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Original article

Extraction of biopolymer from banana peel residue (*Cavendish valery* L.) for bioplastic synthesis

Extracción de biopolímero del residuo de cáscara de banano (*Cavendish valery* L.) para síntesis de bioplásticos

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ABSTRACT: Current research in materials science focuses on the development of biopolymers derived from renewable resources, whose biodegradability makes them sustainable alternatives to petrochemical polymers. These materials contribute to reducing environmental impact while adding value to agro-industrial waste. In this study, two primary matrices were used: fresh banana peel and pure starch extracted from green banana, through a total of five experimental trials. Both raw materials were incorporated into a complex solution under controlled conditions to induce polymer dissolution, regulating parameters such as temperature, agitation, and component ratios. The objective of this work was to develop and optimize an efficient protocol for the extraction and purification of biopolymers from *Musa Cavendish Valery* L. residues. The results showed that the nature of the raw material and the starch content directly influence the structural and functional quality of the biopolymers obtained. The rigorous execution of the protocol led to the formation of stable membranes with characteristics comparable to those of biopolymers, making them suitable for application in the manufacture of single-use bioplastics. Overall, the findings confirm the feasibility of utilizing agro-industrial residues to produce biodegradable, sustainable materials with strong potential to replace conventional plastics derived from fossil sources

Key words: Starch, biodegradable, natural polymer.

RESUMEN: La investigación actual en ciencia de materiales se centra en el desarrollo de biopolímeros derivados de recursos renovables, con la capacidad de biodegradación los convierte en alternativas sostenibles frente a los polímeros petroquímicos. Estos materiales permiten reducir el impacto ambiental y valorizar los desechos agroindustriales. En este estudio se utilizaron dos matrices primarias: cáscara de banano fresca y almidón puro obtenido de banano verde, elaborándose cinco ensayos experimentales. Ambas materias primas fueron incorporadas en una solución compleja bajo condiciones controladas para inducir la disolución polimérica, regulando parámetros como temperatura, agitación y proporción de componentes. El trabajo tuvo como objetivo desarrollar y optimizar un protocolo eficiente para la extracción y purificación de biopolímeros a partir de residuos de *Musa Cavendish Valery* L. Los resultados demostraron que la naturaleza de la materia prima y el contenido de almidón influyen directamente en la calidad estructural y funcional de los biopolímeros obtenidos. La ejecución rigurosa del protocolo permitió formar membranas estables con características semejantes a un biopolímero para poderlas aplicar en la fabricación de bioplásticos de un solo uso. En conjunto, los hallazgos confirman la viabilidad del aprovechamiento de residuos agroindustriales para producir materiales biodegradables, sostenibles y con alto potencial para sustituir plásticos convencionales derivados de fuentes fósiles.

Palabras clave: Almidón, biodegradable, biodegradabilidad.

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INTRODUCTION

Waste production, originating from human activity, is characterized by being a heterogeneous mass whose effective reintegration into natural cycles remains a key challenge, resulting in progressive environmental accumulation (1). This accumulation represents a broad environmental concern, as both the rate of generation and the chemical complexity of waste hinder its natural decomposition (2). Over time, this imposes a considerable burden on non-renewable resources, demanding the development of appropriate study and management strategies to preserve environmental quality and public health (1). When classifying waste by origin, the considerable production from the primary sector (agriculture and livestock) stands out (3). Although these wastes are predominantly organic (approximately 60 %) and inherently biodegradable, their high concentration in localized areas can accelerate contamination processes and require longer times for complete decomposition (4). Banana (*Musa paradisiaca* L.) cultivation plays a vital economic role in tropical and subtropical regions. The scale of its global production, particularly in contexts such as Ecuador, results in the generation of large volumes of residual biomass during fruit processing (5). Despite the commercial value of bananas, the most abundant by-product generated is the peel, constituting nearly 95 % of the unused material. This figure highlights the inefficiency in raw material utilization, which prioritizes almost exclusively human consumption, inevitably contributing to the growing amount of unmanaged agro-industrial waste (6). Biologically, banana peel is a rich matrix of macromolecules. Its structural composition includes cellulose (25 %), hemicellulose (15 %), and lignin (60 %) (7). In addition, when green, it presents a high starch concentration, positioning it as an excellent yet underutilized source for biopolymer extraction, which can later be employed in the manufacture of biodegradable plastic materials (8). Biopolymers synthesized from renewable natural resources offer a sustainable alternative, as their physicochemical and thermoplastic properties are comparable to those of petrochemical polymers, with the added benefit of being inherently biodegradable (2). Specifically, the extraction of biopolymers (such as starch) from agro-industrial waste is a key strategy aimed at revalorizing these by-products for the manufacture of such materials. These materials essentially serve to replace conventional non-degradable plastics in various applications, contributing to the mitigation of CO_2 emissions (9). Their application is particularly critical in the development of high-consumption, short-life materials such as single-use packaging and utensils. Being biodegradable, these biopolymers ensure that such items do not persist after disposal, reintegrating into natural cycles without the environmental accumulation characteristic of petroleum-derived plastics (1). Therefore, the objective is to standardize a protocol for biopolymer extraction from different varieties and maturity stages of banana peel (*Musa paradisiaca* L.) to evaluate its yield and potential application in the development of biodegradable materials, such as single-use packaging and utensils, using residual biomass discarded in banana farms due to quality or maturity criteria.

