

THE PHYSICAL–MECHANICAL, MORPHOLOGICAL CHARACTERIZATION, AND BIODEGRADABILITY EVALUATION OF BIOPLASTIC FROM MANGO PEEL

Caracterización físico-mecánica, morfológica y evaluación de la biodegradabilidad de bioplásticos a partir de cáscara de mango

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Key words: *Mangifera indica*, agro-industrial by-product, waste valorization, sustainable materials.

ABSTRACT

The accumulation of non-degradable conventional plastics and their environmental impacts have driven the search for sustainable alternatives. In this study, bioplastic films were produced using mango peel extract (MPE) at concentrations of 5%, 10%, and 15% (g/100 mL) to characterize their physical, mechanical, and morphological properties, as well as evaluate its biodegradability. Using a scanning electron microscope (SEM), it was demonstrated that the bioplastic prepared with 15% MPE stood out in physical properties (color, $\Delta E \approx 10.87$), mechanical properties (elongation: 77%; tensile and puncture strength: ≈ 2.65 MPa and 1.03 N), and morphological properties (surface uniformity and homogeneity). However, the bioplastic with 5% MPE exhibited greater biodegradability, achieving 57% decomposition in 28 days, which is faster than that of conventional plastics. It was determined that the incorporation of MPE improves both mechanical and morphological properties; however, higher MPE concentrations tend to decrease the biodegradation rate, which is relevant for applications and formulation design. These findings highlight the potential of mango peel-based bioplastics as viable ecological alternatives, with promising applications in various industrial sectors.

Palabras clave: *Mangifera indica*, subproducto agroindustrial, valorización de residuos, materiales sostenibles.

RESUMEN

La acumulación de plásticos convencionales no degradables y sus impactos ambientales han impulsado la búsqueda de alternativas sostenibles. En este estudio se elaboraron películas de bioplástico utilizando extracto de cáscara de mango (MPE) en concentraciones de 5 %, 10 % y 15 % (g/100 mL), con el objetivo de caracterizar sus propiedades físicas, mecánicas y morfológicas, así como evaluar su biodegradabilidad. Mediante microscopía electrónica de barrido (SEM) se demostró que el bioplástico elaborado con 15 % de MPE se destacó en las propiedades físicas (color, $\Delta E \approx 10.87$),

mecánicas (elongación: 77 %; resistencia a la tracción y a la punción: $\approx$ 2.65 MPa y 1.03 N) y morfológicas (uniformidad y homogeneidad superficial). No obstante, el bioplástico con 5 % de MPE mostró una mayor biodegradabilidad, alcanzando el 57 % de descomposición en 28 días, lo que lo hace más biodegradable que los plásticos convencionales. Se determinó que la incorporación de MPE mejora las propiedades mecánicas y morfológicas, pero concentraciones mayores de MPE tienden a disminuir la velocidad de biodegradación, lo cual es relevante para aplicaciones y el diseño de formulaciones. Estos hallazgos evidencian el potencial del bioplástico a base de cáscara de mango como alternativa ecológica viable, con aplicaciones prometedoras en diversos sectores industriales.

INTRODUCTION

Concerns over the increasing contamination of plastics in the environment have motivated the search for sustainable options that help reduce pollution and promote the reuse of resources (PNUMA 2021). The use of bioplastics made from renewable materials is presented as a practical and important alternative solution (Rodríguez et al. 2019). Furthermore, interest in evaluating the biodegradation time of bioplastics made from agro-industrial byproducts has increased considerably (Anugrahwidya et al. 2021, Abu Ubaidah et al. 2024, Kharb and Saharan 2024, Jayalath et al. 2025, Orizano-Ponce et al. 2025). However, the challenge remains of ensuring that the production of biodegradable bioplastics is technically and economically viable compared to conventional plastics (Anli Dino et al. 2025, Sultan et al. 2025).

Mango (*Mangifera indica* L.) is a widely consumed tropical fruit that generates a substantial number of by-products, mainly seed (9-40%) and peel (7-24%) according to Rojas et al. (2015), Oliver-Simancas et al. (2021), and García-Mahecha et al. (2023). Corresponding to proximal analyses on a dry basis, mango peel has the following chemical composition: moisture (66.0-75.0 %), crude protein (1.76-11.67%), crude fat (2.16-2.66%), crude fiber (3.28-7.40%, mainly pectin, cellulose, and hemicelluloses), mineral ash (1.16-3.0%), and total carbohydrates (20.80-31.24%, predominantly starch, mainly in the form of amylose and amylopectin), as reported by Ajila et al. (2007) and Tesfaye (2017). Furthermore, it is a rich source of phenolic compounds, carotenoids, vitamin C, and vitamin E (Serna-Cock et al. 2016, Farouk 2024). These characteristics demonstrate the potential use of this residue in producing bioplastic films with favorable properties. Additionally, its utilization promotes waste valorization under a circular economy approach and reduces the environmental impacts associated with improper disposal (Siregar et al. 2023).

Currently, studies exploring the use of mango peel extract (MPE) in the manufacture of plastic films have increased (Chaiwarit et al. 2020, Sernaqué Aucahuasi et al. 2020, Nazario-Naveda et al. 2021, Farouk 2024, Fong-in et al. 2025, Lastra-Ripoll et al. 2025, Wang and Zhang 2025). For example, Fernandez Benavides and Gil Castillo (2023) developed a bioplastic with a uniform appearance, a brown coloration, and a flexible and resilient texture, measuring 0.45 mm in thickness and 65 mm in diameter. These important parameters affect both mechanical properties and permeability, as well as the overall performance of the bioplastic. Gallardo and Velazquez (2021) reported that their mango peel-based material (straw) exhibited a tensile strength of 8.86 MPa, an elongation of 10.2%, a hardness of 10.7, with 66.67% moisture, and up to 80% biodegradation. In terms of morphology, Nazario-Naveda et al. (2021) observed that mango peel-derived bioplastic film exhibited a surface without cracks, fissures, or voids, which was attributed to intermolecular forces of protein chains present in the material.

These pieces of evidence suggest that incorporating MPE into bioplastic production could enhance mechanical strength, flexibility, and biodegradability, highlighting its potential as an alternative to conventional plastics, particularly in applications where sustainability is crucial (Rosenboom et al. 2022). Although various studies have explored the use of mango peel in bioplastic elaboration, the precise concentration that maximizes these benefits has not yet been established. In this context, it is essential to perform a comprehensive analysis of the physical, mechanical, and morphological properties that determine the quality of this material.

Therefore, the objective of this research is to analyze the effect of different mango peel extract concentrations on the physical, mechanical, morphological, and biodegradability properties of bioplastic. The findings are expected to provide solid evidence

on the structural viability and biodegradability of these materials and to generate relevant information to support their positioning and promotion as a sustainable and technically viable alternative to traditional plastics.

MATERIALS AND METHODS

Procedures for the preparation of bioplastic films

This study was conducted at the Laboratorio de Análisis por Instrumentación of the Escuela Profesional de Ingeniería Agroindustrial at Universidad Nacional Hemilio Valdizan and at the Laboratorio de Microscopía Electrónica de Barrido (SEM) of Universidad de Huánuco, both located in Huánuco, Peru.

Obtaining mango peel extract

Two kilograms of mango (*Mangifera indica*, papaya mango variety) were purchased at the wholesale market in Huánuco, with a maturity index of 2 (green). Fruits were classified by variety, ripeness, and size, and then randomly selected, excluding those that were ripe, damaged, or contaminated. After washing with potable water and rinsing with distilled water, 400 g of peel (pericarp) were manually removed. Then, 100 g of chopped pericarp were blended with 100 mL of distilled water in a blender (Blender Classic, Oster). Commercial corn starch (amylose $\approx$ 28%) and glycerin ($\geq$ 99.5%) were used as plasticizers. The mixture was filtered using an organza fabric, and the extract was used in the preparation of bioplastics.

