Comparison of the Efficiency of Bioplastic Generated from Vicia Faba (Broad Bean) Waste and Low-Density Polyethylene (LDPE)

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***Abstract*—The main problem lies in the growing accumulation of plastic waste derived from fossil sources, which decomposes extremely slowly, especially in the case of Low-Density Polyethylene (LDPE), a widely used material whose discarding contributes to the proliferation of microplastics in ecosystems. This situation is aggravated in regions such as Huancayo, Peru, where the inadequate management of plastic waste is a critical challenge, coupled with the lack of adequate use of organic waste, which limits the implementation of effective recycling and recovery strategies, increasing the pollution load in the environment. In view of this problem, the efficiency of bioplastics made from starch extracted from Broad Bean Pod (Vicia faba) was investigated in comparison with LDPE bags, in order to assess their viability as a biodegradable alternative. The study began by obtaining the starch, for which broad bean pod residues were collected, liquefied and then left to rest in containers, thus favouring sedimentation, followed by a drying process. Once the starch was isolated, bioplastics were made using glycerol as a plasticiser. Various physicochemical properties of the starch were evaluated, such as gelatinisation temperature, bulk density, solubility, pH, viscosity, ash content, amylose to amylopectin ratio, and Fourier Transform Infrared Spectroscopy (FTIR) spectroscopy; and the bioplastics obtained were tested for thickness, moisture content, solubility, permeability, as well as mechanical properties such as tensile strength and elongation. The results showed that the bioplastics made from starch had a density of 1.296g/ml, a tensile strength of 2.41MPa and an elongation ranging from 46.67% to 186.67%. In addition, the bioplastics were found to be water soluble in a range of 2.358% to 51.974%, demonstrating their biodegradable character, unlike conventional plastics that are insoluble and non-biodegradable. Although bioplastics have a slightly lower mechanical performance, their biodegradability positions them as a more sustainable alternative, contributing to the reduction of the environmental impact caused by plastic waste.**

***Keywords*—Broad Bean Pod starch, bioplastics, low-density polyethylene, sustainability, glycerol**

I. Introduction

In 2024, the global generation of plastic waste reached 51.7 million tons per year [1]. These plastics, mostly derived from fossil fuels such as petroleum, natural gas and coal, represent one of the main sources of environmental pollution [2]. The magnitude of this problem affects both biodiversity and human health, as microplastics persist in aquatic ecosystems, including marine habitats, and plastic debris accumulates in terrestrial areas [3, 4]. Alarmingly, 98% of plastics come from non-biodegradable fossil sources, and only 9% are recycled, intensifying the challenge towards global sustainability [5]. This problem is further exacerbated by the widespread use of Low-Density Polyethylene (LDPE), a material that can take more than 500 years to decompose [6]. In places such as Huancayo, Peru, where approximately 200 tons of solid waste are generated daily [7], a significant portion comes from central chess markets, such as the Mercado Mayorista and Mercado Modelo, which contribute about 60 tons daily, including both plastic and organic waste, which remain a challenge for proper management [8]. The accumulation of this waste not only degrades the environment, but also directly impacts the quality of life of local communities, underscoring the urgent need for sustainable solutions. In addition, Vicia faba (fava broad bean pod), a widely cultivated legume in Peru, is the second most important legume in the country after broad bean pod s. This plant occupies about 52,400 hectares in the Andes and produces 86,400 tons annually, with a growth of close to 100% in the last seven years, concentrated in regions such as Junín, Arequipa and Huancavelica [9]. However, despite their relevance, broad bean pods are in most cases discarded without proper use [10, 11]. In response to these problems, the utilization of organic wastes for the production of bioplastics has gained relevance. For example, cassava bioplastic is known for its high biodegradability and water resistance, corn bioplastic mimics the properties of conventional plastic with excellent moldability, potato bioplastic is flexible and easy to process, and rice bioplastic offers transparency and mechanical strength, making it ideal for packaging and films [12–14]. Despite the benefits already observed in the use of bioplastics, a significant gap persists regarding the utilization of Vicia faba waste, which opens the door to new discoveries on other potential organic wastes. The main objective of this study is to compare the effectiveness of bioplastic produced from Vicia faba waste with LDPE, through a comprehensive characterization of its physical, chemical and mechanical properties. This will allow evaluating the potential of bioplastics as a sustainable alternative, contributing to the reduction of environmental impact and promoting the transition towards a greener and more resilient economy.

II. Literary Review

Among the bioplastics studied, those derived from agricultural waste stand out as sustainable alternatives due to their abundance, low cost and biodegradability. Starch-based bioplastics, such as those from corn, cassava, and potato, have been extensively investigated for their good film-forming properties [13]. However, it is essential to optimize their characteristics through specific adjustments that allow them to be adapted to various applications and overcome the intrinsic limitations of the base materials [15]. For example, at the Biological Sciences Training and Research Unit in Côte d'Ivoire, biodegradable bioplastics were developed from cassava starch and maize, including variants composed of Cola cordifolia. The results showed that cassava bioplastics were more biodegradable than corn bioplastics, reaching up to 78.85% degradation under optimal conditions, such as a humidity of 15%. However, biodegradation decreased with higher humidity due to excessive dilution, and temperatures above 30°C affected microbial activity. In addition, it was observed that composite bioplastics significantly improved degradation compared to simple ones, showing their potential as biodegradable packaging under controlled conditions [16].

In Malaysia, the Department of Physics and Chemistry analyzed bioplastics based on corn starch with concentrations between 10% and 20%, combined with glycerol as a plasticizer. It was found that a concentration of 20% starch and 20% glycerol optimized the mechanical properties, achieving a tensile strength of 1.28±0.10 MPa, a Young's modulus of 14.67±2.43 MPa and an elongation at break of 12.69±4.87%. These bioplastics demonstrated high stiffness, albeit with less flexibility, and lower water absorption in films with lower starch content, highlighting the importance of optimizing ratios for specific applications [17].