MATERIALS AND METHODS

Experimental Design

The biopolymer extraction process was carried out using banana peel from different varieties and maturity stages. This experimental variation was implemented to determine the biomass source with optimal properties for the intended application, since the macromolecular composition of starch and fibers may vary significantly among different types of material. The raw material for the assays was obtained directly from agro-industrial discards in local banana farms (specifically, biomass unsuitable for commercialization or export due to advanced maturity or superficial defects). Extraction was performed by applying variations in formulation parameters, temperature, and agitation depending on the type of assay. In all cases, sodium metabisulfite ($Na_2S_2O_5$) was used as an antioxidant agent to prevent oxidation of natural compounds present in the biomass. Each assay was conducted independently and on different days to ensure controlled conditions and avoid interference between procedures.

Trial 1. Dried Peel

Banana peels were washed with distilled water and treated with 2.04 g of sodium metabisulfite. After drying and grinding, a homogenized powder sample was obtained by quartering. The biomass was subjected to wet cooking with distilled water until boiling to facilitate the release of structural components, then oven-dried for 24 h. The sample was subsequently ground again to obtain a fine powder. For biopolymer formulation, 50 g of dried biomass, 50 mL of pure glycerin, 50 mL of 100 % vinegar, and 50 mL of distilled water were used. The mixture was stirred and heated at 60 °C, then dried at the same temperature to remove moisture and form the biopolymeric film.

Trial 2. Fresh Peel (peel and endocarp)

Mature banana peel with endocarp was washed with distilled water and immersed in a boiling sodium metabisulfite solution for 30 min to inhibit enzymatic activity. Partial drying was performed, and the sample was blended to obtain a homogeneous paste. From this paste, 25 mL were mixed with 3 mL of hydrochloric acid (HCl) 0.1 M, 3 mL of sodium hydroxide (NaOH) 0.1 M, and 2 mL of pure glycerol (100 %). The mixture was poured into a Petri dish and oven-dried at 103 °C for 30 min, promoting moisture removal and film formation.

Trial 3. Fresh Peel - Endocarp Only

Mature banana peel was washed, separated from the fruit, and scraped to obtain the endocarp. This was placed in distilled water with sodium metabisulfite and oven-dried for 24 h. The remaining peel was blended and dried following the same procedure. Once dried, the material was ground and sieved to obtain a homogeneous sample. From this, 10 g of biomass powder, 60 mL of distilled water, 5 mL of pure glycerin, and 5 mL of 100 % vinegar were used. The mixture was stirred at 800 rpm and 100 °C on a magnetic stirrer, then oven-dried at 45 °C to obtain the film (10).

Trial 4. Fresh Peel - Without Endocarp

The same pretreatment described above was applied, but using peel without endocarp. A total of 5 g of sample, 20 mL of distilled water, 2.5 mL of pure glycerin, and 2.5 mL of 100 % vinegar were used. The mixture was stirred at 800 rpm and 30 °C (corrected temperature) on a magnetic stirrer. Finally, it was poured into a conditioned Petri dish and oven-dried at 45 °C under controlled conditions, yielding the biopolymer.