Preparation of bioplastic films with mango peel

In a beaker containing 50 mL of distilled water, a magnetic stirrer (MS-H280-Pro, DLAB) was used. Mango peel extract was added at concentrations of 5%, 10%, and 15% (g/100 mL). Additionally, 4 g of cornstarch, 4 mL of glycerin, 4 mL of vinegar, and 0.15 mL of cinnamon essential oil were incorporated, with the same concentrations in all treatments, varying only the extract (**Table I**). The control sample (0%) did not include extract. Mixtures were homogenized

at 200 rpm for 30 min at 140 °C until gelatinization (Nazario-Naveda et al. 2021). Each formulation (0-15%) was poured (15 mL) into Petri dishes, dried in an oven (MMM Medcenter, ECOCELL) at 50 °C for 24-48 hours, and then cooled for 3 hours at room temperature. The bioplastics were removed and placed on parchment paper for physical-mechanical, morphological, and biodegradability analyses (**Fig. 1**).

Evaluation of physical-mechanical and morphological properties of the bioplastic

Physical properties

Thickness

The thickness of the bioplastic was determined using the methodology of Oluwasina et al. (2018) with a Promeq digital flat-head micrometer (German origin), on 2×2 cm² samples. Three measurements were taken at different points of each sample.

Density

Density was determined according to ASTM D792-20, Standard Test Methods for Density and Specific Gravity of Plastics by displacement (ASTM 2020). Samples of 2×2 cm² were used, recording thickness with a Promeq digital flat-head micrometer (0-12.7 mm/0.5" $\times$ 0.0001 mm/0.00005"), and weights with an analytical balance (model HR-250AZ, Galaxy-A&D, Japan). Density was calculated using Equation (1):

$$\text{Density} = \frac{M}{A \times D} \quad (1)$$

Where M is the mass (g), A is the area (cm²), and D is the thickness (cm).

Moisture

Moisture analysis followed the methodology of Oluwasina et al. (2018) with modifications in sample size. Samples of 5×5 cm² were weighed on an analytical balance and then placed in an oven (MMM Medcenter, ECOCELL) at 90-105 °C for 24 hours. Afterwards, the bioplastic cuts were placed in a desiccator and reweighed. Moisture was calculated with Equation (2):

TABLE I. BIOPLASTIC FORMULATION BASED ON MANGO PEEL EXTRACT (MPE).

Treatment	H ₂ O (mL)	MPE (%)	Corn-starch (g)	Glycerin (mL)	Vinegar (mL)	Essential oil (mL)
0% (control)	50	0	4	4	4	0.15
5%	50	5	4	4	4	0.15
10%	50	10	4	4	4	0.15
15%	50	15	4	4	4	0.15

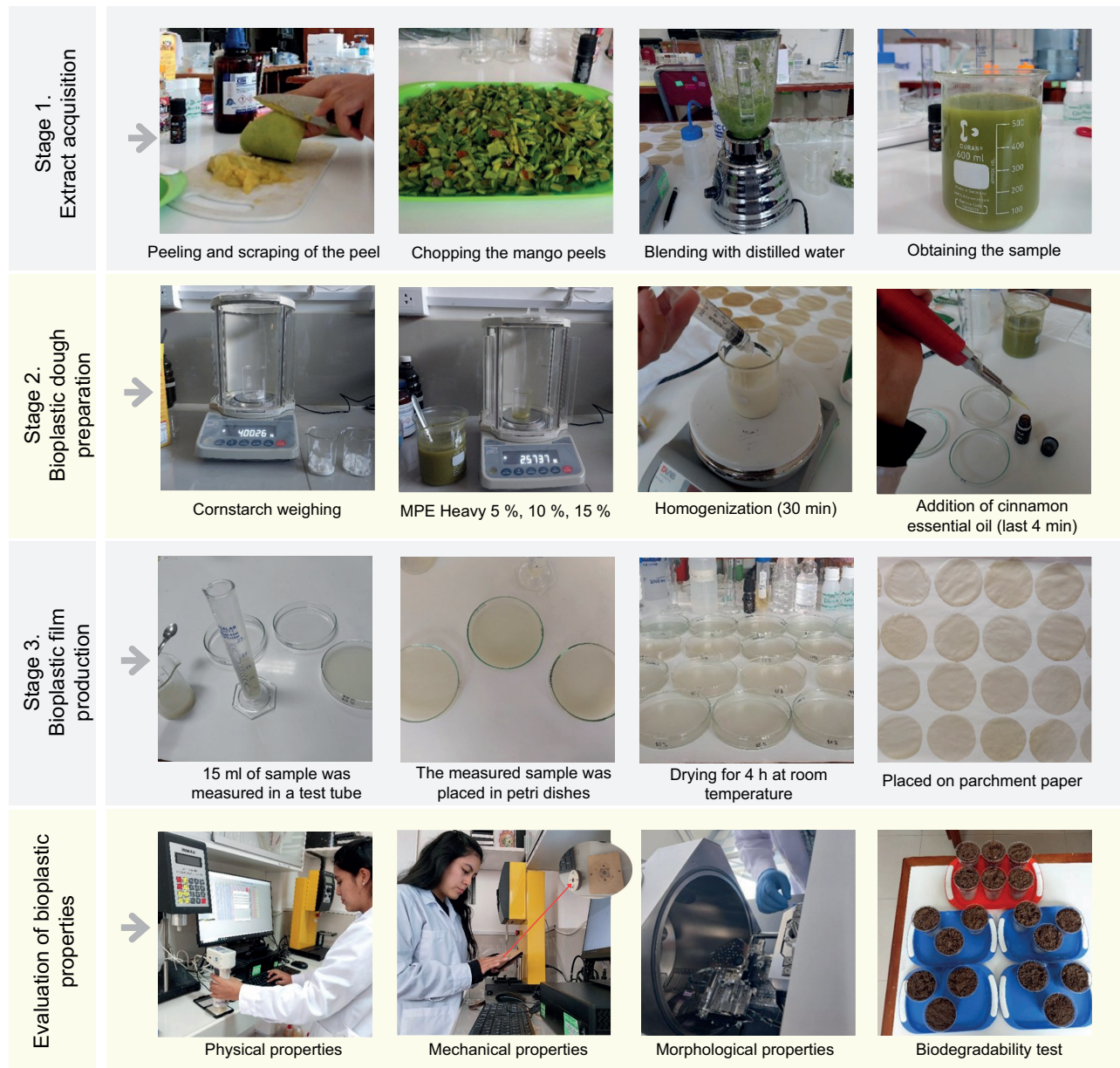


Fig. 1. Scheme of the preparation and evaluation process of mango peel extract-based bioplastic films.

$$\text{Moisture (\%)} = \left(\frac{W_1 - W_2}{W_1} \right) \times 100 \quad (2)$$

Where W_1 is the wet weight, and W_2 is the dry weight.

Opacity

Opacity was analyzed according to Oluwasina et al. (2018) with modifications using three replicates per sample. Bioplastics of 4 cm × 1 cm were

measured for thickness with a digital micrometer. Absorbance was recorded with a Genesys™ UV-Vis 150 spectrophotometer (Thermo Scientific™, Waltham, MA, USA) at 600 nm. Opacity was calculated with Equation (3):

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

Where Abs₆₀₀ is the value of absorbance at 600 nm, and x is the thickness of the bioplastic.

Solubility

Solubility analysis followed the method of Whan et al. (2007) with slight modifications. Samples ($2 \times 2 \text{ cm}^2$) were oven-dried at 105°C for three hours, cooled for 10 minutes in a glass desiccator, and weighed (W_0). Then, they were immersed in 40 mL of distilled water in covered beakers for 24 h. Undissolved fractions (W_1) were dried again (3 h at 105°C), cooled, and reweighed. Solubility was calculated with Equation (4)

$$\text{Solubility (\%)} = \left(\frac{W_0 - W_1}{W_0} \right) \times 100 \quad (4)$$

Where W_0 is the initial dry weight, and W_1 is the undissolved dry weight.