In addition, in Pakistan, the Department of Chemistry, Science and Technology Division, worked with bioplastics derived from potato peels as a source of starch. The bioplastics obtained showed a tensile strength of 11.6±0.15MPa and a Young's modulus of 170±0.86MPa, positioning potato starch as a viable alternative for applications requiring higher structural strength [18, 19]. On the other hand, in Indonesia, the Department of Engineering and Materials Science developed bioplastics from bean starch with a proportion of 93% water by weight, obtaining bioplastics with a tensile strength of 11.5MPa and a rigidity of 0.98GPa, evidencing their potential for demanding mechanical applications [20].

In New Zealand, the Faculty of Science and Engineering investigated bioplastics derived from discolored blood treated with peracetic acid, achieving a Young's modulus between 32.2MPa and 1217.17MPa, a tensile strength of 2.6 to 8.8MPa, and elongations between 1.8% and 88.1%, depending on the proportions of SDS and TEG used in the process [21].

Finally, in Portugal, the Institute of Materials of Aveiro used carob powder as raw material, obtaining transparent bioplastics with an elongation at break of 90% and angles of contact with water between 60° and 90°, standing out for their hydrophobic nature and potential for food applications [22].

Due to the limited research on faba bean husks (Vicia faba), an agricultural by-product, compared to other starch sources, there is a need to delve deeper into their technical characteristics and potential for bioplastic production. The broad bean, native to Western Asia and northeastern Africa, is a legume of the Fabaceae family, whose large, flat-shaped, green or brown seeds grow in elongated pods [23, 24]. In addition to being an important source of vegetable proteins, with a significant content of essential amino acids, carbohydrates, fiber and minerals such as iron and potassium, it is used in human and animal food in the preparation of stews, soups and salads, as well as in the preparation of products such as flours and cakes [25]. It also has applications in agriculture as a green manure, due to its ability to fix nitrogen in the soil, improving fertility. In this context, starch extracted from bean husks stands out for its ability to form films with superior water barrier properties than cereal starches [26], and its relatively high gelatinization temperature (around 72–73°C) provides advantages in bioplastic processing, especially in applications requiring moderate thermal resistance [27]. Therefore, these distinctive physicochemical properties make the starch in bean husks a promising candidate for the manufacture of bioplastics, particularly in the packaging industry and other sectors that demand sustainable materials with specific technical characteristics.

These cases demonstrate how the proper selection of raw materials and the adjustment of additive proportions are essential to obtain bioplastics with high biodegradability and suitable mechanical properties. Differences in results across regions and research approaches reflect the versatility of bioplastics and their ability to adapt to various industrial and environmental needs. However, there is a significant gap in comparative studies that directly evaluate the efficacy of broad bean pod-based bioplastics versus conventional LDPE. Although the environmental benefits of bioplastics are well documented, further research is needed to improve their properties and make them a viable alternative in various industrial applications. This study contributes to the growing body of knowledge on sustainable materials by addressing these gaps.

III. Materials and Methods

A. Raw Materials

Vicia *faba* (green bean), a legume highly valued both for its nutritional contribution and for its ability to enrich agricultural soils [28], is positioned as the central axis of this research, as highlighted in the literature review. In this study, the residues generated after processing were used, specifically husks and by-products discarded during the separation of edible seeds. This waste, collected in the Mayorista and Modelo markets in Huancayo, was accessible thanks to the intense commercial activity that ensures a daily generation of fresh material. Green broad bean pod, which are particularly rich in starch, are not only an abundant and inexpensive resource, but also offer enormous potential for the production of biodegradable bioplastics, directly contributing to the search for sustainable solutions.

Waste collection focused exclusively on *green broad bean pod* to ensure high starch content and preserve the freshness of the material. Through systematic random sampling, waste was collected at different times and days of the week, capturing the variability in its generation. This meticulous process ensured that the material collected was representative and appropriate for the purpose of the study. Subsequently, the shells were transported to the laboratory in polyethylene bags, under strict controlled conditions, avoiding any alteration in their composition. In addition, the processing was carried out within 24h of collection, preserving the properties of the starch for transformation into bioplastics. In this way, the focus on green *broad bean pod* harvesting stands out not only for its environmental value, but also for its ability to turn a common waste into an innovative and sustainable solution.

B. Extraction of Starch from Broad Bean Pod

Starch was extracted using a wet method adapted from the Food and Agriculture Organization of the United Nations (FAO) guidelines [29], following a careful process to preserve the quality of the material. Initially, the collected broad bean pods were thoroughly washed with distilled water to remove surface dirt and debris. They were then cut into small pieces using disinfected knives and gloves, thus ensuring a hygienic process. Next, 200 grams of these shells were weighed and mixed in a blender with 500 mL of distilled water and processed into a homogeneous suspension. The resulting mixture was filtered through a fine mesh cloth to separate the coarse solids from the liquid. The filtrate was transferred to clean plastic containers, where it was left to settle for 24h. Subsequently, excess water was carefully removed to isolate the starch sediment. Finally, the sedimented starch was dried in an oven at a constant temperature of 40°C for 24h to obtain a completely dry starch. This extracted material was used as the basis for the production of bioplastics, demonstrating a sustainable approach to efficiently utilise agricultural waste.

C. Bioplastics Preparation

The extracted starch, as mentioned in item B, was used to obtain bioplastics. For this purpose, solutions were prepared according to the formulations detailed in Table 1, including four treatments (G1, G2, G3 and G4), each with four replicates (R1, R2, R3, R4). These formulations varied in the amount of starch and glycerol, with the volumes of distilled water (25mL) and acetic acid (5mL) held constant. In G1, 1g starch and 0.5mL glycerol were used; in G2, 1g starch and 1mL glycerol; in G3, 2g starch and 0.5mL glycerol; and in G4, 2g starch and 1mL glycerol.

