

Physicochemical properties of biodegradable mung bean starch-chitosan-glycerol edible films incorporated with banana peel extract

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Abstract. Food packaging plays a crucial role in protecting food from damage and contamination during transport and storage. However, the widespread use of plastic packaging contributes significantly to environmental problems, with the majority ending up in landfills. For this study, biodegradable edible films were developed from mung bean starch, chitosan, glycerol, and varying levels of banana peel extract (BPE). Films containing 15% BPE (Y2-15) demonstrated the most balanced properties in terms of moderate thickness (0.063 mm), moisture content (4.95%), low water solubility (43.86%), strong tensile strength (0.021 MPa), high flexibility (70.15%), high lightness ($L^*74.89\pm0.57$), with colour ($a^* - 0.14\pm0.05$) and ($b^* 12.58\pm0.35$). Y2-15 also had excellent barrier properties against water vapour ($4.87\pm0.18\times10^{-10}$ g.m/Pa.s.m) and oxygen ($1.91\pm0.37\times10^{-17}$ kg·m·m⁻²·s⁻¹·Pa⁻¹). These findings indicate that incorporating BPE enhances the functional qualities of edible films, offering a promising, eco-friendly alternative to conventional plastic packaging. The approach aligns with Sustainable Development Goals (SDG) 12 (Responsible Consumption and Production) and SDG 13 (Climate Action).

1 Introduction

Food packaging helps maintain product freshness and safety; however, conventional plastic packaging poses environmental concerns due to its resistance to natural degradation. Around 36% of plastic is used for packaging, but a major percentage, up to 85%, ends up in landfills or nature, becoming the harmful microplastics [1]. Thus, biodegradable and edible films made from natural materials like starch, proteins, and lipids are being explored as alternatives to plastic packaging. For example, mung bean starch contains high amylose content, making

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it a strong alternative for strong, clear films [2]. Chitosan also forms good films and has antimicrobial properties, but it needs glycerol to make it less brittle [3].

Another substance, banana peels, which are usually thrown away, are actually rich in fibre and natural compounds. Its properties can be used to improve film strength and reduce waste [4]. Thus, based on the findings above, edible films were developed in this study using mung bean starch, chitosan, and glycerol, with banana peel extract. Then, these films were used to examine the influence of the extract on the film's properties, and the extend of its potential was studied to find out its suitability as an eco-friendly packaging. This effort answers the call to reduce plastic consumption and advance sustainability objectives. This effort also promotes SDG 12 by exploring the use of banana peels to develop biodegradable films that can reduce waste, and SDG 13 by creating an alternative to plastic that could lower greenhouse gas emissions.

2 Materials and methods

2.1 Materials

The bananas (*Musa acuminata*) (stage 5 to 6) were purchased from the supermarket in the Kuala Pilah area, and mung bean starch was purchased from online shops. Other chemicals such as chitosan, glycerol, 80% ethanol and anhydrous citric acid used in this study were provided by the Laboratory of Food Science and Technology, UiTM Kuala Pilah.

2.2 Extraction of banana peels

Banana peels were cleaned and dried at 60°C for one day, then ground into powder. The powder was then soaked in 80% ethanol with constant stirring. Next, it was filtered using Whatman No. 1 paper and evaporated using a vacuum rotary evaporator. The extraction method followed [5] with slight modifications.

2.3 Preparation of edible film formulations

Mung bean starch was dissolved in 100 mL of distilled water and heated at 80°C for 10 minutes with stirring to ensure complete gelatinisation. Chitosan was prepared by dissolving it in 1% (w/v) citric acid solution, and stirred at 200 rpm for 15 minutes at room temperature (23±2°C). Starch and chitosan solutions were mixed in ratios of 1:1 (X), 2:1 (Y), and 5:1 (Z), then heated to 80°C and stirred evenly.

To prepare the chitosan–mung bean starch–glycerol solution, 15% and 20% (w/w) glycerol were added and stirred for 10 minutes. The mixture was then sonicated for 10 minutes. Banana peel extract (BPE) (0%, 15%, 30%) was added to each formulation and stirred at room temperature. Each 100 mL film solution was cast into petri dishes and dried at 50±5°C for 24 hours.