Trial 5. Green Banana (Starch)

Green bananas were washed, peeled, and immersed in distilled water with sodium metabisulfite to prevent oxidation. The peels were blended, sieved, and washed three times, and the washing liquids were left to rest for two days to allow starch precipitation. The extracted starch was used as the base for the biopolymer, combining 2 g of starch, 2 mL of pure glycerin, 2 mL of 100 % vinegar, and 15 mL of distilled water. The mixture was subjected to constant stirring at 500 rpm and 200 °C on a magnetic stirrer, then oven-dried at 45 °C, yielding a uniform biopolymeric film.

Evaluation of transparency and biodegradability of biopolymers

The treatments were selected for the evaluation of transparency and biodegradability.

Transparency

To evaluate the degree of transparency of the biopolymers, the samples were sectioned into films of 2.5 cm × 1 cm, obtaining five replicates for each assay. Each film was microscopically analyzed through three observations in different areas of the surface in order to determine the optical homogeneity of the material. Transparency was assessed using a Likert scale, where: 1 (completely opaque), 2 (slightly opaque), 3 (semi-transparent), 4 (transparent), and 5 (completely transparent) (11).

Biodegradability

To evaluate the photo-induced degradation of the biopolymers, the samples were exposed to ultraviolet (UV) radiation at a wavelength of 365 nm for a period of six days. The initial and final weight of each sample was recorded to determine the mass variation associated with the degradation process (12).

Statistical analysis

Data analysis was performed using SPSS software, version 27. Comparison of the variables Transparency (Likert) and Weight Loss (Biodegradability) among the five independent assays was conducted using the Kruskal-Wallis test. Statistically significant differences ($p < 0.05$) were subsequently evaluated through pairwise comparisons with Bonferroni correction, in order to determine the optimal protocol in terms of optical properties and degradation.

RESULTS AND DISCUSSION

Five experimental assays were implemented with the objective of establishing a protocol for biopolymer extraction from different stages of banana peel (green and ripe). Regarding the results obtained in Assay 1, the treatment with dried banana peel resulted in the production of a solid black material that crumbled easily upon handling and did not exhibit the cohesion required to form a film. This material displayed a non-homogeneous appearance and a cracked surface. These findings demonstrate that dried banana peel, under the tested conditions, is not a viable direct source for the manufacture of single-use biodegradable materials that require structural integrity and film-forming capacity (Figure 1).

Figure 1. Biopolymer extraction from dried banana peel.

In Trial 2, where mature banana peel with endocarp was employed, the process resulted in a non-homogeneous yellow paste with a viscous and sticky texture. This mixture spread without forming a uniform layer in the Petri dish and, after drying, the material did not consolidate into a film structure, remaining in a non-uniform form. This experimental condition revealed two critical limitations: first, the material did not develop the cohesion and structural integrity required to form a film; and second, the yellow coloration evidences the concentration of pigments inherent to the mature peel, which significantly reduces the transparency and optical quality of the biopolymer (Figure 2).

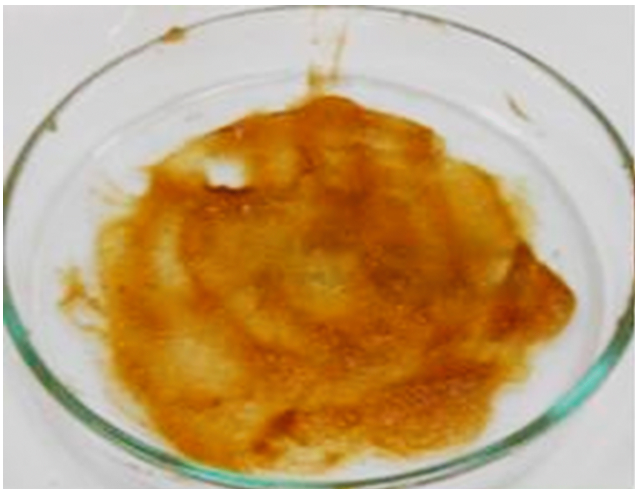

Figure 2. Extraction of the biopolymer using mature banana peel (peel and endocarp)

In Trial 3, which employed biomass obtained from fresh endocarp, distinct results were observed. After formulation and drying, a pale yellow-orange film was obtained. This material exhibited a smooth and relatively uniform surface, with visible film formation and considerable cohesion, although with some minor imperfections on its surface. The resulting material allowed handling as a film (Figure 3).