Table 1. Inputs for bioplastics production

Treatment	Composition	Replicas
G1	1g starch	R1, R2, R3, R4
	0.5mL glycerol	
	25mL H_2O	
	5mL acetic acid	
G2	1g starch	R1, R2, R3, R4
	1mL glycerol	
	25mL H_2O	
	5mL acetic acid	
G3	2g starch	R1, R2, R3, R4
	0.5mL glycerol	
	25mL H_2O	
	5mL acetic acid	
G4	2g starch	R1, R2, R3, R4
	1mL glycerol	
	25mL H_2O	
	5mL acetic acid	

Each mixture was heated in a beaker placed over a burner, protected with a wire mesh. The temperature was monitored with a thermometer and stirred constantly until the gelatinisation temperature was reached and maintained. During this process, glycerol ($C_3H_8O_3$) and acetic acid (CH_3COOH) were incorporated as plasticisers, facilitating the formation of the bioplastic. Once the solutions were completely homogenised, they were poured into glass Petri dishes, which were covered with aluminium foil to minimise excessive evaporation. The solutions were left to dry at room temperature for 72h, obtaining the bioplastic, which was ready for further testing.

D. Physicochemical Characterization of Starch Extracted from Broad Bean Pod for the Production of Bioplastics

The characterization analysis of the starch extracted from the broad bean pod included various tests to evaluate its physical and chemical properties:

Determination of the gelatinisation temperature: A mixture of 10g of starch in 50mL of distilled water was prepared and heated in a water bath at 85°C with constant stirring. During the process, the formation of a gel was observed and the temperature reached, which corresponds to the gelatinisation temperature of the starch, was recorded.

Determination of Apparent Density: A graduated measuring cylinder was used, which was first weighed empty and then filled with starch without compacting it. After recording the final weight of the cylinder with starch, the bulk density was calculated using the density formula by dividing the mass by the volume occupied.

Solubility evaluation: 1.25g of starch was dissolved in 30 mL of distilled water heated to 60°C. The mixture was stirred for 30mins then centrifuged at 4900RPM for 10 minutes to separate the insoluble material. The supernatant was dried at 105°C to constant weight, and from the difference in weight the percentage solubility of the starch was calculated.

pH measurement: A solution of starch dissolved in distilled water was prepared and its pH was measured using a pH meter previously calibrated with buffer solutions at 25°C. The value obtained reflected the pH of the starch. The value obtained reflected the pH of the starch solution, indicating its acidity or neutrality.

Viscosity determination: 25g of starch were dissolved in 500 mL of distilled water, and the mixture was brought to boiling point for 15mins. It was then allowed to cool to room temperature (25°C) and the viscosity was measured using a Brookfield viscometer and the value corresponding to the fluidity of the starch solution was obtained.

Ash content: 1g of starch was weighed and placed in a porcelain crucible, which was heated in an oven at 550°C for 3.5h. After this time, the crucible was allowed to cool in a desiccator and weighed again. The ash content was calculated as the difference between the initial and final weight of the crucible.

Amylose/amylopectin ratio: A starch solution was prepared and reacted with an iodine solution. The presence of amylose or amylopectin was indicated by the formation of blue or reddish colours, respectively. The colour intensity was measured spectrophotometrically at specific wavelengths, and the results were compared with a calibration curve to determine the proportion of amylose and amylopectin.

Fourier Transform Infrared Spectroscopy (FTIR): A starch sample was prepared in tablet form using a mixture with KBr and analysed using an FTIR spectrophotometer in the range of 4000 to 400 cm^{-1}. The peaks obtained from the FTIR spectrum made it possible to identify the functional groups present in the starch and to characterise its chemical properties.

E. Analysis for the Characterization of Bioplastics Derived from Broad Bean Pod

The characterization analysis of the bioplastics derived from broad bean pod starch was carried out through a series of tests aimed at evaluating their mechanical properties, following specific protocols for each parameter.

First, the thickness of the bioplastic films was measured by cutting 2.5cm×2.5cm samples and using a precision gauge (caliper). The recorded values were averaged to obtain a representative result.

The moisture content was determined using a gravimetric procedure, in which samples were weighed before and after being dried in an oven at 105°C for 24h. This process made it possible to calculate the amount of wastewater present in the material.

Water solubility was evaluated by immersing the bioplastic films in distilled water under controlled stirring conditions. The samples were then filtered and dried, allowing the amount of dissolved material to be measured, reflecting the bioplastic's ability to interact with water.

The Water Vapor Transmission Rate (WVTR) was determined by a permeability test. In this, samples were placed on test tubes containing activated silica and weighed daily for five days. The recorded weight changes were used as indicators of the amount of moisture transmitted through the material.

Mechanical properties, such as tensile strength and elongation, were analyzed through specific tests that evaluated the structural behavior of the bioplastic against applied forces. These tests made it possible to identify the material's ability to withstand stresses and deformations without failing.

Finally, Fourier Transform Infrared Spectroscopy (FTIR) was used to identify the chemical bonds present in the bioplastic. This analysis revealed the molecular interactions formed during the production process and their influence on the final properties of the material.

Together, these tests provided a comprehensive characterization of bioplastics derived from broad bean pod starch, highlighting their potential for various sustainable applications.

F. Mechanical Properties

The mechanical properties of the broad bean pod starch derived bioplastics were analyzed by tensile tests following the ASTM D638 (2020) standard, using an Instron 5500 (2022) universal testing machine to ensure accurate and reproducible results [30]. The bioplastic films were cut into standard specimens and subjected to increasing forces until fractured, measuring key parameters such as tensile strength, elongation and elastic modulus. Each trial was performed in triplicate, ensuring the reliability of the data obtained. This analysis made it possible to evaluate the material's ability to resist stresses, deform without breaking and recover its shape under loads, fundamental aspects for its application in real environments. The averaged results highlighted the balance between rigidity and flexibility of bioplastics, underscoring their potential as sustainable and functional materials in various industries.

IV. Results

This section presents the results obtained throughout the study, from the initial characterization of the raw material (broad bean pod) to the comparison between the bioplastics developed and the Low-Density Polyethylene (LDPE) bags. The analyses carried out on the bioplastics are detailed, including tests for moisture, solubility, permeability and mechanical properties, as well as the evaluation of the physicochemical characteristics of the extracted starch and its suitability as a raw material.

