased. Films with higher POP content exhibited greater resistance and lower elongation. Moreover, their results demonstrated that the antioxidant content, particularly phenolic compounds, significantly improved with POP incorporation. Regarding antimicrobial activity, gelatin films against *Staphylococcus aureus* and *Escherichia coli* showed enhanced effectiveness with higher POP incorporation. These findings indicate that orange peel has strong potential for producing biopolymer films.

Another related study was carried out by Dao et al. (2022), in which pectin was extracted from coffee cherries. Although pectin constitutes approximately 50 % of coffee pulp, it is often not utilized, becoming one of the most abundant agricultural wastes in the food industry. The selected variety for this research was *Coffea arabica* L., from which pectin and cellulose were obtained using an eco-friendly method. The results showed that extraction with an acidified solvent at a pH of 3.1 and 84.3 °C for 4.3 h allowed recovery of 16.7 % pectin from coffee pulp. On the other hand, applying a two-step procedure—steam pretreatment at 170 °C for 30 min followed by bleaching with H_2O_2 at 40 °C for 10 h—yielded 54 % cellulose recovery from coffee pulp. Biopolymer films obtained from mixtures of coffee pectin and microcrystalline cellulose exhibited a smooth surface, high transparency, tensile strength of 3 MPa, and elongation of 4 %.

Based on the evidence presented above, it has been established that biopolymers can be obtained from organic waste. Considering the high production of plantain in Ecuador (Pacheco et al., 2021), plantain peel (*Musa paradisiaca*) was selected for this research, which aims to develop and evaluate a biopolymer derived from a residue of the food industry.

2 Materials and Methods

2.1 Extraction of starch from plantain peel

The organic residue selected for this research was plantain peel due to its high carbohydrate content (Anhwange et al., 2009). The plantain peel was obtained in the city of Santo Domingo, Ecuador, collected from several vendors dedicated to the preparation and sale of *chifles*.
The peels were carefully washed with warm water to remove any foreign material, then sliced and chopped. After pretreatment, acid hydrolysis was carried out using hydrochloric acid. Subsequently, deionized water was added to a beaker containing the hydrolyzed pulp, which was left to rest for approximately 8 hours. The extraction process was performed using a centrifuge (DM0412P with a capacity of 100 to 4500 rpm), selecting three rpm levels (900, 1500, 3000) according to the study of Altemimi (2018), who also standardized the centrifugation time at 15 minutes.

The centrifuged samples were filtered through a 180 μm sieve. The filtrate was then allowed to settle, and caustic soda was added to separate the protein content from the starch and to neutralize the acidity of the remaining starch. Afterwards, deionized water was added several times to remove the excess of caustic soda through a washing process. The resulting wet starch was dried in a tray dehydrator (DESHI 10) at a standardized temperature of 55 °C for 6 h, based on the research of Juárez Chunga (2022). It was then pulverized (PULVERIZER 10, 1.5 HP motor) until 95 % of the powder passed through a 120 μm

sieve, according to the Ecuadorian technical standard for wheat flour (NTE INEN 612, 2006). Finally, the pulverized material was vacuum-packed to maintain 10 % moisture content.

2.2 Preparation of plantain peel biopolymeric film (PBCP)

The preparation of plantain peel biopolymeric films (PBCP) was carried out under atmospheric conditions. Following the method used by Kim and Min (2012), the solution formed from the pulverized extract at different rpm (900, 1500, 3000) and 30 % or 50 % (w/w) glycerol was heated at 70, 80, or 90 °C for 45 minutes.
The films were molded by pipetting the mixture onto Teflon plates (14×10 cm) placed on a leveled ceramic surface; the volume of the film-forming solution was selected to produce films with a thickness of 0.2–0.3 mm. After one hour, the film was placed in a temperature/humidity chamber at 23 ± 2 °C and 50 % RH for 48 hours.