Color

Color was analyzed with a colorimeter (CR-400, Konica Minolta, Japan). Samples were 90 mm in diameter, with four measurements per sample (Ferraz et al. 2023). Results were expressed in the Cielab system (L^* , a^* , b^*). The color difference was determined using Equation (5) (Hernández et al. 2016).

$$\Delta E^* = \sqrt{(L_{\text{standard}} - L_{\text{sample}})^2 + (a_{\text{standard}}^* - a_{\text{sample}}^*)^2 + (b_{\text{standard}}^* - b_{\text{sample}}^*)^2} \quad (5)$$

Where L^* is brightness, a^* is red/green (a^+ red, a^- green), and b^* is yellow/blue (b^+ yellow, b^- blue).

Mechanical properties

Tensile strength, elongation, and traction force were evaluated in accordance with the ASTM D882-18 standard (ASTM 2018). A CT3-25K texturometer (Brookfield, USA) with traction clamps was used. Samples ($1.5 \times 5.0 \text{ cm}$) were placed between clamps separated by 3.0 cm. The test was performed at a speed of 5.00 mm/s with an activation load of 0.05 N until rupture. The device, connected to a computer, generated graphs of load (N) versus clamp separation (mm) as a function of time (s). The tensile strength was represented by the peak load (N), calculated by the texture analyzer.

Elongation

Elongation was calculated using Equation (6):

$$E (\%) = \left(\frac{C_f - C_i}{C_i} \right) \times 100 \quad (6)$$

Where E is the elongation at break, expressed in %, C_f is the length of the sample at the time of breakage (mm), and C_i is the initial length of the sample (mm).

Traction force

Traction force was represented by the peak load (N), calculated using the texture analyzer (CT3-25K Brookfield, USA). The result corresponds to the average of 12 repetitions for each sample concentration.

$$F = \text{peak load (N)} \quad (7)$$

Tensile strength

Tensile strength (MPa) was calculated using Equation (8), where F is the peak load force (N), h is the thickness of the strip (mm), and L is the width of the strip (mm), h and L representing the area:

$$TS = \frac{F}{h \times L} \quad (8)$$

Puncture strength

Puncture was determined using the texture analyzer (CT3-25K Brookfield, USA). Samples measuring $2 \times 2 \text{ cm}^2$ were used, with six samples evaluated for each bioplastic treatment. The test was performed at a formation speed of 1.00 mm/s with an activation load of 0.05 N until the sample was pierced by the probe (TA 39).

Morphological properties

Morphological analysis of the bioplastic was performed using the SEM (Thermo Scientific PRISMA E-Ultradry, USA). The sample size was $1 \times 1 \text{ cm}^2$, placed on 25 mm carbon disks located on the stub or holder to be positioned in the SEM sample holder. The work was carried out under low vacuum, with a sample holder level of 10 mm for electron beam emission and sample visualization, at a pressure of 0.75 Torr, 15 kV, using a scale of 2 mm at $\times 100$ magnification and a scale of 200 μm at $\times 1000$ magnification (Nazario-Naveda et al. 2021).

Laboratory-scale biodegradability test

Biodegradability analysis was performed according to Oluwasina et al. (2018) with modifications in exposure time. A laboratory burial test was conducted for 28 days, with evaluations made every seven days. Samples ($2 \times 2 \text{ cm}^2$) were placed in transparent plastic cups (10 cm in diameter, with holes) containing 250 g of moist soil. Previously, they were dried in an oven ($90\text{--}105^\circ\text{C}$, 6 h), cooled for 10 min in a desiccator, and buried at 3.5 cm. Every seven days, the weight was measured after oven-drying (105°C , 5 min). To maintain conditions, 10 mL of distilled water was added daily, and temperature ($23\text{--}25^\circ\text{C}$) and humidity

were controlled. The procedure was also applied to compostable and conventional plastics. The test was performed in triplicate on five sampling dates over a 28-day period. The biodegradability percentage was calculated using Equation (9).

$$\text{Biodegradability (\%)} = \left(\frac{W_0 - W_t}{W_0} \right) \times 100 \quad (9)$$

Where W_0 is the initial weight of the sample before drying but prior to burial, and W_t is the final weight of the sample after burial.

Statistical analysis

The data were statistically analyzed by first applying the Shapiro-Wilk normality test to verify the distribution of the data. Then, analysis of variance (Anova) was performed to evaluate the significant differences among mango peel concentrations in terms of physical, mechanical, and morphological properties. Specific differences were identified using Tukey's post hoc test. Both tests were applied at a 95% significance level. Analyses were conducted using Infostat software (version 2020) and MS Excel.

RESULTS

The results presented below are organized according to physical, mechanical, and morphological properties. Subsequently, the results corresponding to biodegradation are shown. Since physical and mechanical properties correspond to continuous data, they were analyzed using the Shapiro-Wilk normality test, which did not show statistical significance ($p > 0.05$), indicating that the data follow a normal distribution.

Physical properties

Table II describes the results of the physical properties. The values represent the mean and standard deviation of the physical properties of the bioplastics for each treatment. The control was compared with treatments with the addition of 5%, 10%, and 15% MPE to evaluate statistical differences. Anova results did not reveal significant statistical differences in the physical properties, except for color. Therefore, the addition of MPE at concentrations of 5%, 10%, and 15% was not sufficient to generate appreciable changes in the physical properties. Regarding color, the control (0% MPE addition) presented the lowest mean of 3.02, compared to the 15% treatment, which obtained the highest value of 10.87. Meanwhile, in the 5% and 10% mango peel treatments, no statistical differences were observed in the color of the bioplastic.

Mechanical properties

Concerning the elongation (**Fig. 2A**), the Tukey test showed two differentiated groups: the control 0% and the 5% treatment with lower values of 57.59% and 58.14%, respectively; and the 10% and 15% treatments, with homogeneous behavior and higher elongation percentages of 68.63% and 76.99%, respectively. For tensile strength at break (**Fig. 2B**), it is observed that the control (0%) and the 5% and 10% mango peel extract treatments did not show statistically significant differences. However, with the addition of 15%, statistically significant differences were observed, reaching a value of 2.65 MPa. In contrast, for tensile force (**Fig. 2C**), no significant differences were observed among the treatments, indicating that the extract does not significantly influence the material's breaking resistance.

TABLE II. PHYSICAL PROPERTIES OF BIOPLASTIC WITH DIFFERENT CONCENTRATIONS OF MANGO PEEL EXTRACT.

Property	Mango peel concentrations			
	0% (Control)	5%	10%	15%
Thickness (mm)	0.343 ± 0.004 ^a	0.324 ± 0.019 ^a	0.362 ± 0.026 ^a	0.382 ± 0.048 ^a
Density (g/cm ³)	1.312 ± 0.090 ^a	1.205 ± 0.072 ^a	1.103 ± 0.172 ^a	1.079 ± 0.147 ^a
Moisture (%)	37.084 ± 3.462 ^a	38.953 ± 9.876 ^a	34.290 ± 6.956 ^a	32.639 ± 2.342 ^a
Opacity (%)	0.685 ± 0.279 ^a	0.787 ± 0.135 ^a	0.819 ± 0.017 ^a	0.831 ± 0.124 ^a
Solubility (%)	57.177 ± 1.019 ^a	53.675 ± 0.470 ^a	52.801 ± 2.780 ^a	54.534 ± 10.446 ^a
Color	3.028 ± 0.872 ^a	6.616 ± 0.522 ^b	7.386 ± 0.582 ^b	10.873 ± 1.400 ^c

Mean ± standard deviation (triplicate). Different lowercase letters indicate statistically significant differences (Tukey test, $p < 0.05$).