A. Physical Characterization of Broad Bean Pod

Table 2 presents the physical characteristics of the raw material used, specifically the broad bean pod, evaluating parameters such as weight and length for five samples. The results show an average weight of 7.152 grams and an average length of 12.94 centimeters, highlighting the uniformity in the size and weight of the raw material. This uniformity is crucial to ensure the efficiency of the extraction process and the formulation of bioplastics.

Table 2. Physical properties of broad bean pod: weight and length

Broad bean pod	Weight (g)	Length (cm)
1	7.357	12.6
2	6.412	11.35
3	6.659	12.6
4	7.594	13.4
5	7.736	14.75
Stocking	7.152	12.94

B. Characterization of the Wet Starch Extraction Process

Table 3 presents the results of the wet starch extraction process, in which various combinations of stirring speed (RPM) and time were applied. Average yields ranged from 6.35 grams under minimal conditions to 67.5 grams under conditions of higher stirring speed and processing time. These results demonstrate that increasing both the stirring speed and the processing time significantly improves the efficiency of starch extraction.

Table 3. Yield of starch extracted from broad bean pod

Treatment	Variables	Repetition	Water volume (mL)	Weight (g)	Starch Product (g)	R Media	Total
G1	RPM 1 : t 1	R1	500	200	5.4	6.35	25.4
		R2			5.7		
		R3			7.2		
		R4			7.1		
G2	RPM 1 : t 2	R1			17	15.5	62
		R2			15		
		R3			16		
		R4			14		
G3	RPM 2: t 1	R1			45	43.75	175
		R2			41		
		R3			47		
		R4			42		
G4	RPM 2: t 2	R1			67	67.5	270
		R2			66		
		R3			68		
		R4			69		

C. Yield of Starch Extracted from Broad Bean Pod

The results presented in Table 4 show that the starch yield of the pea pod increases as treatment conditions improve. The T1 treatment produced the lowest yield, with a mean of 3.175%, followed by the T2, with a mean yield of 7.75%. The T3 treatment produced a significantly higher yield, with a mean of 21.875%, and the T4 treatment achieved the highest yield, with a mean of 33.75%. These results suggest that the T4 treatment conditions are the most effective for starch extraction, significantly outperforming the other treatments in terms of efficacy.

Table 4. Starch yield

No	Treatment	Yield (%)	Stocking
1	T1	2.7, 3.175, 2.85, 3.6, 3.55	3.175
2	S2	8.5, 7.75, 7.5, 8, 7	7.75
3	S3	22.5, 21.875, 20.5, 23.5, 21	21.875
4	S4	33.5, 33.75, 33, 34, 34.5	33.75

D. Physicochemical Characterization of Starch Extracted from Broad Bean Pod

The analysis of broad bean pod starch shows that its properties are mostly within the ranges established by the relevant standards and institutions. The gelatinization temperature is 72.18°C, which is within the standard range of 65–85°C according to INEN 1456, indicating suitable behavior for conventional applications. Its bulk density of 1.296g/ml is lower than the FAO standard of 1.560g/ml, suggesting higher porosity. The solubility is 7.32%, which is within the range of 0.27%–12.32% according to the FAO, indicating a moderate dissolution capacity in water. The pH of 5.69 is within the range of 5.5–6.5 set by the INEN 1456 standard, so it is slightly acidic. However, the viscosity is significantly higher, with a value of 3276.9 SP compared to the standard range of 840–1500 SP according to ISI 17-1, implying a higher resistance to flow. Finally, the ash content is 0.61%, exceeding the maximum limit of 0.12% set by the AOAC, indicating a higher number of inorganic impurities. These results suggest that broad bean pod starch is suitable for various applications, although certain parameters, such as viscosity and ash content, may require adjustments depending on its end-use. These results are summarized in Table 5.

Fig. 1 shows the proportions of amylose and amylopectin in starch, with 20.48% amylose and 77.81% amylopectin. These results indicate that the extracted starch has a high concentration of amylopectin, which favors its application in the production of bioplastics due to its ability to form cohesive and flexible structures.

Table 5. Physicochemical properties of starch

Analysis	Broad bean pod starch	Standard	Standards/ Institution
Gelatinization Temperature	72.18°C	65–85°C	INEN 1456
Bulk density	1,296 g/ml	1,560 g/ml	FAO
Solubility	7.32%	0.27%–12.32%	FAO
pH	5.69	5.5-6.5	INEN 1456
Viscosity	3276.9 SP	840-1500SP	ISI 17-1
Ash content	0.61%	< 0.12%	AOAC

Table 6. Amylose and Amylopectin (INAP)

Analysis	Broad bean pod starch	Institution
Amylose	20.48%	INIAP
Amylopectin	77.81%	INIAP

Table 7 presents the data obtained from the FTIR analysis, identifying the wavelengths (in cm^{-1}) and their respective transmission percentages (%T), as well as the associated functional groups and observations on the type of vibration. Important bands stand out, such as the elongation of the O-H group at 3379.980 cm^{-1} with a 74.359% transmission rate, the vinyl stretch of the C-H bond at 3059.861 cm^{-1}, and the carbonyl stretch (C=O) at 1711.992 cm^{-1} with a high transmission percentage (95.128%). Likewise, stretches and deformations of C≡C (triple carbon-carbon bond, alkyne group), C=C (double carbon-carbon bond, alkene group), C-H (aliphatic, methyl or methylene group), and C-O (ether or alcohol group) bonds are identified, confirming the diversity of functional groups present in the sample.