Figure 3. Biopolymer from banana endocarp

In Trial 4, where fresh peel without endocarp was employed, the production of an opaque yellow biopolymeric film was achieved, with a markedly smoother surface and superior uniformity compared to the previous trials. This film detached from the Petri dish as a continuous and well-formed sheet (Figure 4).

Figure 4. Extraction of the polymer using fresh banana endocarp only, without peel

The final trial, based on the extraction and use of precipitated starch from green banana, yielded the best results in film formation. A transparent biopolymeric film with a very pale yellow hue was obtained, exhibiting a very smooth surface with the highest optical uniformity and superior structural quality, resembling a packaging material (Figure 5).

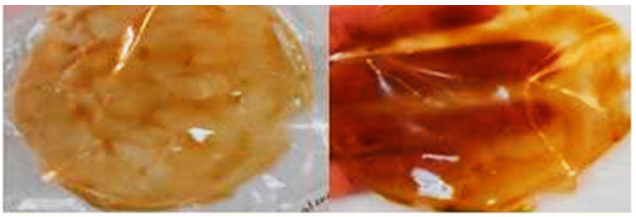

Figure 5. Biopolymers from starch of green banana peel

The results obtained in the transparency evaluation revealed notable differences among the five trials, which are directly related to the nature of the raw material and the extraction protocol applied. Biopolymers produced from dry biomass (Trial 1) were classified as completely opaque (Likert = 1). Those obtained in Trials 2 and 3 exhibited a slightly opaque appearance (Likert = 2), attributed to their heterogeneity and the brownish or yellowish coloration observed. Since the objective of the protocol is to obtain materials suitable for single-use packaging, where approaching transparency is a key functional requirement for commercial acceptance and product visibility, the conditions that resulted in total or slight opacity (Trials 1, 2, and 3) were considered unfeasible for standardization. In contrast, the materials that achieved films close to transparency showed a progressive improvement in their optical properties: the film produced with fresh peel without endocarp (Trial 4) was evaluated as semitransparent (Likert = 3), while that obtained from green banana starch (Trial 5) exhibited the best transparency characteristics, being rated as fully transparent (Likert = 4).

A Kruskal-Wallis test was performed to demonstrate statistically significant differences in the transparency values of the biopolymers among the different trials ($H = 73.000$; $df = 4$; $p < 0.001$). These results highlight variations in the degree of transparency observed according to the type of trial conducted (Table 1). The pairwise comparison table (post hoc), with significance adjusted using the Bonferroni correction, revealed statistically significant differences (adjusted Sig. < 0.05) in the transparency of Trial 1 (dry biomass) when compared with all other trials (T2, T3, T4, and T5). This result statistically confirms that the initial methodology using dry peel produces a significantly different material, which, due to its total opacity, is unfeasible for the development of the transparent material proposed in the protocol standardization. Likewise, both Trial 2 and Trial 3 showed significant differences with T4 and T5, suggesting that the inclusion or exclusion of the endocarp in these cases still does not optimize transparency. However, no significant differences were found between Trial 2 and Trial 3

Table 1. Comparison of the trials using the Kruskal-Wallis test

Summary of the Kruskal-Wallis test for independent samples	
total N	74
Test statistic	73.000[a]
Degrees of freedom	4
Asymptotic significance (two-tailed test)	< 0.001

*p < 0.05 indicates significant differences in transparency among the trials

(adjusted Sig. = 1.000) nor between the two most transparent trials, Trial 4 and Trial 5 (adjusted Sig. = 0.572), which implies that the improvements in transparency achieved between T4 and T5 are not statistically distinct (Table 2).

The total weight loss (biodegradability) after 6 days of exposure to UV radiation was compared among the five independent trials (T1, T2, T3, T4, T5). The overall analysis yielded a statistically significant result of H (4) = 13.189, with an asymptotic significance of $p < 0.004$. This outcome indicates that there are significant differences in the median weight loss (biodegradability) among the experimental conditions applied to the biopolymer, showing a significant effect on the biodegradability of the material exposed to UV radiation (Table 3).