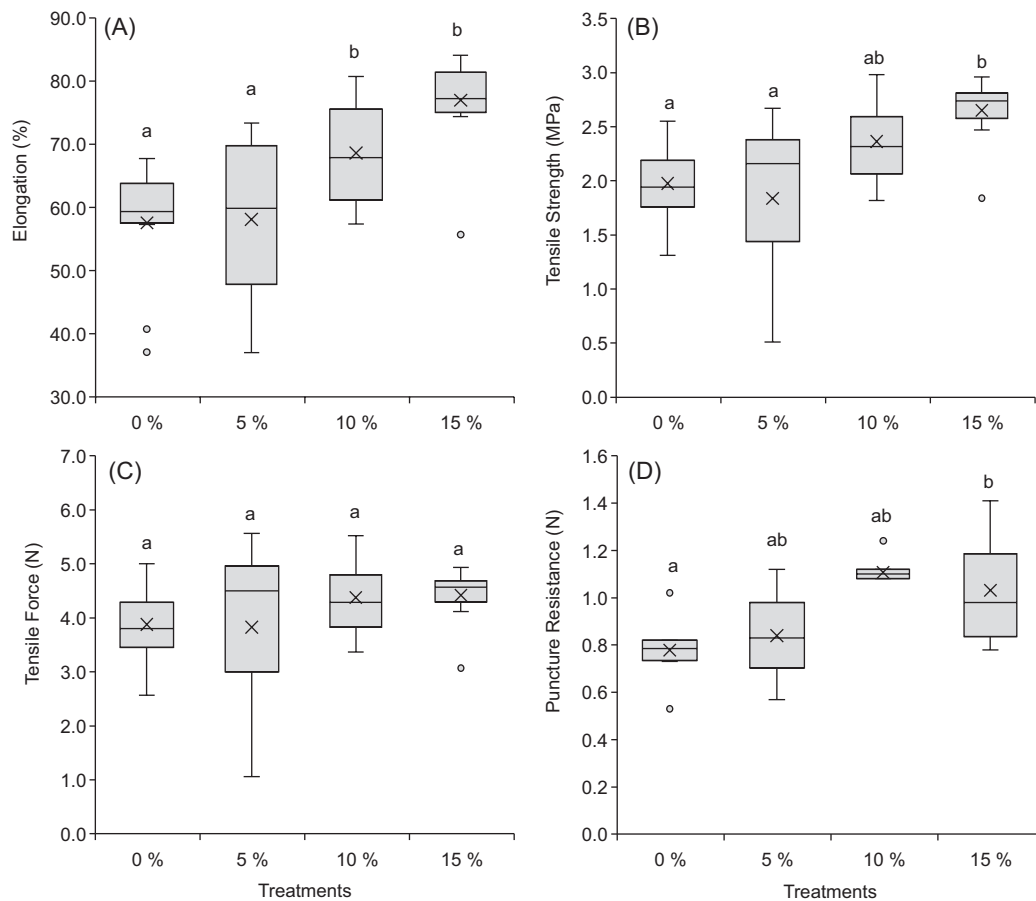


Fig. 2. Mechanical properties of bioplastic with different concentrations of mango peel extract (0%, 5%, 10%, and 15%). Elongation (A), tensile strength at break (B), tensile force (C), and puncture resistance (D). Different lowercase letters indicate statistically significant differences (Tukey test, $p < 0.05$). Boxes represent the interquartile range, bars represent the maximum and minimum values, and the center line identifies the median value. The “x” represents the average value.

Regarding puncture resistance (**Fig. 2D**), significant differences were observed among the treatments. The addition of 5% and 10% extract resulted in a slight increase in this property, although without statistically significant differences. In contrast, with the addition of 15% MPE, a significant increase in the puncture resistance of the bioplastics was observed, reaching values of 1.03 N.

Morphological properties

Figure 3 shows morphological images obtained using SEM at two magnification levels: 100 $\times$ (first column) and 1000 $\times$ (second column), corresponding to the control 0% sample (M), and the 5%, 10%, and 15% treatments, respectively. At concentrations of 5%, 10%, and 15%, and at a magnification of 1000 $\times$, slight fractions of undissolved starch were observed. Likewise, in all samples, a surface with slight protuberances and the presence of fibers from the mango

peel were observed, as well as starch particles that did not gelatinize. In both magnifications, no cracks, roughness, holes, or voids were observed. However, greater uniformity, homogeneity, and surface distribution were evidenced in the bioplastics as the concentration of mango peel increased, suggesting better component integration. Therefore, these results indicate that the best morphological quality was achieved with the addition of 15% MPE.

Biodegradation

Figures 4 and 5 describe the biodegradation results for the different treatments. Conventional plastic exhibited negligible degradation (approximately 1%), whereas the compostable plastic showed a gradual increase in degradation, reaching about 3% after 28 days.

The decomposition of the control bioplastic without MPE (0%) was faster than that of the bioplastics

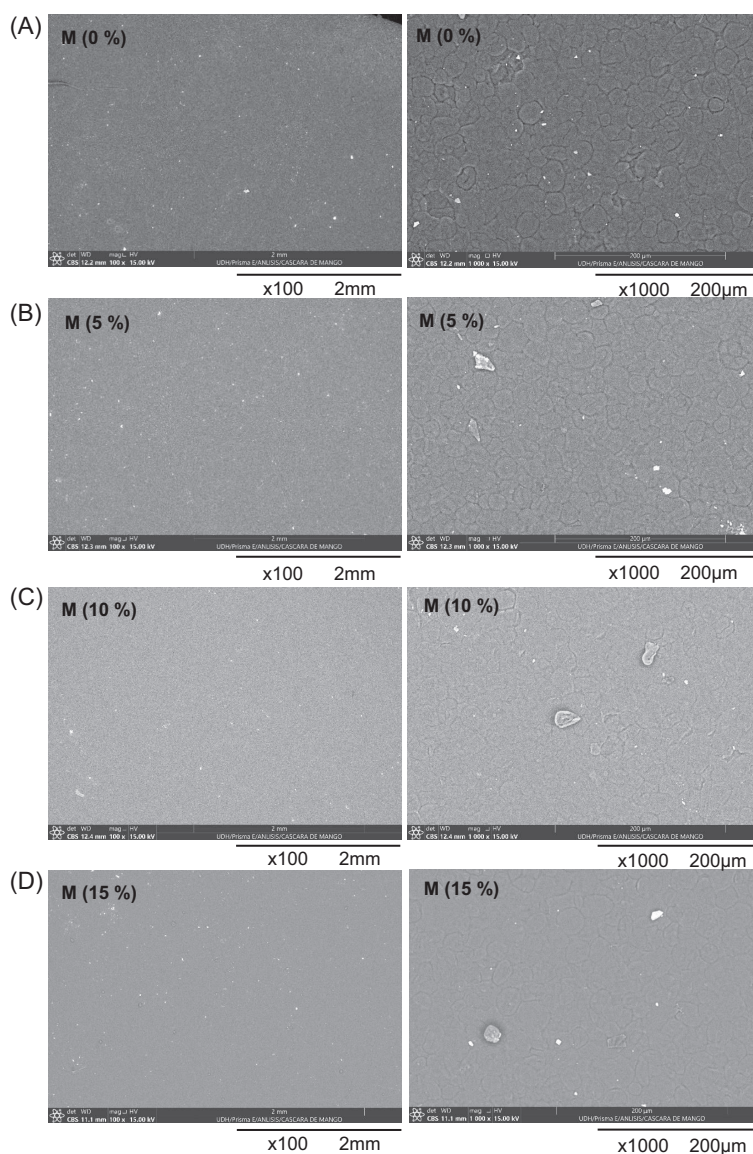


Fig. 3. Micrographs obtained by scanning electron microscope at two magnification levels: 100× (first column) and 1000× (second column) of bioplastic obtained with different concentrations of mango peel extract. M (0%) (A); M (5%) (B); M (10%) (C); and M (15%) (D). M: corresponds to the bioplastic sample. %: corresponds to the concentration of mango peel extract incorporated in each sample.

with extract. In one week, 12% decomposed, and by day 28, decomposition reached up to 90%. The bioplastic with the addition of 15% MPE exhibited the lowest biodegradation rate compared to the 5% and 10% treatments. After seven days, only 3% had degraded, and then the degradation rate increased more slowly, reaching 18% after 28 days.

Regarding the amount of MPE incorporated into the bioplastic formulation, the 5% sample exhibited a constant and relatively high degradation rate, reach-

ing 16% in the first seven days and 57% at 28 days. These results indicate that both the type of material and the amount of MPE influence the degradation of the bioplastics. Bioplastics without extract decomposed more easily compared to those with higher extract concentrations and conventional plastic.