Table 7. FTIR spectrum (Fourier transform infrared spectroscopy)

Wavelength (cm^{-1})	%T	Functional group	Remarks
3379.980	74.359	O-H	Elongation
3059.861	70.513	CH	Vinyl Stretch
3009.316	81.923	CH	Stretch
2561.149	98.333	C≡C	Stretch
2025.372	81.410	C≡C	Stretch
1978.196	84.103	C≡C	Stretch
1914.172	86.667	C=C	Stretch
1772.646	91.026	C=O	Stretch
1711.992	95.128	C=O	Stretch
1621.011	98.205	C=C	Stretch
1449.157	74.359	O-H	Flexion
1371.655	93.589	CH	Flexion
1327.849	98.205	C-O-C	Out-of-plane deformation
1260.456	99.744	C-O	Stretch

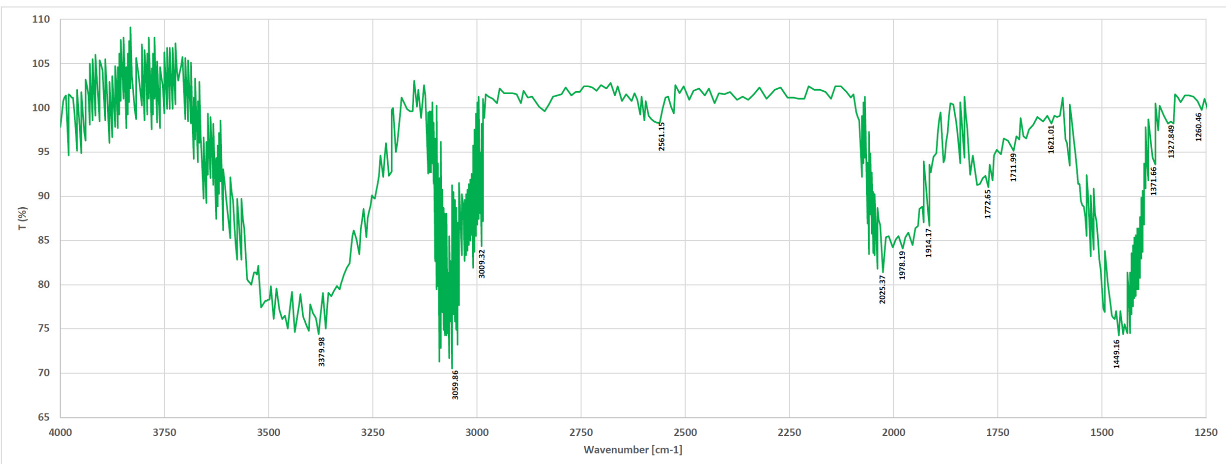

Fig. 1. FTIR Analysis Chart (Starch).

Fig. 1 shows the FTIR spectrum corresponding to the data in Table 7, highlighting the most representative absorption bands of the starch extracted from the broad bean pod. An O-H elongation is observed at 3379.98 cm^{-1}, associated with the hydroxyl groups (-OH) present in the starch, indicating the presence of hydrogen bonds between the starch molecules. The peaks at 1772.65 cm^{-1} correspond to C=O stretches, characteristic of the carbonyl groups (C=O), which are involved in the starch structure. Furthermore, the peaks at 2561.15 cm^{-1}, 2025.37 cm^{-1} and 1978.20 cm^{-1}, correspond to stretching of triple carbon-carbon bonds (C≡C), reflecting the presence of natural unsaturated structures in starch. Finally, the band at 1449.15 cm^{-1} is associated with O-H bending, suggesting the interaction of hydroxyl groups within the starch structure. These vibrations are characteristic of broad bean pod starch, reflecting the molecular interactions present in its structure.

E. Physical-Chemical and Mechanical Characterization of Bioplastic

Table 8 presents the results of the starch yield obtained from faba husks. The data show that the overall process throughput is positively influenced by the increase in stirring speed and processing time, which shows that treatment under optimal conditions generates higher amounts of starch from the initial raw material.

Table 8. Thickness

Sample	Thickness (mm)	Stocking
G1	0.21, 0.26, 0.38, 0.31	0.29
G2	0.32, 0.35, 0.10, 0.14	0.23
G3	0.10, 0.09, 0.09, 0.09	0.09
G4	0.27, 0.20, 0.18, 0.21	0.22

Table 9 presents the moisture data of the bioplastics, showing the differences between the initial and final weights after the drying process. The results demonstrate a measurable reduction in mass, with initial weights ranging from 26.579 to 30.126 grams and final weights from 22.664 to 25.355 grams. Additionally, the table includes the calculated percentage of mass loss and retention for each treatment. These values indicate that the moisture content of the bioplastics varies depending on the formulation used, with mass loss ranging from 9.34% to 18.01%. This variation directly impacts the retention capacity, which fluctuates between 82% and 91%, reflecting how different starch and glycerol concentrations influence the material's stability and drying behavior.

Table 9. Starting and ending weight

N°	Biofilm Initial Weight (g)	Final weight of dry biofilm (g)	Mass Loss (%)	Retention (%)
G1	26.579	24.097	9.34%	91%
G2	26.802	23.453	12.50%	88%
G3	30.126	25.355	15.84%	84%
G4	27.641	22.664	18.01%	82%

Table 10 presents the results of the analysis of moisture content in bioplastics made from broad bean pod starch, calculated based on the data provided in Table 9. The moisture values obtained vary between 9.338% and 18.006%. In particular, bioplastic G1 recorded the lowest moisture content (9.338%), while bioplastic G4 presented the highest (18.006%). These variations show how glycerol, acting as a plasticizer, increases the flexibility of the material and favors water absorption, which led to an increase in moisture content.

Table 10. Humidity

N°	Humidity (%)
G1	9.338
G2	12.495
G3	15.837
G4	18.006

Table 11 assesses the solubility of bioplastics in water, with values ranging from 2.36% to 46.67%. The results reveal that bioplastics with higher amounts of glycerol have higher solubility, while those with lower plasticizer proportions are more resistant to water. This shows that glycerol concentration plays a critical role in determining the stability and behavior of the biofilm under wet conditions.

Table 11. Initial and final weight of bioplastics

N°	Biofilm Initial Weight (g)	Final weight of dry biofilm (g)
G1	0.212	0.207
G2	0.158	0.144
G3	0.304	0.146
G4	0.075	0.040

Table 12 shows the results of the solubility test, calculated from the data in Table 11. The values obtained show a wide variability, ranging from 2.358% in G1 to 51.974% in G3. G3 and G4 bioplastics have higher solubility (51.974% and 46.667%, respectively), indicating greater susceptibility to dissolving in water, possibly due to differences in the proportion of glycerol and starch in their composition. On the contrary, G1 and G2 show lower solubility, with G1 being the most resistant to dissolution.