2.3 Rheological analysis

The rheological properties of the films were determined following the method of Hendrix et al. (2012) using a rotational rheometer (RheolabQC) with a 45 mm stainless steel (304) parallel plate. The film-forming solutions were deposited on a Peltier plate, deionized water was placed in the solvent trap, and a layer of oil was spread around the outer edges of the suspensions to limit water evaporation. The elastic modulus (G') and viscosity (G'') were determined while gradually increasing the temperature from 20 °C to 90 °C at a ramp rate of 1 °C/min. All measurements were validated under conditions of 1 rad/s frequency and 2 % strain.

2.4 Moisture Absorption Kinetics Analysis

The method of Talja, Helen, et al. (2008) was applied with some modifications. Film samples were prepared with dimensions of 5×15 cm, maintaining a thickness of 0.2 ± 0.03 mm, and subsequently subjected to 45 ± 2 °C in a drying oven over silica gel until the samples reached a constant weight. They were conditioned at 23 ± 2 °C in a desiccator with a saturated potassium nitrate solution to ensure 94 % RH. Moisture absorption (MA) was then calculated using the following formula:

$$AH(\%) = \frac{W_t - W_o}{W_o} \times 100 \quad (1)$$

Where W_0 and W_t were the weights of the dry samples and the samples at time t, respectively. Subsequently, following the method of Talja, Helen, et al. (2008), the diffusion coefficient (D) for water in the film samples was calculated from the slope of W_t/W_∞ using the following equation:

$$D = \sqrt{\frac{t}{L^2}} \times \frac{W_t}{W_0} \times 0.6 \quad (2)$$

Where L is half the thickness of the film and W_∞ is the weight of water absorbed at equilibrium.

2.5 Water Vapor Permeability

The water vapor permeability (WVP) of the film was measured according to the ASTM E96-92 method of the American Society for Testing and Materials (McHugh and Krochta, 1994). Briefly, 6 mL of distilled water were added to a polymethyl acrylate sample cup (inner diameter: 46 mm, outer diameter: 87 mm, length: 21 mm), which was then hermetically sealed with the plantain peel biopolymer film (PBCP). The sample cups were placed in a static temperature chamber at 23 ± 2 °C equipped with fans adjusted to an air speed of 152 m/min. In addition, relative humidity (RH) was recorded with a hygrometer (Model THDx).

2.6 Biodegradability Test

The biodegradability of the biopolymer films was evaluated at room temperature over a period of 30 days, following the procedure applied by Iguardia (2013). The tests performed included outdoor degradability and river water degradability. For the first test, the samples were weighed and placed in uncovered glass containers to remain outdoors for 30 days. For the river water biodegradability test, the samples were weighed and immersed in a glass container with water; the containers were sealed, and the samples were left to rest for 30 days. After this period, the samples were weighed, and the biodegradability percentage was calculated using Equation 3:

$$\%\ \text{Biodegradability} = 100 - \left(\frac{\text{final weight}}{\text{initial weight}} \times 100\right) \quad (3)$$

2.7 Statistical Analysis

All measurements were calculated as the average of three values. The treatment factors in this study were: Factor A, the different rpm levels (900, 1500, 3000) at which the plantain peel powder was obtained; Factor B, the 30 % or 50 % (w/w) glycerol added to the formulation; and Factor C, the film heating temperature 80, 90, and 100 °C. Therefore, a completely randomized design with a factorial arrangement ABC was applied, resulting in 18 treatments with 3 replicates each, giving a total of 54 experimental units.

3 Results and Discussion

3.1 Rheological analysis

For the analysis, the initial temperature of the suspensions was 20 ± 2 °C, and the temperatures during the rheological tests ranged from 20 °C to 90 °C, with increased temperature ranges (ΔT) of 20 ± 1, 25 ± 2, and ± 25 °C and an approximate duration of 50 seconds.

The G' values of the PBCP suspensions homogenized at 1 atm are presented in Figure 1. The G' values decreased as the temperature increased from 20 °C to 90 °C. Temperature alters the size distribution of biopolymer aggregates/particles as well as the aggregation structure (Sanchez et al., 1999).