2.4 Thickness

The thickness of the film was measured with a manual vernier calliper with a sensitivity of 0.01 mm at 5 different points. The mean quantity was calculated and recorded as the thickness of the edible films.

2.5 Moisture content

The moisture content of the films was measured using the AOAC gravimetric method, with slight adjustments. First, 0.1 g of every film specimen was dried at $105\pm 2^\circ\text{C}$ for 20 hours. The moisture content is represented in a percentage and computed using the following formula:

$$\text{Moisture (\%)} = \frac{(W_2 - W_1) - (W_3 - W_1)}{(W_2 - W_1)} \times 100 \quad (1)$$

where W_1 is the weight of the empty petri dish (g), W_2 is the weight of the wet sample before drying (g), and W_3 is the weight of the dried sample after drying (g).

2.6 Water solubility

Water solubility of the edible film was measured using a modified method from [6]. About 0.1 g of film was weighed and soaked in 40 mL of distilled water with constant stirring for 12 hours at room temperature. The remaining film was then dried at 105°C until a constant weight was reached. Water solubility (%) was calculated using the following equation:

$$\text{Water solubility (\%)} = \frac{\text{Average initial dry weight} - \text{Average final dry weight}}{\text{Average initial dry weight}} \times 100 \quad (2)$$

2.7 Colour

The films were assessed using a handheld Chroma meter at room temperature. CIE L^* , a^* , and b^* scale colour values were applied, and the scale values $L^*=0$ (black) to 100 (white), $a^*=-60$ (green) to +60 (red), and $b^*=-60$ (blue) to +60 (yellow). A calibration was performed before the measurement was taken, and the chroma meters were calibrated using a calibration reference plate.

2.8 Opacity and transparency

Using the approach outlined by [7], each specimen was sliced into a rectangle and put in a cuvette using a UV spectrophotometer test cell set to 600 nm to measure the films' opacity. Air was utilised as the blank. The formula used to obtain the results of opacity measurements is:

$$\text{Opacity} = \frac{\text{Abs}_{600}}{x} \quad (3)$$

where Abs_{600} is the spectrophotometric absorbance value at 600 nm wavelength and x is the thickness of the edible film in mm.

2.9 Microscope Imaging

Morphological images of the films were captured using a binocular microscope at $100\times$ magnification. Each film was carefully placed on a microscope slide, and the microscope was properly focused to generate clear and accurate images.

2.10 Tensile strength and elongation at break

A tensile test was performed on thin plastic films using a Texture Analyser in accordance with ASTM D882-02. Film samples were cut into uniform strips (10 mm \times 100 mm) and mounted with a 50 mm initial grip separation. The test was conducted at a speed of 8.3 mm/s.

Tensile strength (MPa) was calculated from the maximum stress on the stress-strain curve. Lastly, elongation at break (%) was determined from the strain at the point of failure.

2.11 Water vapour permeability (WVP)

WVP was measured using a modified ASTM E96 method. A test bottle containing water was sealed with the edible film and parafilm, leaving a 10 mm headspace. The bottle was weighed at the start and every two days for 10 days. Moisture loss was determined by plotting weight change (g) over time (hours), and the slope of the resulting straight line represented the rate of moisture loss (g/hour). The water vapour transmission rate (WVTR) was then calculated using the following formula:

$$\text{WVTR (g/h.m}^2\text{)} = \frac{\text{Rate of moisture loss}}{A} \quad (4)$$

where A is the exposed surface area, πr^2 . Permeance was calculated using:

$$\text{Permeance (g/Pa.s.m}^2\text{)} = \frac{\text{WVTR}}{S(\text{RH}_1 - \text{RH}_2)} \quad (5)$$

where S is the saturation vapour pressure of water at 40°C (7.385 kPa), RH_1 is 100% relative humidity inside the can, and RH_2 is 50% relative humidity in the surrounding environment. Finally, the WVP was calculated using:

$$\text{Water vapour permeability (g.m/Pa.s.m}^2\text{)} = \text{Permeance} \times \text{Film thickness (mm)} \quad (6)$$