Table 3. Kruskal-Wallis test for the total weight loss of the biopolymer

Test statistics [a,b]	
	TOTAL LOSS
H de Kruskal-Wallis	13.189
gl	3
Asymptotic sig.	0.004

*p < 0.05 indicates significant differences in biodegradability among the trials

The series of trials implemented evidenced a direct correlation between the pretreatment of the raw material and the functional properties of the final biopolymer. The inviability of Trial 1 (dry peel), which only produced a solid, black, crumbly residue, is interpreted as a consequence of the thermal degradation or pyrolysis suffered by the biomass during drying and cooking (13). This structural damage is the main factor preventing complete starch gelatinization and limiting the plasticizing action of glycerol (14, 15), resulting in a material lacking the structural integrity required for film formation. In Trial 2, the production of a viscous paste that failed to consolidate into a functional film, despite overcoming the extreme degradation observed in Trial 1, is attributed to an imbalance in the formulation. Specifically, the high proportion of soluble sugars (16) and the excess moisture characteristic of mature peel may have acted as anti-plasticizing agents, preventing the consolidation of a stable polymeric network (17).

The results of Trials 3 and 4 represent a significant advance by achieving the formation of manipulable films. The structural success achieved in Trial 3 suggests that the extraction protocol with fresh endocarp preserved the polymeric functionality of the biomass. The improvement in uniformity observed in Trial 4 is probably due to the exclusion of the endocarp and the adjustment of reagents, which favored more complete gelatinization (14), resulting in a continuous and well-formed film. However, the persistence of yellowish or orange hues in both films (T3 and T4) indicates that peel biomass, even when fresh, retains chromophoric compounds and pigments (18) that act as an inherent limitation to the optical potential of biopolymers based on integral biomass.

The transparency evaluation and statistical analysis confirmed these observations. The Kruskal-Wallis test demonstrated significant differences among the trials, validating that the protocol has a decisive effect on optical properties (13). Trial 5 (purified starch) demonstrated optical superiority, as its classification as fully transparent (Likert = 4) confirms that the removal of pigments and lignin is key to maximizing light transmission. Interestingly, the absence of a statistically significant difference in transparency between Trial 4 and Trial 5 (adjusted p = 0.572) suggests that the optimization achieved in Trial 4 offers an attractive balance between process simplicity and optical properties very close to those of purified starch (18).

Finally, regarding biodegradability, the significant difference in weight loss due to photo-induced (UV) degradation is explained by an inverse correlation between purity and UV shielding. The films with higher starch purity (T5) are inherently more susceptible to degradation (19) than the initial trials with high content of phenolic compounds and lignin, which act as natural protective agents against UV radiation (20). This final result confirms that the optimized biopolymer (T5) possesses a highly degradable character, an essential attribute for its application as a sustainable packaging material.

CONCLUSIONS

- The initial methodology based on dry peel (Trial 1) proved ineffective, as the thermal process induced severe polysaccharide degradation that prevented the structural integrity required to form a cohesive film.

Table 2. Comparison of the trials using the Kruskal-Wallis test

Pairwise comparisons of trials					
Sample 1-Sample 2	**Test statistic (H)**	**Desv. Error**	**Standardized Test Statistic**	**Sig.**	**Adjusted Sig[a]**
E1-E2	-22.500	7.492	-3.003	.003	.027
E1-E3	-22.500	7.492	-3.003	.003	.027
E1-E4	-45.000	7.492	-6.007	.000	.000
E1-E5	-59.500	7.624	-7.804	.000	.000
E2-E3	.000	7.492	.000	1.000	1.000
E2-E4	-22.500	7.492	-3.003	.003	.027
E2-E5	-37.000	7.624	-4.853	.000	.000
E3-E4	-22.500	7.492	-3.003	.003	.027
E3-E5	-37.000	7.624	-4.853	.000	.000
E4-E5	-14.500	7.624	-1.902	.057	.572

The significance level is 0.050

In contrast, the exclusion of the endocarp and the adjustment of reagents (Trial 4) represented the key structural optimization, allowing complete starch gelatinization and the production of a continuous film.

- It is concluded that Trial 4 (fresh peel without endocarp) is the most efficient standardized method. Although purified starch (Trial 5) achieved the highest optical classification, the post hoc statistical analysis demonstrated that there is no significant difference in transparency between T4 and T5 (adjusted Sig. = 0.572). Therefore, Trial 4 offers the best balance between operational efficiency and process simplicity for obtaining biopolymers suitable for packaging.
- The photo-induced (UV) degradation analysis confirmed the technological viability of the material. The optimized biopolymer (T5) proved to be highly degradable ($H(4) = 13.189$; $p < 0.004$), validating the usefulness of green banana starch as a raw material for biodegradable packaging applications.

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