Suspensions formulated from starch centrifuged at 3000 rpm exhibited higher G' values than the other treatments. In this regard, Tatirat and Charoenrein (2011) reported that acid hydrolysis and accelerated centrifugation may cause the breakdown of biopolymers. The decreasing pattern of G' values for the suspensions could be explained by the loss of network structure within the PBCP polymers. A higher rpm during the extraction process of plantain peel biopolymer may result in the loss of the biopolymer network and consequently a decrease due to the high energy potential. However, the reduction rates of the suspensions treated at 900, 1500, and 3000 rpm were relatively small (Figure 1), and better G' results were obtained with 30 % glycerol.

According to Sanchez et al. (1999) and later Hendrix et al. (2012), the regrouping of small particles slowed the rate of biopolymer network loss because immediately after treatment the biopolymers in the homogenized suspensions were very small. Nevertheless, these small biopolymer particles could rapidly regroup and form networks through hydrogen bonding, hydrophobic interactions, and charge–charge interactions, particularly when glycerol is used as the plasticizer.

In the present study, the rheological test temperature gradually increased from 20 °C to 90 °C, a range selected because PBCPs are heated to this temperature during preparation. Heating may cause protein denaturation in the suspensions, enhancing protein–protein interactions and reducing their segmental mobility (Pérez-Gago, 2012). However, the influence of protein denaturation, which normally occurs at high temperatures and is manifested by an increase in G', was not observed in this rheological experiment. This may be attributed to the low protein concentration (∼0.43 %) in the suspension. The results suggest that heating the samples between 70 °C and 90 °C for 45 min may induce thermal denaturation of proteins in the film-forming suspensions, but under this experimental condition, it was not critical to achieving the expected physical properties.

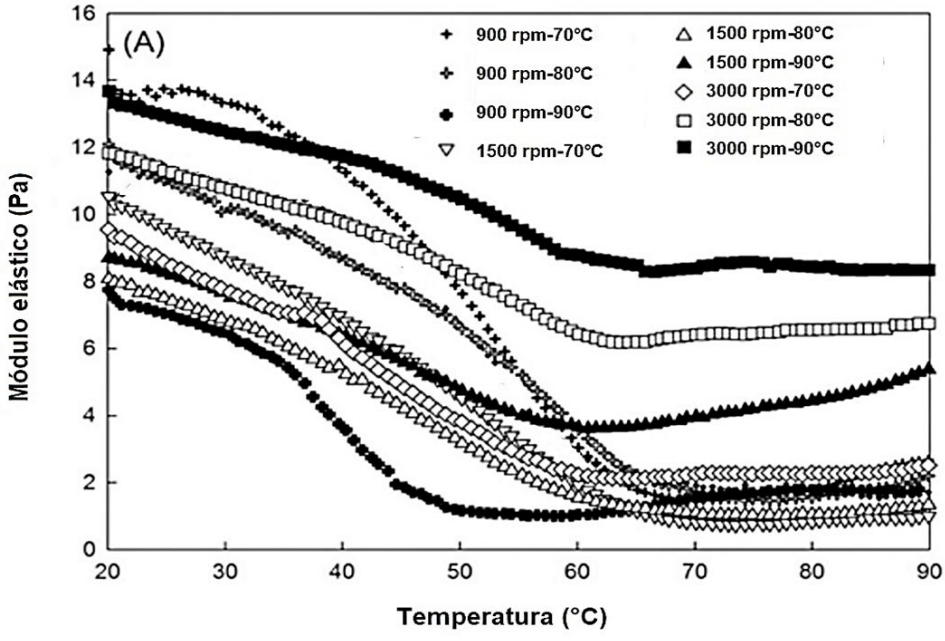

Figure 1. Elastic modulus (G') of the film-forming suspensions prepared with centrifuged powder at different revolutions per minute (900, 1500, 3000) and heated at different temperatures of 70, 80, 90 °C.