The most notable observation in **figure 5** is the difference in the percentage of biodegradation over 28 days. Significant variations are observed among the treatments, especially between conventional and

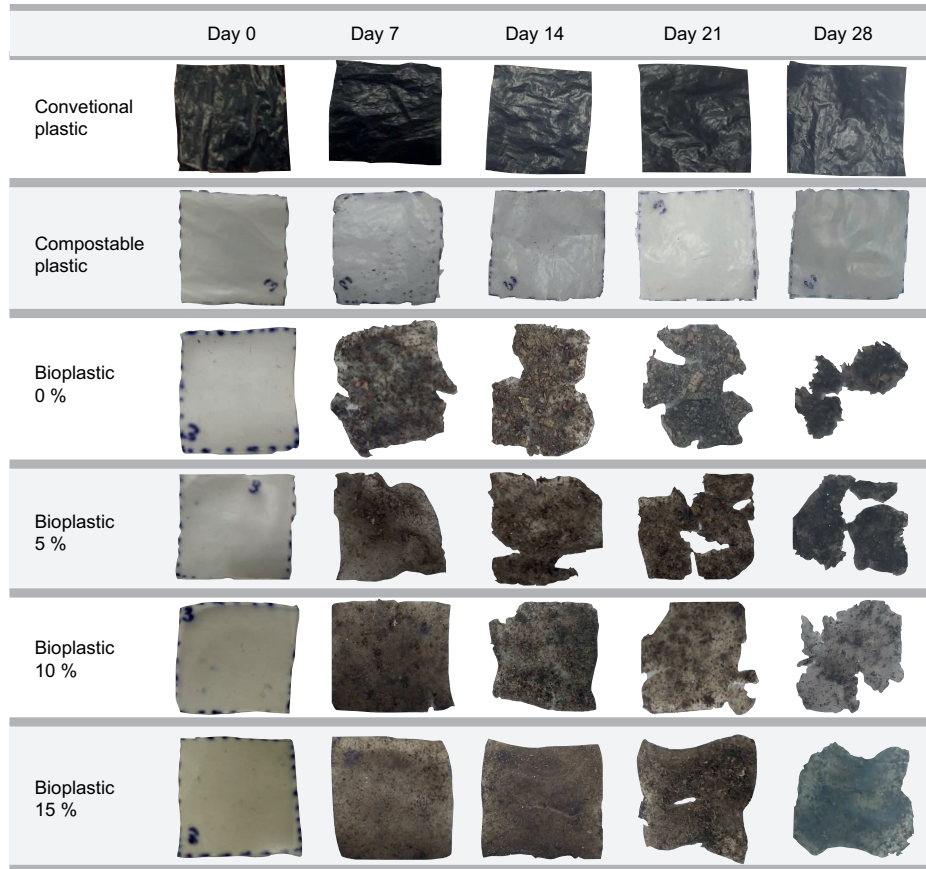


Fig. 4. Biodegradation process of conventional, compostable, and bioplastics made with mango peel extract at different concentrations (0%, 5%, 10%, and 15%). The images show the evolution of biodegradation over intervals of 0, 7, 14, 21, and 28 days.

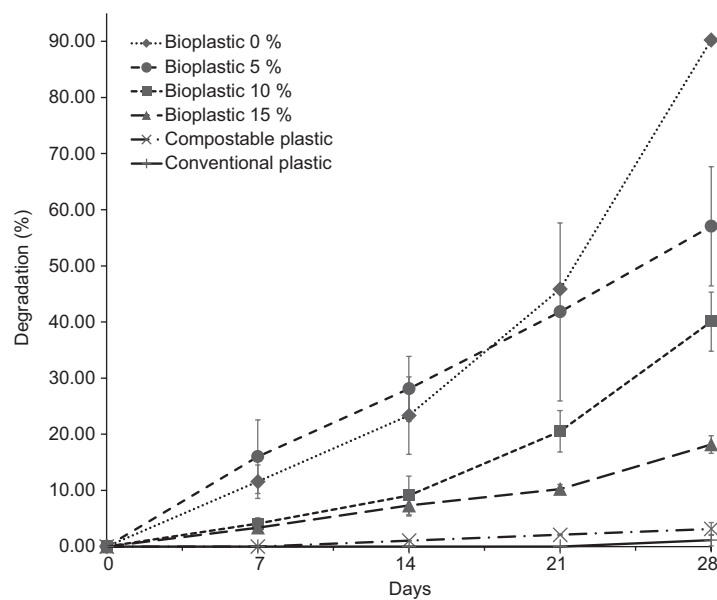


Fig. 5. Biodegradation rate (%) of conventional plastic, compostable plastic, and mango peel-based bioplastics (0%, 5%, 10%, 15%). The values represent the percentage of biodegradation observed at 7, 14, 21, and 28 days. Error bars represent standard deviation.

compostable plastic compared to the bioplastics. Among the bioplastics, the one that showed the most significant decomposition was the control. Within the bioplastics made with mango peel extract concentrations, the 5% concentration decomposed the fastest, whereas the 15% concentration showed the slowest decomposition.

DISCUSSION

Physical properties

Thickness influences mechanical and permeability properties. In this study, the range was from 0.343 mm (0%) to 0.382 mm (15%), with no significant differences. Hernández-Lozano et al. (2025) reported increases up to 0.61 mm with 17.2% mango peel powder. The combination of polymers also modifies the thickness: bioplastics with 22.2% cassava, corn, and rice starch, 11.1% gelatin, 2.78% corn oil, and 63.89% water, achieved thicknesses of 0.24 mm (corn) and 0.26 mm (rice and cassava), as reported by Jayalath et al. (2025). The slight increase observed could be attributed to the plasticizer, which weakens molecular interactions and leads to the formation of less compact polymer matrices (Adilah et al. 2018, Gonçalves et al. 2019). Drying and manufacturing conditions also influence thickness (Adilah et al. 2018). Together, thickness and density affect mechanical properties, permeability, and opacity, possibly due to polyphenol-peptide interactions (Sultan et al. 2024).

Density ranged from 1.31 g/cm³ (0%) to 1.08 g/cm³ (15%), with an 18% reduction. Similar results were reported by Nazario-Naveda et al. (2021) in mango extract bioplastics (0.80–1.12 g/cm³, 5–15%). Sultan et al. (2024) found densities of 1.32 g/cm³ in pulp bioplastics and 1.64 g/cm³ in potato peel bioplastics, indicating the influence of the raw material. The increase is attributed to the improved alignment of cellulose fibers within the starch matrix, resulting in more compact structures (Anugrahwidya et al. 2021). Although the values exceed the typical density of polypropylene, 0.90 g/cm³ according to ASTM D792-20 (ASTM 2020), this comparison depends on the measurement method. The type and proportion of biopolymers, plasticizers, and additives influence variations in the properties. Thus, the obtained densities are moderate and advantageous for applications requiring a balance between lightness, strength, and biodegradability.

Moisture decreased from 38.95% (5%) to 32.63% (15%), without significant differences, suggesting a relationship with the amount added. In contrast,

Nazario-Naveda et al. (2021) reported increases of 21.95% and 24.02% in bioplastics with 5% and 10% MPE, attributed to higher glycerol (5 g potato starch, 5 mL glycerol, 5 mL vinegar). Sultan et al. (2024) observed increases from 5.55% to 29.9% in potato peel bioplastics with glycerol, confirming its hygroscopic capacity. In cassava, moisture levels depended on pH, reaching 26.25% at a pH of 7.5 (Anchundia et al. 2025). These variations are influenced by the formulation and drying process. Moderate moisture improves flexibility during processing, whereas excess moisture compromises integrity, increases microbial degradation, and reduces starch stability (Titone et al. 2021, Enwere et al. 2024).

Opacity slightly increased with MPE: 0.69% (0%), 0.79% (5%), 0.81% (10%), and 0.83% (15%), without significant differences. De Azevedo et al. (2020) reported 0.49–1.15% in corn and potato films with ash silicate. Other studies have found 0.92% in bitter yam bioplastics with glycerol (Oluwasina et al. 2018); Gonçalves et al. (2019) observed a reduction when glycerol was decreased (from 0.95% with 50% to 0.92% with 0%). The low levels obtained indicate high transparency, which is desirable in packaging and coatings (Tomerlin et al. 2023). However, higher opacity can improve UV protection (Navasingh et al. 2023).