2.12 Oxygen permeability (OP)

Oxygen permeability (OP) was measured using the deoxidiser absorption method based on [8]. A test bottle containing 1.8 g of deoxidiser was sealed with the film and parafilm, then placed in an airtight container at 75% relative humidity and 23°C. The bottle was weighed before and after 48 hours. OP was calculated using the following equation:

$$\text{OP} = \frac{(\Delta m \times d)}{A \times t \times P} \quad (7)$$

where Δm is the quantity of O_2 absorbed by the deoxidiser (kg), d is the thickness of the film (m), A is the effective area of the film (m^2), t is the equilibrium time (s), and P (Pa) is the partial pressure differential of oxygen along the film.

2.13 Statistical analysis

Data were analysed using SPSS version 29.0 (Windows) with analysis of variance (ANOVA). Results are presented as mean \pm standard deviation (SD), with significance set at $p < 0.05$. A three-way ANOVA based on a $3 \times 2 \times 3$ full factorial design was used to assess interactions among three independent factors. Once significant interactions were found, a two-way ANOVA was used for further analysis.

3 Results and discussion

3.1 Thickness, moisture content and water solubility

The thickness of the edible films was significantly affected by both the chitosan-to-starch ratio and the addition of BPE (Table 1). Based on the observation, the thickness of the films

increased with higher BPE levels, contributed by solid content and polyphenol interactions. Films with more chitosan (from X to Z) were also thicker, as chitosan has a natural thickening effect [9]. Notably, Y1 and Y2 films with 15% BPE had optimal thickness, significantly higher than X films, suggesting improved structure without losing flexibility.

As shown in Table 2, moisture content increased with higher BPE, especially at 30%, due to hydrophilic compounds like pectin and fibre. Higher chitosan levels reduced moisture content by limiting water-binding from starch. However, when the chitosan level is too high, it can create uneven films, and moisture can be trapped in the films. Films with 20% glycerol also had higher moisture due to the ability of the glycerol to absorb water [10].

Water solubility results (Table 2) followed a similar trend. At the same time, X1 and X2 showed no significant difference. Higher chitosan increased network density, reducing solubility. Y2 with 15% BPE showed the lowest solubility, indicating strong water resistance and good film structure, making it suitable for food packaging.

Table 1. Thickness of the films.

Formula	Thickness (mm)		
	BPE 0%	BPE 15%	BPE 30%
X1	0.050±0.000 ^{Cc}	0.057±0.005 ^{Bc}	0.068±0.003 ^{Ac}
X2	0.050±0.000 ^{Cc}	0.057±0.005 ^{Bc}	0.068±0.002 ^{Ac}
Y1	0.052±0.003 ^{Cb}	0.062±0.005 ^{Bb}	0.067±0.003 ^{Ab}
Y2	0.052±0.003 ^{Cb}	0.063±0.005 ^{Bb}	0.068±0.003 ^{Ab}
Z1	0.065±0.005 ^{Ca}	0.066±0.005 ^{Ba}	0.072±0.003 ^{Aa}
Z2	0.066±0.002 ^{Ca}	0.067±0.002 ^{Ba}	0.072±0.003 ^{Aa}

Note: Mean values ± standard deviation. Different lowercase letters in the same column indicate significant differences ($p < 0.05$) between formulations. Different capital letters in the same row indicate significant differences ($p < 0.05$) between banana peel extract (BPE) concentrations.

Table 2. Moisture content and water solubility of the film.