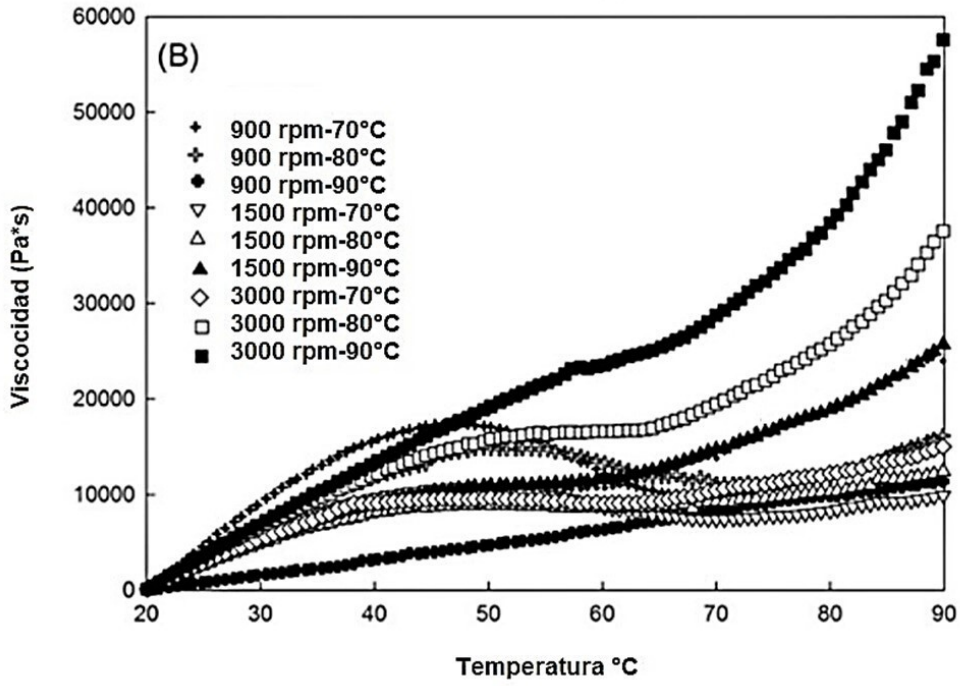

Figure 2. Viscosity (G'') of the film-forming suspensions prepared with centrifuged powder at different revolutions per minute (900, 1500, 3000) and heated at different temperatures of 70, 80, 90 °C.

The G' values for all suspensions remained relatively constant between 4 and 8 Pa across the entire evaluated temperature range. Similar results were reported by Sablani et al. (2009) and Hendrix et al. (2012) in previous studies on film formation using biopolymer suspensions from apple peels and defatted mustard flour, respectively.

Regarding the suspensions prepared with powder centrifuged at 3000 rpm and at a film homogenization temperature of 90 °C, viscosity values were higher than those of the other treatments (Figure 2). Likewise, suspensions processed at 1500 rpm and 90 °C exhibited a viscosity profile similar to those prepared at 3000 rpm and 90 °C; however, the viscosity was significantly higher in the latter suspensions. In addition, the analysis showed that the higher the testing temperature, the greater the viscosity of the samples. A viscosity of 57,570 Pa·s was obtained in suspensions subjected to 90 °C, which was the highest value recorded. This may be attributed to increased intermolecular crosslinking between polymers, such as cellulose present in PBCP at elevated temperatures, resulting in gel formation (Coma et al., 2003).

3.2 Moisture absorption kinetics analysis

Regarding the results on water absorption, the samples conditioned at 94 % RH and 23 °C over time (Figure 3) revealed that water absorption was greater in PBCP containing 50 % glycerol, meaning that these films exhibited a wider hydration range. The inclusion of polar and hydrophilic glycerol molecules, which can act as strong hydrophilic centers that bind readily and firmly to water, likely results in an increase in surface hydrophilicity and facilitates water molecule absorption (Kang et al., 2015). Moreover, the similar polar and hydrophilic characteristics of water molecules and the biopolymer film matrices may lead to strong cohesion between molecules and matrices due to hydrogen bonding (Kang et al., 2015).