Table 12. Solubility

N°	Solubility (%)
G1	2.358
G2	8.861
G3	51.974
G4	46.667

Table 13 presents the permeability results of the bioplastics, evaluating parameters such as initial weight, final weight, time, area and thickness. The results indicate that thinner bioplastics, such as G3 (0.093mm), show lower permeability, suggesting that a more compact structure improves resistance to liquid or gas penetration. In contrast, thicker bioplastics show slightly higher permeability.

Table 13. Preliminary data for biofilm permeability

N°	Biofilm Starting Weight (g)	Final weight biofilm (g)	Time (h)	AREA (m^2)	THICKNESS (mm)
G1	29.128	29.263	24	0.000206119	0.290
G2	29.269	29.304	24	0.000206119	0.228
G3	28.663	28.671	24	0.000206119	0.093
G4	29.066	29.074	24	0.000206119	0.215

Table 14 shows the permeability results, calculated from the data in Table 11 revealing that G1 has the highest permeability (7.914 mm-g/m²-h), while G3 has the lowest (0.150 mm-g/m²-h), indicating a greater barrier capacity against the penetration of gases or liquids in the latter. Bioplastics G2 and G4 have intermediate values (1.610 and 0.348 mm-g/m²-h, respectively). These differences in permeability are directly related to the thickness, starch distribution, and glycerol content in the formulations, which affect the compactness and structure of the bioplastics.

Table 14. Permeability

N°	Permeability (mm g/m² h)
G1	7.914
G2	1.610
G3	0.150
G4	0.348

F. *Mechanical Testing on Bioplastics*

Table 15 shows the results of the tensile strength, considering that all groups were made with bioplastics with dimensions of 2.5 by 2.5cm. It is observed that bioplastics made with formulation G3 have the highest tensile strength (average 2.41MPa) and the highest modulus of elasticity (average 8.738MPa). This is due to the higher amount of starch used in this formulation (2g), which favours a denser structure and a more robust polymeric network, significantly improving the cohesion and strength of the bioplastic. In comparison, G1, with only 1 g of starch, shows lower strength and stiffness values, suggesting a lower cross-linking capacity and a less robust structure. Furthermore, the concentrations of glycerol and water in each formulation play a key role in the formation of the polymer matrix, with G3 concentrations improving and optimising its mechanical properties.

Table 15. Tensile test

Samples	Thickness (mm)	Tensile strength (MPa)	Stocking	Modulus of Elasticity (MPa)	Stocking
G1	0.21	1.78	1.37	6.78	6.503
	0.26	1.50		6.24	
	0.38	0.99		6.87	
	0.31	1.22		6.12	
G2	0.32	1.13	1.77	7.32	7.458
	0.35	0.81		7.12	
	0.10	2.68		7.50	
	0.14	2.45		7.89	
G3	0.10	2.11	2.41	8.52	8.738
	0.09	2.51		8.81	
	0.09	2.50		8.81	
	0.09	2.51		8.81	
G4	0.27	1.74	2.16	7.54	7.170
	0.20	2.17		7.02	
	0.18	2.72		6.99	
	0.21	1.99		7.13	

Fig. 2 shows the behavior of the tensile strength of bioplastics in MPa units, accompanied by a trend line that represents the fit of the experimental data. The results show that most of the experimental points are close to the trend line, indicating good consistency in measurements. This fit reflects a predictable pattern in tensile strength behavior, facilitating the interpretation of the data and highlighting the reliability of the model used to describe the mechanical properties of bioplastics. The graphical representation complements the tabulated data, offering a clear visual perspective of the results.

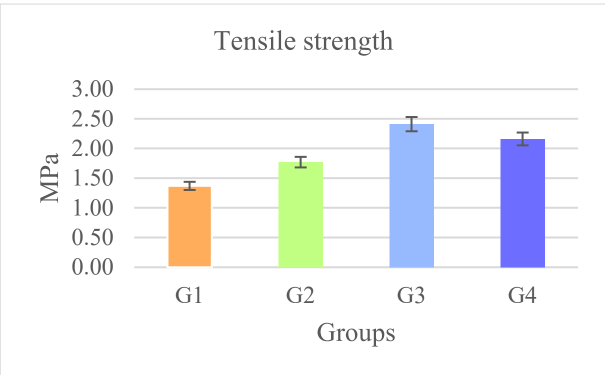

Fig. 2. Tensile test graph.

Fig. 3 shows the relationship between the modulus of elasticity (Y-axis) and the thickness of the bioplastic (X-axis), evidencing a decreasing trend represented by the dotted regression line. This indicates an inverse relationship, where an increase in the thickness of the bioplastic is associated with a decrease in the modulus of elasticity, which varies between about 6 and 9 units. Although the data show some dispersion around the line, the general trend suggests that a greater thickness of the bioplastic reduces its stiffness in the range studied.

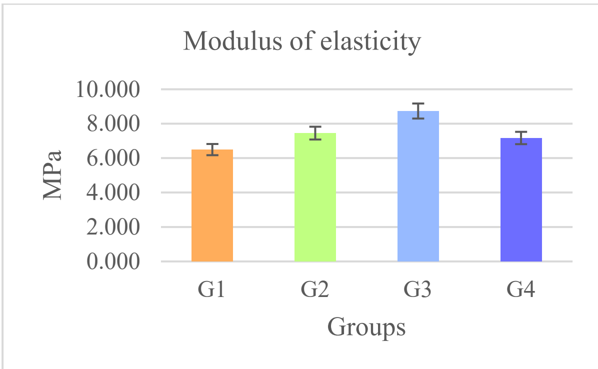

Fig. 3. Graph of the Modulus of Elasticity Test.

Table 16 G1 showed the lowest elongation (73.33%) compared to G2, which showed the highest elongation (186.67%). The G4 samples showed a relatively lower elongation than the other samples, with values ranging from 46.67% to 80%. This suggests differences in the flexibility and elasticity of bioplastics, potentially related to their composition.