Formula	Moisture content (%)			Water solubility (%)		
	BPE 0%	BPE 15%	BPE 30%	BPE 0%	BPE 15%	BPE 30%
X1	11.96±0.74 ^{Bb}	20.97±0.82 ^{Bb}	22.26±0.83 ^{Ab}	59.11±0.68 ^{Ca}	67.16±0.68 ^{Ba}	69.35±0.85 ^{Aa}
X2	15.99±0.78 ^{Ba}	21.65±0.62 ^{Ba}	29.33±0.90 ^{Aa}	63.25±0.92 ^{Ca}	63.01±0.71 ^{Ba}	66.70±0.68 ^{Aa}
Y1	2.99±0.74 ^{Bf}	3.80±0.52 ^{Bf}	17.49±0.40 ^{Af}	44.51±0.84 ^{Cd}	47.46±0.86 ^{Bd}	66.20±0.89 ^{Ad}
Y2	4.48±0.91 ^{Bc}	4.95±0.49 ^{Bc}	19.65±0.91 ^{Ae}	40.82±0.63 ^{Cc}	43.86±0.50 ^{Bc}	61.86±0.80 ^{Ae}
Z1	4.67±0.70 ^{Bd}	10.21±0.51 ^{Bd}	22.50±0.69 ^{Ad}	54.11±0.82 ^{Cb}	64.43±0.77 ^{Bb}	60.94±0.66 ^{Ab}
Z2	7.08±0.71 ^{Bc}	14.17±0.76 ^{Bc}	25.53±0.86 ^{Ac}	45.51±0.94 ^{Cc}	51.66±0.53 ^{Bc}	66.36±0.82 ^{Ac}

Note: Mean values ± standard deviation. Different lowercase letters in the same column indicate significant differences ($P < 0.05$) between formulations. Different capital letters in the same row indicate significant differences ($P < 0.05$) between banana peel extract (BPE) concentrations.

3.2 Colour analysis, opacity and microscope imaging

The colour of the films was significantly affected by BPE concentration and the chitosan-to-starch ratio (Table 3). Higher BPE levels made the films darker (lower L^*), redder (higher a^*), and yellower (higher b^*) due to natural pigments and polyphenols [11]. Among all, Y2-15 had the most balanced and visually appealing colour at 15% BPE.

As shown in Table 4, film opacity increased with more BPE, due to light-scattering pigments and solid particles, which also improved UV protection. Films with more chitosan, like Z1 and Z2, were also opaquer due to their denser structure [12]. Y2-15 maintained moderate opacity, offering both clarity and light protection, making it ideal for packaging. Fig. 1 supported these findings: 0% BPE films were more transparent, while 15% and 30% BPE films were darker and less transparent.

Fig. 2 showed that X films had rough, uneven surfaces with aggregates, indicating poor blending. Meanwhile, Y films had smooth, uniform textures, showing better compatibility and film quality. Lastly, Z films were moderately rough with bumps and pits. Higher BPE levels caused more surface irregularities, likely due to phase separation or aggregation. These changes were influenced by both the chitosan-to-starch ratio and the nature of BPE [13].

Table 3. Colour analysis of the films.

Formula		Colour analysis		
		BPE 0%	BPE 15%	BPE 30%
L^*	X1	75.39±0.37 ^{Aa}	72.35±0.15 ^{Ba}	66.10±0.59 ^{Ca}
	X2	77.04±0.54 ^{Ab}	71.68±0.55 ^{Bb}	61.61±0.29 ^{Cb}
	Y1	74.92±0.83 ^{Ac}	67.67±0.39 ^{Bc}	64.38±0.35 ^{Cc}
	Y2	74.96±0.83 ^{Aa}	74.89±0.57 ^{Ba}	64.79±0.44 ^{Ca}
	Z1	76.44±0.50 ^{Abc}	70.62±0.03 ^{Bbc}	61.51±0.78 ^{Cbc}
	Z2	76.12±0.50 ^{Ab}	71.73±0.61 ^{Bb}	62.58±0.31 ^{Cb}
a^*	X1	-0.59±0.04 ^{Cc}	-0.43±0.13 ^{Bc}	0.07±0.07 ^{Ac}
	X2	-0.61±0.04 ^{Cbc}	-0.22±0.06 ^{Bbc}	0.59±0.23 ^{Abc}
	Y1	-0.78±0.14 ^{Cb}	-0.56±0.14 ^{Bb}	1.72±0.65 ^{Ab}
	Y2	-0.91±0.09 ^{Cc}	-0.14±0.05 ^{Bc}	0.13±0.20 ^{Ac}
	Z1	-0.94±0.13 ^{Cbc}	-0.54±0.10 ^{Bbc}	1.41±0.60 ^{Abc}
	Z2	-0.97±0.14 ^{Cbc}	-0.33±0.02 ^{Bbc}	0.91±0.10 ^{Abc}
b^*	X1	4.73±0.16 ^{Cd}	8.37±0.59 ^{Bd}	14.53±0.77 ^{Ad}
	X2	5.26±0.12 ^{Cbc}	14.00±0.61 ^{Bbc}	19.82±0.91 ^{Abc}
	Y1	6.97±0.83 ^{Cb}	13.01±0.56 ^{Bb}	18.53±0.96 ^{Ab}
	Y2	7.96±0.90 ^{Ca}	12.58±0.35 ^{Ba}	18.98±1.22 ^{Aa}
	Z1	7.40±0.03 ^{Ccd}	10.04±0.59 ^{Bcd}	22.31±0.67 ^{Accd}
	Z2	7.47±0.41 ^{Cab}	16.45±0.07 ^{Bab}	18.69±0.96 ^{Ab}