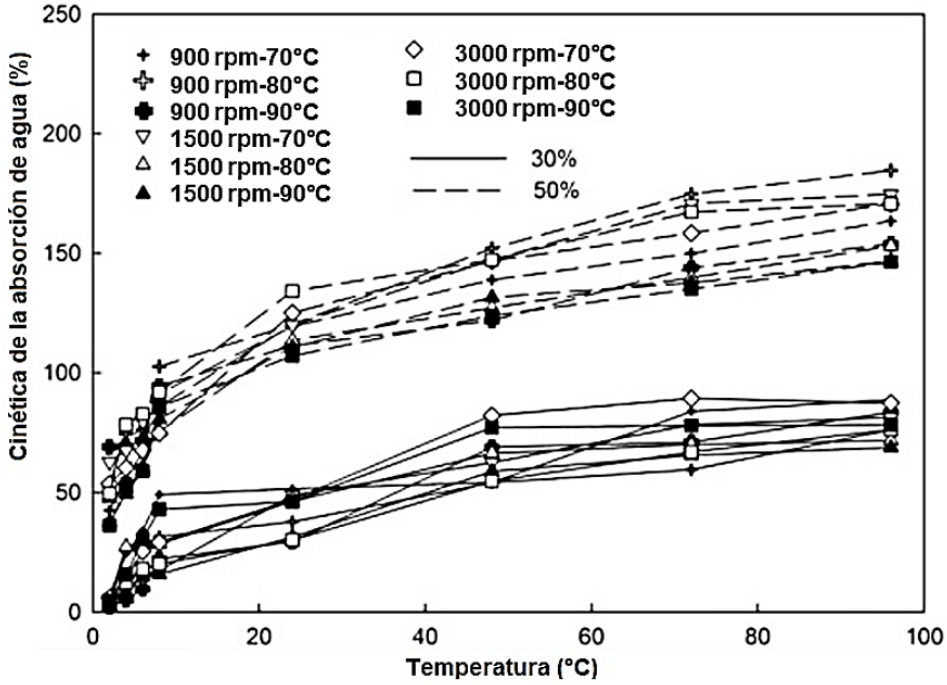

Figure 3. Water absorption kinetics of plantain peel-based films plasticized with glycerol formed from film-forming suspensions.

The water absorption results were strongly affected by the glycerol concentration but not by the heating temperature parameters or the centrifugation rpm prior to obtaining the powder (Figure 3). This finding is consistent with a previous study that demonstrated that the water absorption of biopolymer films made from apple peels was not affected by varying HPH pressure levels (138–207 MPa) or temperature (Sablani et al., 2009).

The D values for the films studied, conditioned at 94 % RH and containing 30 % and 50 % glycerol, ranged from 3.1×10^{-10} to 3.7×10^{-10} cm^2/s and 3.9×10^{-10} to 4.9×10^{-10} cm^2/s, respectively. The available volume for the expansion of water molecules in the film matrix increases as the amount of glycerol as a plasticizer increases. The present findings indicate that PBCP films can be formulated to provide a desired moisture migration rate by adjusting the amount of glycerol.

The D values calculated in this study were comparable to those from other investigations in which biopolymer films were developed; for example, apple peel-based films (0.82–2.62×10^{-10} cm^2/s) reported by Sablani et al. (2009). However, these values are lower than those reported for microfibrillated cellulose films (6.8×10^{-10} cm^2/s) developed by Minelli et al. (2010), or the data (12.6–31.8×10^{-10} cm^2/s) presented by Taghavi Kevij et al. (2021) for keratin films, and they also differ from the D values (36.3×10^{-10} cm^2/s) calculated for amylose starch films in the study of Muscat et al. (2014).

3.3 Water vapor permeability test

The WVP results of the films are shown in Table 1.

The thicknesses of the films containing 30 % and 50 % glycerol were 0.2 ± 0.03 mm and did not differ significantly ($p > 0.05$). WVP was generally higher in films with 50 % glycerol (Table 1), which may be explained by the fact that water vapor transmission through a hydrophilic film depends both on the diffusivity and the solubility of water molecules in the film matrix (Pak et al., 2020).

Table 1. Water vapor permeability (WVP) of plantain peel-based films.