Table 16. Elongation

Samples	Thickness (mm)	Initial gauge measurement (mm)	Initial Length (mm)	Final Length (mm)	Elongation (%)
G1	0.21	0.03	0.256	0.278	73.33%
	0.26	0.03	0.257	0.283	86.67%
	0.38	0.03	0.258	0.298	133.33%
	0.31	0.03	0.255	0.303	160.00%
G2	0.32	0.03	0.255	0.311	186.67%
	0.35	0.03	0.258	0.304	153.33%
	0.10	0.03	0.259	0.315	186.67%
	0.14	0.03	0.253	0.299	153.33%
G3	0.10	0.03	0.258	0.276	60.00%
	0.09	0.03	0.257	0.281	80.00%
	0.09	0.03	0.259	0.287	93.33%
	0.09	0.03	0.254	0.278	80.00%
G4	0.27	0.03	0.253	0.267	46.67%
	0.20	0.03	0.262	0.286	80.00%
	0.18	0.03	0.263	0.278	50.00%
	0.21	0.03	0.268	0.286	60.00%

Table 17 FTIR analysis identifies the presence of functional groups associated with starch bioplastics such as O-H (stretching), C-H (stretching and bending), C≡C (stretching) and C=O (stretching), among others, indicating the chemical composition and interactions within the biofilm structure.

The FTIR spectrum shown in Fig. 4 reveals several functional groups characteristic of the analysed sample. The most noticeable bands include stretches of O-H bonds around 3484 cm^{-1}, associated with hydroxyl (-OH) groups, present in starch and glycerol. The C-H stretches in the region of 3112–3072 cm^{-1} correspond to compounds with vinyl bonds, related to the additives used. The signals at 2045-1951 cm^{-1} correspond to stretches of C≡C triple bonds, present in the unsaturated structures. The bands at 1745–1669 cm^{-1} correspond to stretches of C=O bonds, characteristic of carbonyl compounds, from glycerol or esters formed in the formulation. C=C stretches are identified at 1596–1487 cm^{-1}, while C-H bond deformations at 1430–1357 cm^{-1} reflect interactions within the starch structure. Finally, absorptions at 1278–1212 cm^{-1} correspond to C-O stretches, indicating the presence of esters or related compounds. This analysis accurately identifies the functional groups present and their origin in the components used.

Table 17. FTIR spectrum (Fourier transform infrared spectroscopy)

Wavelength (cm^{-1})	%T	Functional group	Remarks
3484.849	22.544	O-H	Stretching
3112.121	67.839	CH	Vinyl stretch
3072.727	72.892	CH	Stretching
2045.455	96.063	C≡C	Stretching
1951.515	82.997	C≡C	Stretching
1745.455	76.202	C=O	Stretching
1669.697	77.596	C=O	Stretching
1596.969	88.571	C=C	Aromatic Stretch
1487.879	75.157	C=C	Aromatic Stretch
1430.303	67.666	CH	Fold
1421.212	62.613	CH	Fold
1357.576	34.042	CH	Fold
1278.788	83.171	C-O	Stretching
1212.121	87.003	C-O	Stretching

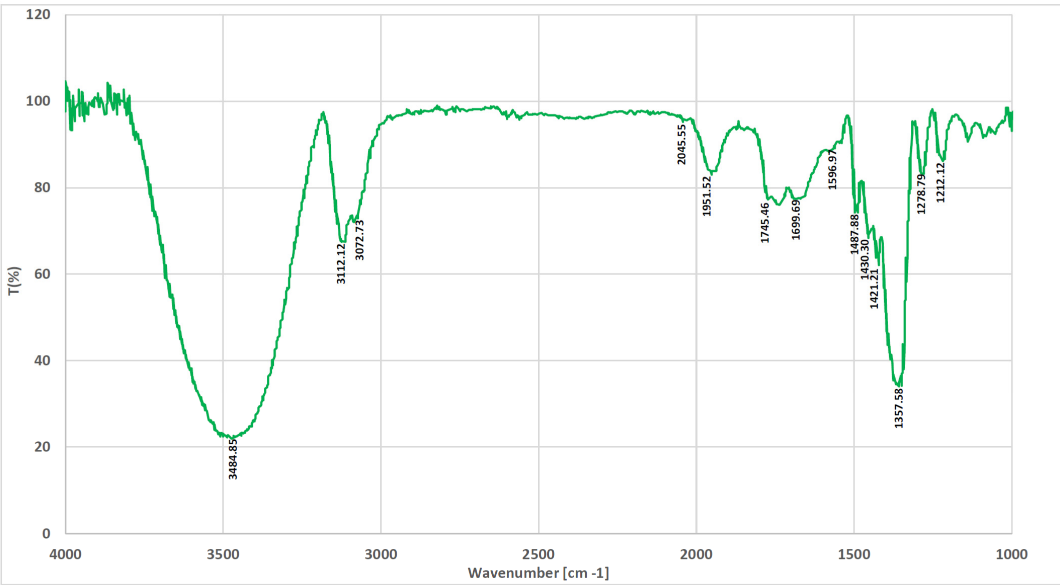

Fig. 4. FTIR Analysis Chart (Bioplastic)

It should be emphasized that interactions between the different components of bioplastics, such as starch hydroxyl groups and glycerol functional groups, as well as C=O and C≡C bonds, play a crucial role in the formation of a structural network that directly affects the mechanical and thermal properties of bioplastics. These interactions improve the flexibility and strength of the material, influence its behavior towards factors such as moisture, temperature and biodegradability. Therefore, the interactions within the components are determinant in the performance and functionality of bioplastics, and are fundamental in the design and optimization of these materials.

G. Features and Specifications of Low-Density Polyethylene (LDPE) Bag

Bag made of low-density polyethylene, a transparent natural thermoplastic material, ideal for general use. It is more flexible than high-density polyethylene and offers good processability. It does not require personal protective equipment for handling and storage, although high temperatures and combustion sources should be avoided [31].

Table 18 shows the main physical characteristics of low-density polyethylene used in bag manufacturing. These properties, such as density, tensile strength, elongation and maximum temperature of use, highlight key attributes related to its lightness, flexibility and ability to withstand mechanical and thermal stresses. These values provide essential information to understand their performance and potential applications in various contexts.