Note: Mean values ± standard deviation. Different lowercase letters in the same column indicate significant differences ($P < 0.05$) between formulations. Different capital letters in the same row indicate significant differences ($P < 0.05$) between banana peel extract (BPE) concentrations.

Table 4. Opacity of the film.

Formula	Opacity (Abs/mm)		
	BPE 0%	BPE 15%	BPE 30%
X1	2.18±0.20 ^{Cd}	2.75±0.04 ^{Bd}	3.21±0.25 ^{Ad}
X2	2.36±0.16 ^{Cd}	2.64±0.20 ^{Bd}	3.09±0.01 ^{Ad}
Y1	2.42±0.01 ^{Cc}	3.14±0.01 ^{Bc}	4.87±0.32 ^{Ac}
Y2	2.46±0.08 ^{Cb}	3.11±0.34 ^{Bb}	5.90±0.52 ^{Ab}
Z1	3.78±0.25 ^{Cb}	3.40±0.20 ^{Bb}	4.88±0.04 ^{Ab}
Z2	3.74±0.13 ^{Ca}	4.41±0.04 ^{Ba}	5.82±0.12 ^{Aa}

Note: Mean values ± standard deviation. Different lowercase letters in the same column indicate significant differences ($P < 0.05$) between formulations. Different capital letters in the same row indicate significant differences ($P < 0.05$) between banana peel extract (BPE) concentrations.

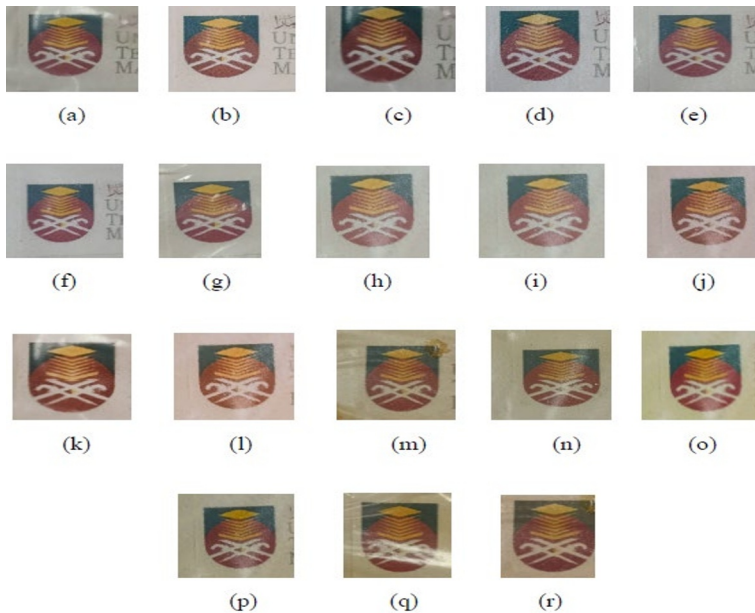


Fig. 1. Visual comparison among edible films (a) X1-0, (b) X2-0, (c) Y1-0, (d) Y2-0, (e) Z1-0, (f) Z2-0, (g) X1-15, (h) X2-15, (i) Y1-15, (j) Y2-15, (k) Z1-15, (l) Z2-15, (m) X1-30, (n) X2-30, (o) Y1-30, (p) Y2-30, (q) Z1-30, (r) Z2-30 respectively.