Glycerol content (% w/w)	Powder centrifugation (rpm)	Heating temperature (°C)	WVP (g·mm/kPa·h·m^2)
30	900	70	3.54
		80	2.79
		90	3.03
	1500	70	3.26
		80	3.36
		90	3.47
	3000	70	3.19
		80	3.79
		90	4.23
50	900	70	3.84
		80	3.96
		90	4.34
	1500	70	4.01
		80	3.95
		90	4.44
	3000	70	4.45
		80	4.62
		90	4.98

The higher WVP in films with 50 % glycerol compared to those with 30 % glycerol may result from decreased intermolecular attractions, greater spacing between molecular chains, and higher mobility within the film matrix due to the inclusion of more glycerol molecules between the polymer chains (Caicedo et al., 2022). The inclusion of glycerol could enhance water diffusivity through the PBCP film system by reducing the number of obstacles blocking water molecules as they pass through the biopolymer network (Sothornvit and Krochta, 2005).

The strong hydrophilicity of glycerol molecules, along with the different heating temperatures and centrifugation rpm, did not influence WVP at any glycerol concentration ($p > 0.05$). As described above, it can be assumed that particle size is reduced as revolutions per minute and temperature increase. A reduced particle size could decrease WVP, as under these circumstances it becomes more difficult for water molecules to find a pathway to diffuse through the matrix (Dangaran et al., 2006). However, in the present study, no such effect on WVP was observed with increased temperature or rpm in the films, which is likely due to the re-agglomeration of small biopolymer particles during film formation (García et al., 2020). The use of an emulsifier is suggested to prevent re-agglomeration.

The WVP values of PBCP films under the different conditions ranged between 2.8 and 5.0 g·mm/(kPa·h·m^2) (Table 2), which is comparable to previous findings using soy protein isolate, defatted mustard flour, fish gelatin, and apple peel, as reported by Sablani et al. (2009), Hendrix et al. (2012), Cho and Rhee (2004), and Kim and Min (2012), respectively. However, the WVP results of PBCP films were higher compared with studies that included methylcellulose (6.8 g·mm/(kPa·h·m^2)), porcine skin gelatin (0.1–6.3 g·mm/(kPa·h·m^2)), sodium caseinate (4.0 g·mm/(kPa·h·m^2)), and beeswax (3.8–7.0 g·mm/(kPa·h·m^2)), as referenced in the studies of Talja, Peura, et al. (2008) and Avena-Bustillos et al. (2006). On the other hand, Vargas et al. (2008) reported higher WVP values in studies using potato starch (8.0 g·mm/(kPa·h·m^2)) and brown algae alginate (14.0 g·mm/(kPa·h·m^2)). The high WVP in the present study can be attributed to the hydrophilic nature of PBCP polymers and the polar nature of glycerol. A high WVP could limit the use of these films for food with low or intermediate moisture levels (Valero-Valdivieso et al., 2013). Therefore, further research is suggested to develop methods for producing films with reduced moisture sensitivity that could be applied to foods with high moisture levels.

3.4 Biodegradability

Test According to the data obtained, the film prepared at 3000 rpm, heated at 90 °C, and containing 50 % glycerol showed the highest degradability both under outdoor

conditions and in aqueous medium, with percentages of 47 % and 55 %, respectively. These values are comparable to the study conducted by Garcia (2019), which reported biodegradability percentages of 43 % to 47 % in biopolymer films over a one-month period.

4 Conclusions

Water absorption at equilibrium was higher and moisture barrier capacity was lower in films with 50 % glycerol. Therefore, since the moisture sensitivity of PBCP films was strongly influenced by glycerol concentration, the sensitivity of the film can be modulated by varying glycerol concentration. Regarding biodegradability, PBCPs showed values similar to those reported in other studies; however, their efficiency should be assessed under anaerobic conditions.

In addition, the use of an emulsifier is recommended to improve re-agglomeration, followed by new measurements to more accurately identify the effect of heating temperatures on the properties of plantain peel biopolymer films.

Author Contributions

J.T.: Conceptualization, investigation, methodology, resources, supervision, validation, writing – review and editing. **R.J.:** Data curation, funding acquisition, project administration. **M.S.:** Formal analysis, visualization, writing – original draft.

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