Solubility, an indicator of moisture resistance and degradability, was high, with values of 57.18% (0%), 53.68% (5%), 52.80% (10%), and 54.53% (15%), showing no significant differences. In bioplastics with 4% gelatin, 30% glycerol, and MPE (1–5%), a decrease was observed from 23.31% to 20.06% (Adilah et al. 2018). Hernández-Lozano et al. (2025) reported higher solubility in peel bioplastics (50%) than in seed (30.22%). These values limit their use in packaging requiring brief moisture resistance. The use of dialdehyde starch reduces hydrophilicity and solubility: Oluwasina et al. (2018) reported 4.23% with a 100% solution versus 7.9% with 60%. The amylose-amylopectin ratio also influences material viability (Navasingh et al. 2023). Our results suggest that highly soluble bioplastics, although limited to packaging, are useful in applications requiring rapid degradation. Regarding color, bioplastics should be transparent to resemble synthetic polymers and ensure acceptance. In this study, higher MPE increased the surface gray tone (**Fig. 4**), attributed to pigments such as β -carotene. Acosta (2021) described brown-gray tones resulting from enzymatic browning, a process caused by polyphenol oxidase, which depends on temperature and pH. Gallardo and Velázquez (2021) observed dark yellow in the mango and grape,

while Fernández Benavides and Gil Castillo (2023) reported translucent brown in the mango seed. These findings confirm that formulation and composition have a significant impact on color, a key factor in determining perceived quality.

Mechanical properties

Elongation increased with MPE, from 68.63% at 10% to 76.99% at 15%, similar to the values reported for caladium bicolor starch bioplastics (77.0%) by Enwere et al. (2024). In contrast, films with 4% gelatin, 30% glycerol, and MPE (1-5%) showed lower elongations (50.68-42.09%), as reported by Adilah et al. (2018). In our study, the increase is attributed to the use of low glycerol (4 mL), which favors a homogeneous network with hydrogen bonds without saturating it, thereby enhancing flexibility (Sultan et al. 2024, Fauziah et al. 2025). Thickness influenced elongation: 0.026 mm bioplastics showed 8.8% elongation with pectin and peel (1:2), according to Chaiwarit et al. (2020), while ours reached 0.343-0.382 mm and 76.99% elongation at 15% MPE.

Overall, the tensile strength was low (2.65 MPa for the bioplastic containing 15% MPE) compared to polyethylene plastics, which exceed 10 MPa (Lanh et al., 2023). In bioplastics with gelatin, glycerol, and MPE (1-5%), the strength ranged from 8.22 to 15.78 MPa (Adilah et al. 2018), attributed to the presence of pectin and amylose. Pectin and peel blends (3:0 and 1.5:1.5) recorded 8.17 and ~13 MPa (Chaiwarit et al. 2020). In our case, strength and elongation followed the same pattern, likely due to the presence of glycerol, which is consistent with studies showing that increasing glycerol (0-10%) improves both properties (Fauziah et al. 2025). Thus, MPE increases elongation but reduces tensile strength, although at higher concentrations, the latter effect is slightly improved.

Tensile force showed no significant differences among treatments, indicating that MPE did not influence it. Puncture resistance slightly increased up to 1.03 N (15%), in parallel with elongation (76.99%), strength (2.65 MPa), and thickness (0.382 mm). This effect is associated with the physical modification of starch by heat and moisture, as observed in green banana bioplastics, which exhibit a tensile strength of 27.09 MPa, 6.0% elongation, and a puncture strength of 251.8 N (Viana et al. 2022). Additionally, organic fillers help dissipate stress and improve integrity (Kim et al. 2025). Overall, the bioplastics demonstrated good flexibility but limited strength, making them suitable for flexible packaging, biodegradable wraps, and low-load bags, rather than structural applications.

In general terms, the physical properties did not exhibit statistically significant differences, suggesting that the addition of MPE at concentrations of 5 to 15% was insufficient to generate appreciable changes in these parameters. In contrast, the mechanical properties exhibited variations, particularly in elongation and tensile strength, which can be attributed to the lignocellulosic and fibrous composition of the mango peel extract, acting as a reinforcement for the polymer matrix (García-Mahecha et al. 2023). Likewise, the increase in MPE favored elongation, possibly due to the presence of pectins and soluble biopolymers that increase the material's flexibility before breaking (Hernández-Lozano et al. 2025).

Morphological properties

Microstructures with MPE were homogeneous and compact, without voids, and featured minimal granular structures at 5-15%. They coincide with smooth surfaces reported in potato bioplastics with 15% mango peel extract (Nazario-Naveda et al. 2021). In contrast, mango seed films showed insoluble clumps due to insufficient agitation (Maulida et al. 2018). In films with gelatin and MPE (1-5%), granular structures increased, but a compact network was maintained, attributed to intermolecular forces (Adilah et al. 2018). The matrix influences morphology: cassava bioplastics exhibit smooth surfaces with voids, corn is rough and porous, and rice is intermediate, with pores and cracks (Jayalath et al. 2025). In our samples, MPE favored the formation of a continuous polymer network.

Biodegradation

At 28 days, biodegradation reached 90% (control), 57% (5%), 40% (10%), and 18% (15%), higher than conventional plastic (1%) and compostable plastic (3%). Similar results were observed with aqueous peel extract, with weight loss decreasing from 79% at 5% to 33% at 15%, as reported by Nazario-Naveda et al. (2021). This is attributed to a low starch-extract interaction, resulting in less compact films. Greater loss at low concentrations is related to the cleavage of the α -1,4-glucosidic starch bond versus the β -glucosidic cellulose bond (Torres et al. 2011). Increasing pectin levels enhances hydrophobicity and contact angle (Chaiwarit et al. 2020).

Biodegradability also depends on formulation: bioplastics with 10 g of peel and 20 mL of glycerol reached 93.06% biodegradation in four weeks (Sernaqué Auccahuasi et al. 2020). The starch source influences the results, with cassava (67.00%), rice (51.81%), and corn (47.72%) observed after seven

days (Jayalath et al. 2025). The environment where degradation occurs modifies the results: a bioplastic composed of peel starch, glycerol, carboxymethylcellulose, and calcium carbonate exhibited degradation rates of 41.99% in water (after 35 days), 53.84% in soil, and 9.43% outdoors after 53 days (Proaño 2021).

Finally, variations in mechanical, morphological, and biodegradation properties depend on the formulation, additives, and the percentage of raw materials. The incorporation of MPE-modified structure and composition highlights the need to optimize its proportion to improve properties and guide specific applications.

CONCLUSION

The results show that the incorporation of MPE did not affect the physical properties of the bioplastic, except for color, which intensified at higher concentrations. In terms of mechanical properties, significant changes were observed in elongation, tensile strength, and puncture strength, especially at 15%, while the tensile force remained stable. Morphologically, SEM images revealed non-gelatinized particles without relevant defects (cracks or holes), indicating good material formation. Regarding biodegradability, bioplastics with 5% extract degraded faster than those with 15%, suggesting that excess lignocellulosic residues can slow the process.

Overall, bioplastics with MPE present favorable physical-mechanical, morphological, and biodegradation properties, consolidating them as a sustainable alternative to conventional plastics. The incorporation of mango peel extract primarily influenced elongation and fracture resistance, confirming that adjusting the composition enables the optimization of these properties. Nevertheless, this study has limitations, including methodological variations in property measurement (thickness and density) and the absence of tests at a larger scale or under diverse environmental conditions. Therefore, future studies are recommended to evaluate performance in real-world environments, expand formulations, and enhance experimental standardization to improve the reproducibility and comparability of results.