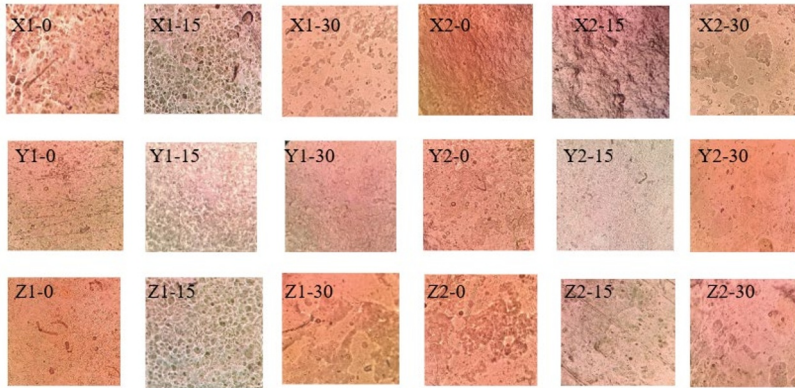


Fig. 2. Light microscopy images of the film surfaces: X1-0, X1-15, X1-30 X2-0, X2-15, X2-30, Y1-0, Y1-15, Y1-30, Y2-C, Y2-15, Y2-30, Y1-0, Z1-15, Z1-30, Z2-0, Z2-15, and Z2-30, 0-control (0%), 15-15%BPE, 30-30%BPE.

3.3 Tensile strength and elongation at break

Table 5 shows that tensile strength decreased as BPE concentration increased from 0% to 30%. This finding is likely because the polyphenols and fibres in BPE can disrupt the internal structure of the films at higher levels, making them weaker [7]. Despite this, the Y2 formulation showed the highest tensile strength at all BPE levels, suggesting its chitosan-to-starch ratio forms a stronger and more stable film.

Table 5. Tensile strength and elongation at break of the films

Formula	Strength (MPa)			Elongation at break (%)		
	BPE 0%	BPE 15%	BPE 30%	BPE 0%	BPE 15%	BPE 30%
X1	0.010±0.01 ^{Ad}	0.006±0.00 ^{Bd}	0.001±0.01 ^{Cd}	48.02±19.95 ^{Bc}	39.73±4.10 ^{Ac}	62.97±10.17 ^{Ac}
X2	0.010±0.00 ^{Ad}	0.005±0.00 ^{Bd}	0.003±0.00 ^{Cd}	50.38±12.85 ^{Ba}	50.38±11.74 ^{Aa}	91.80±9.75 ^{Aa}
Y1	0.017±0.00 ^{Acd}	0.014±0.01 ^{Bcd}	0.003±0.00 ^{Ccd}	27.64±10.73 ^{Bd}	54.83±9.76 ^{Ad}	48.07±10.13 ^{Ad}
Y2	0.035±0.01 ^{Aa}	0.021±0.00 ^{Ba}	0.018±0.00 ^{Ca}	29.18±6.17 ^{Bb}	70.15±4.36 ^{Ab}	50.41±4.62 ^{Ab}
Z1	0.018±0.01 ^{Ac}	0.009±0.02 ^{Bc}	0.002±0.00 ^{Cc}	24.43±3.70 ^{Bc}	34.70±1.70 ^{Ac}	36.04±8.16 ^{Ac}
Z2	0.028±0.01 ^{Ab}	0.016±0.00 ^{Bb}	0.004±0.00 ^{Cb}	26.47±4.68 ^{Bde}	35.22±2.13 ^{Adc}	40.4±10.58 ^{Adc}

Note: Mean values ± standard deviation. Different lowercase letters in the same column indicate significant differences ($P < 0.05$) between formulations. Different capital letters in the same row indicate significant differences ($P < 0.05$) between banana peel extract (BPE) concentrations.

Table 5 shows that elongation at break increased with more BPE, especially in Y and Z formulations, because BPE contains water-attracting compounds that make the film stretch easier. Y2 had the highest flexibility at 15% BPE, and X2 was the most flexible at 30% BPE. Glycerol also played a role, as it was found that films with 20% glycerol, like Y2-15, were more stretchable than those with 15% because glycerol softens the film. Overall, Y2-15 had both good strength and flexibility, while X2-30 was the most flexible.

3.4 Water vapour permeability (WVP) and oxygen permeability (OP)

Table 6 shows that BPE and film type affected water vapour permeability (WVP). WVP decreased at 15% BPE because BPE filled small gaps within the film matrix and improved the barrier. But at 30% BPE, WVP increased again, likely due to too much moisture-attracting content or an uneven film. While, Y2-15 had the lowest WVP, showing the best moisture resistance.

Oxygen permeability (OP) also showed a similar trend. OP decreased at 15% BPE as the film structure became more compact, but increased at 30% BPE, likely due to structural damage. The Y2-15 formulation exhibited the lowest OP, indicating superior oxygen barrier performance, essential for maintaining food freshness and reducing spoilage [14]. In summary, Y2-15 was the best film for blocking both moisture and oxygen, making it ideal for food packaging.

Table 6. Water vapour permeability and oxygen permeability of the films

Formula	WVP×10 ⁻¹⁰ (g.m/Pa.s.m)			OP×10 ⁻¹⁷ (kg·m·m ⁻² ·s ⁻¹ ·Pa ⁻¹)		
	BPE 0%	BPE 15%	BPE 30%	BPE 0%	BPE 15%	BPE 30%
X1	7.22±0.53 ^{Bc}	5.18±0.15 ^{Cc}	8.54±1.12 ^{Ac}	7.11±0.21 ^{Ba}	4.22±0.26 ^{Ca}	9.13±0.69 ^{Aa}
X2	8.05±0.49 ^{Bd}	7.21±0.73 ^{Cd}	9.29±0.87 ^{Ad}	5.15±0.62 ^{Bb}	4.43±0.37 ^{Cb}	8.92±0.34 ^{Ab}
Y1	7.92±0.26 ^{Bbc}	6.19±0.26 ^{Cbc}	8.05±0.61 ^{Abc}	4.96±0.25 ^{Bc}	2.48±0.25 ^{Cc}	6.97±0.26 ^{Ac}
Y2	5.85±0.24 ^{Ba}	4.87±0.18 ^{Ca}	7.88±0.27 ^{Aa}	3.80±0.48 ^{Bc}	1.91±0.37 ^{Cc}	5.63±0.34 ^{Ae}
Z1	6.56±0.41 ^{Bb}	5.79±0.45 ^{Cb}	7.56±0.28 ^{Ab}	3.39±0.27 ^{Bde}	3.08±0.33 ^{Cde}	4.10±0.15 ^{Ade}
Z2	6.24±0.70 ^{Bb}	5.41±0.90 ^{Cb}	7.90±0.91 ^{Ab}	3.23±0.21 ^{Bd}	3.82±0.35 ^{Cd}	4.01±0.30 ^{Ad}

Note: Mean values ± standard deviation. Different lowercase letters in the same column indicate significant differences ($P < 0.05$) between formulations. Different capital letters in the same row indicate significant differences ($P < 0.05$) between banana peel extract (BPE) concentrations.

4 Conclusion

This study successfully produced biodegradable edible films formulated from mung bean starch, chitosan, glycerol, and varying proportions of banana peel extract (BPE). The chitosan-to-starch ratio and BPE concentration significantly influenced the characteristics of the films. Among the formulations, the 15% BPE film (Y2-15) exhibited the most desirable balance of thickness, moisture content, flexibility, strength, lightness, low solubility, and strong barrier performance, making it well-suited for food packaging applications. This work contributes to SDG 12 by valorising banana peels into biodegradable materials, thereby reducing waste, and to SDG 13 by providing an alternative to plastic packaging that can lower greenhouse gas emissions.

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