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REFERENCES

- Abu Ubaidah A. S., Mohamad Puad N. I., Hamzah F., Azmi A. S. and Ahmad Nor Y. (2024). Synthesis of bioplastics and the effects of additives on the mechanical, thermal and biodegradable properties. *Polymers from Renewable Resources* 15 (4), 430-490. <https://doi.org/10.1177/20412479241292148>
- Acosta D. Y. (2021). Aprovechamiento de residuos de maracuyá (*Passiflora edulis*) y mango (*Mangifera indica*) para la elaboración de un bioplástico. B.Sc. Thesis. Facultad de Ingenierías y Arquitectura, Universidad de Pamplona. Pamplona, Colombia, 57 pp.
- Adilah A. N., Jamilah B., Noranizan M. A. and Hanani Z. A. N. (2018). Utilization of mango peel extracts on the biodegradable films for active packaging. *Food Packaging and Shelf Life* 16, 1-7. <https://doi.org/10.1016/j.fpsl.2018.01.006>
- Ajila C. M., Bhat S. G. and Prasada Rao U. J. S. (2007). Valuable components of raw and ripe peels from two Indian mango varieties. *Food Chemistry* 102 (4), 1006-1011. <https://doi.org/10.1016/J.FOOD-CHEM.2006.06.036>
- Anchundia L., Piedra F. J., Alcívar J. A. M., Mendoza V. S., Guerrero D. I. V., Intriago S. N. G., Muñoz W. A. G., Pérez G. L. R., Alava R. L., Delgado O. B. and Piedra C. J. (2025). Effect of pH on the physicochemical properties of a Cassava peel starch biopolymer. *Cellular Physiology and Biochemistry* 59 (1), 21-33. <https://doi.org/10.33594/000000753>
- Anli Dino A., Kishore G., Rokhum S. L. and Baskar G. (2025). Bioplastic production using waste macroalgal biomass: A holistic review on challenges, prospects, economic viability and sustainability analysis. *Journal of Environmental Chemical Engineering* 13 (2), 116108. <https://doi.org/10.1016/J.JECE.2025.116108>
- Anugrahwidya R., Armynah B. and Tahir D. (2021). Bioplastics starch-based with additional fiber and nanoparticle: Characteristics and biodegradation performance: A Review. *Journal of Polymers and the Environment* 29 (11), 3459-3476. <https://doi.org/10.1007/S10924-021-02152-Z/FIGURES/5>
- ASTM (2018). Standard test method for tensile properties of thin plastic sheeting. American Society for Testing

- and Materials [online]. <https://store.astm.org/d0882-18.html> 26/09/2025
- ASTM (2020). Standard test methods for density and specific gravity (relative density) of plastics by displacement. American Society for Testing and Materials [online]. <https://store.astm.org/d0792-20.html> 26/09/2025
- Chaiwarit T., Masavang S., Mahe J., Sommano S., Ruksiriwanich W., Brachais C. H., Chambin O. and Jantrawut P. (2020). Mango (cv. Nam Dokmai) peel as a source of pectin and its potential use as a film-forming polymer. *Food Hydrocolloids* 102, 105611-105611. <https://doi.org/10.1016/J.FOODHYD.2019.105611>
- de Azevedo L. C., Rovani S., Santos J. J., Dias D. B., Nascimento S. S., Oliveira F. F., Silva L. G. A. and Fungaro D. A. (2020). Biodegradable films derived from corn and potato starch and study of the effect of silicate extracted from sugarcane waste ash. *ACS Applied Polymer Materials* 2 (6), 2160-2169. <https://doi.org/10.1021/ACSAPM.0C00124>
- Enwere C. F., Okafor I. S., Adeleke A. A., Petrus N., Jakada K., Olosho A. I., Ikubanni P. P., Paramasivam P. and Ayuba S. (2024). Production of bioplastic films from wild cocoyam (*Caladium bicolor*) starch. *Results in Engineering* 24, 103132. <https://doi.org/10.1016/j.rineng.2024.103132>
- Farouk A. (2024). Towards sustainable food packaging films using cellulose acetate and polyvinylidene fluoride matrix enriched with mango peel extract. *Biomass Conversion and Biorefinery* 14 (7), 8957-8978. <https://doi.org/10.1007/S13399-023-04986-0/FIGURES/11>
- Fauziah A. N., Adriana R., Hayati A. T., Marlina A., Yustinah and Ndruru, S. T. C. L. (2025). Physical performance of glycerol-plasticized cassava peel starch-carboxymethyl cellulose bioplastic. *Emergent Materials*. <https://doi.org/10.1007/s42247-025-01027-6>
- Fernández Benavides F. V. and Gil Castillo A. K. (2023). Análisis de la viabilidad de una biopelícula fabricada a partir del almidón de la semilla del mango Tommy para uso en ingeniería de tejidos. B.Sc. Thesis. Facultad de Ingeniería, Universidad Autónoma de Occidente. Santiago de Cali, Colombia, 62 pp.
- Ferraz A. R., Goulão M., Santo C. E., Anjos O., Serralheiro M. L. and Pintado C. M. B. S. (2023). Novel, edible melanin-protein-based bioactive films for cheeses: Antimicrobial, mechanical and chemical characteristics. *Foods* 12 (9), 1806. <https://doi.org/10.3390/foods12091806>
- Fong-in S., Khwanchai P., Prommajak T. and Klinmalai P. (2025). Valorization of mango peel: Physicochemical properties, bioactive compounds, antioxidant activity, and glass transition temperature of freeze-dried mango powder. *Waste and Biomass Valorization* 16 (10), 5273-5285. <https://doi.org/10.1007/S12649-025-02989-8>
- Gallardo C. and Velázquez X. (2021). Elaboración de sorbetes biodegradables a partir de cáscara de *Mangifera indica* y *Vitis vinifera*. B.Sc. Thesis. Facultad de Ingeniería y Arquitectura, Universidad César Vallejo. Lima, Perú, 109 pp.
- García-Mahecha M., Soto-Valdez H., Carvajal-Millan E., Madera-Santana T. J., Lomeli-Ramírez M. G. and Colín-Chávez C. (2023). Bioactive compounds in extracts from the agro-industrial waste of mango. *Molecules* 28 (1), 458. <https://doi.org/10.3390/MOLECULES28010458>
- Gonçalves S. M., dos Santos D. C., Motta J. F. G., dos Santos R. R., Chávez D. W. H., and de Melo N. R. (2019). Structure and functional properties of cellulose acetate films incorporated with glycerol. *Carbohydrate Polymers* 209, 190-197. <https://doi.org/10.1016/j.carbpol.2019.01.031>
- Hernández B., Sáenz C., Alberdi C. and Diñeiro J. (2016). CIELAB color coordinates versus relative proportions of myoglobin redox forms in the description of fresh meat appearance. *Journal of Food Science and Technology* 53 (12), 4159-4167. <https://doi.org/10.1007/s13197-016-2394-6>
- Hernández-Lozano L. C., Berger P., Cachutt-Alvarado C. and Domínguez-Soberanes J. (2025). Sustainable solutions: Biodegradable polymers derived from mango residues. *Polymer* 319, 127980. <https://doi.org/10.1016/j.polymer.2024.127980>
- Jayalath U. T., Samaraweera H. and Samarasinghe A. (2025). Development and characterization of gelatin-starch bioplastics: A comparative study of cassava, corn, and rice-based alternatives. *Sustainable Chemistry for the Environment* 9, 100190. <https://doi.org/10.1016/j.scenv.2024.100190>
- Kharb J. and Saharan R. (2024). Development of biodegradable and eco-friendly fruit peel-derived bioplastic film with antibacterial potential for food packaging application. *Biomass Conversion and Biorefinery* 15 (7), 10839-10854. <https://doi.org/10.1007/S13399-024-05834-5>
- Kim J., Choi W., Park H., Jo S., Park K., Cho H., Oh Y., Choi M., Choi B., Ryu D. Y., Koh W.G., Woo S., Choi S., Kwak T., Kimm H. and Hong J. (2025). Tunable mechanical properties in biodegradable cellulosic bioplastics achieved via ring-opening polymerization. *ACS Nano* 19 (12), 11961-11972. <https://doi.org/10.1021/acsnano.4c16563>
- Lanh N. T., Thuan T. N. and Nga P. T. H. (2023). Morphological and tensile strength of low-density polyethylene/polyethylene terephthalate blends. *Advances in Transdisciplinary Engineering* 40, 204-210. <https://doi.org/10.3233/ATDE230460>

- Lastra-Ripoll S. E., Mieles-Gómez L., Ramirez-Brewer D., Marsiglia-Fuentes R., Quintana S. E. and García-Zapateiro L. A. (2025). Developing biodegradable films from mango (*Mangifera indica*) starch and extract: A rheological and physical study. *Gels* 11 (10), 825. <https://doi.org/10.3390/GELS11100825>
- Maulida, Kartika T., Harahap M. B. and Ginting M. H. S. (2018). Utilization of mango seed starch in manufacture of bioplastic reinforced with microparticle clay using glycerol as plasticizer. *IOP Conference Series: Materials Science and Engineering* 309 (1), 012068. <https://doi.org/10.1088/1757-899X/309/1/012068>
- Navasingh R. J. H., Gurunathan M. K., Nikolova M. P. and Królczyk J. B. (2023). Sustainable bioplastics for food packaging produced from renewable natural sources. *Polymers* 15 (18), 3760. <https://doi.org/10.3390/polym15183760>
- Nazario-Naveda R. R., Rojas-Flores S. J., Angelats-Silva L., Gallozzo-Cardenas M. M. and Valverde-Díaz E. I. (2021). Películas biodegradables de almidón de papa reforzadas con extracto acuoso de piel de mango para su uso como envase activo. *Proceedings. 19th LACCEI International Multi-Conference for Engineering, Education Caribbean Conference for Engineering and Technology: "Prospective and trends in technology and skills for sustainable social development" "Leveraging emerging technologies to construct the future"*. Buenos Aires, Argentina. 19 - 23 de julio, 2021. <https://doi.org/10.18687/LACCEI2021.1.1.479>
- Oliver-Simancas R., Labrador-Fernández L., Díaz-Maroto M. C., Pérez-Coello M. S. and Alañón M. E. (2021). Comprehensive research on mango by-products applications in food industry. *Trends in Food Science and Technology* 118, 179-188. <https://doi.org/10.1016/j.tifs.2021.09.024>
- Oluwasina O., Falola T., Wahab O. and Idahagbon N. (2018). Enhancement of physical and mechanical properties of *Dioscorea dumetorum* starch films with dialdehyde starch solution. *Starch* 70, 1700148. <https://doi.org/10.1002/star.201700148>
- Orizano-Ponce E., Santillán G., Chamorro-Gómez R. E., Villanueva-Tiburcio J. E., Estacio-Laguna R., Cueto-Rosales C. R., Palma-Lozano D., Cámara F. and Cano, D. (2025). Effect of ultrasound on the physical, morphological, and mechanical properties of bioplastic obtained from lucuma seed starch (*Pouteria lucuma*). *Applied Food Research* 5 (1), 100990. <https://doi.org/10.1016/j.afres.2025.100990>
- PNUMA (2021). Cómo reducir el impacto de los plásticos de un solo uso. *Chemicals and Pollution Action. Programa de las Naciones Unidas para el Medio Ambiente* [online]. <https://www.unep.org/es/noticias-y-reportajes/reportajes/como-reducir-el-impacto-de-los-plasticos-de-un-solo-uso> 04/03/2025
- Proaño V. (2021). Obtención de una película a partir de cáscara de mango (*Mangifera indica*) para el uso en alimentos. B.Sc. Thesis. Facultad de Ciencias, Escuela Superior Politécnica de Chimborazo. Riobamba, Ecuador, 81 pp.
- Rodríguez A., Rodrigues M. and Sotomayor O. (2019). Hacia una bioeconomía sostenible en América Latina y el Caribe: elementos para una visión regional [online]. <https://repositorio.cepal.org/server/api/core/bitstreams/f23d8b68-db93-4013-8556-18ab4061d01e/content> 26/09/2025
- Rojas R., Contreras-Esquivel J. C., Orozco-Esquivel M. T., Muñoz C., Aguirre-Joya J. A. and Aguilar C. N. (2015). Mango peel as source of antioxidants and pectin: microwave assisted extraction. *Waste and Biomass Valorization* 6 (6), 1095-1102. <https://doi.org/10.1007/s12649-015-9401-4>
- Rosenboom J., Langer R. and Traverso G. (2022). Bioplastics for a circular economy. *Nature Reviews Materials* 7 (2), 117-137. <https://doi.org/10.1038/s41578-021-00407-8>
- Serna-Cock L., García-Gonzales E. and Torres-León C. (2016). Agro-industrial potential of the mango peel based on its nutritional and functional properties. *Food Reviews International* 32 (4), 364-376. <https://doi.org/10.1080/87559129.2015.1094815>
- Sernaqué Auccahuasi F. A., Huamán Mogollón L. del C., Pecho Chipa H. and Chacón Chacón M. E. (2020). Biodegradabilidad de los bioplásticos elaborados a partir de cáscaras de *Mangifera indica* y *Musa paradisiaca*. *Centro Agrícola* 47 (4), 22-31. http://scielo.sld.cu/scielo.php?script=sci_arttext&pid=S0253-57852020000400022&lng=es&nrm=iso&tng=es
- Siregar M., Raihan R. and Cahyono C. (2023). Application of circular economy in manufacturing industry in Indonesia. *AMCA Journal of Community Development* 3 (1), 19-24. <https://doi.org/10.51773/ajcd.v3i1.211>
- Sultan A., Sultan H., Shahzad W., Kareem A., Liaqat A., Ashraf Z., Shahid A., Rauf A., Saeed S., Mehmood T., Zahra M., Soto-Bubert A. and Acevedo R. (2024). Comparative analysis of physical and mechanical properties of starch-based bioplastic derived from the pulp and peel of potatoes. *Journal of the Indian Chemical Society* 101 (10), 101301. <https://doi.org/10.1016/j.jics.2024.101301>
- Sultan M., Ali N., Naseem M., Islam M., Kareem A., Yang Y., Khan F., Gul S., Khan A., Ali F., Al Balushi R. A., Al-Hinaai M. M. and Al-Harthy T. (2025). Management of bioplastic waste: a critical analysis of biodegradation and recycling approaches. *Journal of Polymer*

- Research 32 (10), 362. <https://doi.org/10.1007/S10965-025-04561-3>
- Tesfaye T. (2017). Valorization of mango fruit by-products: physicochemical characterization and future prospect. *Chemical and Process Engineering Research* 50, 22-34. <https://www.iiste.org/Journals/index.php/CPER/article/view/36360>
- Titone V., Correnti A. and La Mantia F. P. (2021). Effect of moisture content on the processing and mechanical properties of a biodegradable polyester. *Polymers* 13 (10), 1616. <https://doi.org/10.3390/polym13101616>
- Tomerlin R., Valdec D., Tomiša M. and Vusić D. (2023). The impact of underlying opaque white coating parameters on flexographic print quality. *Applied Sciences* 13 (15), 8575. <https://doi.org/10.3390/app13158575>
- Torres F. G., Troncoso O. P., Torres C., Díaz D. A. and Amaya E. (2011). Biodegradability and mechanical properties of starch films from Andean crops. *International Journal of Biological Macromolecules* 48 (4), 603-606. <https://doi.org/10.1016/j.ijbiomac.2011.01.026>
- Viana E. B. M., Leite N. O., Ribeiro J. S., Almeida M. F., Souza C. C. E., Resende J. V., Santos L. S. and Veloso C. M. (2022). Development of starch-based bioplastics of green plantain banana (*Musa paradisiaca* L.) modified with heat-moisture treatment (HMT). *Food Packaging and Shelf Life* 31, 100776-100776. <https://doi.org/10.1016/J.FPSL.2021.100776>
- Wang A. and Zhang Y. (2025). Development of novel biodegradable bioplastics for packaging film using mango peels. *Journal of Emerging Investigators* 8, 1-9. <https://doi.org/10.59720/24-171>
- Whan J., Jun L. and Perry K. (2007). Mechanical and barrier properties of biodegradable soy protein isolate-based films coated with polylactic acid. *LWT - Food Science and Technology* 40 (2), 232-238. <https://doi.org/10.1016/j.lwt.2005.10.002>