Table 18. Mechanical characteristics of polyethylene [31]

Property	Value
Density	0.92–0.93 g/cm³
Tensile strength	0.9–2.5 MPa
Elongation	550–600 %
Maximum Operating Temperature	82–100

H. Comparison of Physicochemical and Mechanical Properties between Broad Bean Pod Starch Bioplastics and Low-Density Polyethylene (LDPE) Bags

Table 19 shows the comparison between broad bean pod starch bioplastics and low-density polyethylene (LDPE) bags, based on the technical data sheet. Bioplastics stand out for their higher density and biodegradability, which makes them more sustainable compared to LDPE, which is not biodegradable and contributes to plastic pollution. Although LDPE has significantly higher elasticity, with elongation up to 600% [31], bioplastics compensate for this limitation by offering higher tensile strength on average, making them more resilient under direct forces. In addition, LDPE outperforms bioplastics in thermal resistance and low permeability, making it more suitable for demanding applications and in humid environments. On the other hand, bioplastics, being soluble in water, are more useful for short-term uses and in dry conditions. In short, the choice between the two materials will depend on whether specific mechanical properties, sustainability or functionality are prioritized in the context of use.

Table 19. Broad bean pod starch bioplastics vs. low-density polyethylene bag (LDPE [31])

Property	Broad bean pod starch (Bioplastics)	Low-density polyethylene (LDPE) bag	Interpretation
Density	1,296 g/ml	0.92–0.93 g/cm³	Starch bioplastics are denser, which may indicate a more compact structure, but could affect the properties of flexibility and lightness compared to LDPE.
Tensile strength	1.37–2.41 MPa	0.9–2.5 MPa	Both materials have comparable tensile strength, but LDPE typically offers more consistent strength across uses.
Elongation	46.67%–186.67%	550%–600%	LDPE features significantly higher elongation, making it more stretchable and resistant to breakage under stress compared to starch bioplastics.
Maximum Operating Temperature	Not specified, gelatinization begins at 72.18 °C	82–100 °C	LDPE can withstand higher temperatures without deforming, while starch bioplastics can lose structural integrity near their point of gelatinization.
Solubility in water	2.358%–51.974% (depending on formulation)	Insoluble	Starch bioplastics are soluble, especially with high glycerol contents, which limits their use in humid conditions, but makes them biodegradable and environmentally friendly.
Permeability	0.150–7.914 mm·g/m²·h	Low (specific value not indicated)	LDPE offers better barrier properties against gases and liquids, while starch bioplastics vary significantly in permeability depending on composition.
Environmental Impact	Biodegradable	Non-biodegradable	Starch bioplastics are more environmentally friendly due to their biodegradability, while LDPE contributes to long-term plastic waste problems.

I. Applications of Broad Bean Pod Starch Bioplastic Based on Its Properties

- Density

Application: Biodegradable packaging materials and containers.

Description: Broad bean pod starch bioplastics have a higher density, which implies a more compact structure and, therefore, greater robustness. This property makes them suitable for packaging applications where a stronger but biodegradable material is required, such as food or agricultural packaging, where stability and compactness are valued without compromising sustainability.

- Tensile (or compressive) strength

Application: edible films and food coatings.

Description: Broad bean pod starch bioplastics exhibit tensile strength comparable to LDPE, making them suitable for the manufacture of edible films and food coatings. Although they do not reach the same strength as LDPE, their biodegradability and adaptability to various formulations make them suitable for the food industry, where safety and sustainability are valued.

- Elongation

Application: Protective coatings in agriculture.

Description: Broad bean pod starch bioplastics have lower elongation than LDPE, which limits their use in applications requiring high elasticity. However, they are suitable for agricultural films where high flexibility is not needed, such as in weed control or crop protection. Their rigidity makes them a more sustainable alternative to traditional plastics for temporary applications in agriculture.

- Maximum operating temperature

Application: Coatings and packaging for heat sensitive products.

Description: Gelatisation of broad bean pod starch bioplastics occurs at relatively low temperatures (72°C), which limits their use in applications requiring high heat resistance. They are therefore ideal for products that will not be exposed to high temperatures, such as certain types of food or cosmetic packaging, but are not suitable for those requiring higher thermal resistance.

- Water solubility

Application: Biodegradable single use products.

Description: The water solubility of broad bean pod starch bioplastics, especially when they contain glycerol, limits their use in humid environments. However, this property makes them suitable for single-use applications, such as packaging or containers that decompose rapidly in the environment. They are also ideal in applications where biodegradability is critical, such as in the food and agricultural industries.

- Permeability

Application: Moisture control coatings.

Description: Broad bean pod starch bioplastics exhibit higher permeability than LDPE, making them useful in applications where moisture control is not crucial. They are suitable for agricultural products, such as crop protection coatings, or food packaging that does not require an airtight barrier against liquids or gases. This property also makes them suitable for applications where biodegradability is more important than complete moisture protection.

- Environmental impact

Application: Sustainable solutions for packaging and disposable products.

Description: Thanks to their biodegradability, broad bean pod starch bioplastics have a significantly lower environmental impact compared to LDPE, making them a preferred choice for packaging, disposable utensils and single-use products. They are especially useful in industries looking to reduce their carbon footprint and minimise the accumulation of plastic waste, contributing to environmental sustainability.

V. Discussion

According to Sandra *et al.* [32, 33], they used bean protein reinforced with cellulose nanocrystals obtained by pineapple hydrolysis to make biodegradable plastics for food packaging, achieving good results with a tensile strength of 4MPa and an elongation between 200 and 250%, using a glycerol concentration of 40%. We agree with the findings of this research; however, unlike them, who used cellulose nanocrystals as reinforcement, we used only broad bean pod starch and glycerol. Despite this difference in composition, our results were also positive, achieving a tensile strength of 2.5MPa. In addition, we achieved an elongation of 186.67%, a good performance considering that we did not use additional reinforcements.

According to Yang *et al.* [34] in their research, they used 70 grams of cassava starch combined with palm oil and epoxidised palm oil, both at a ratio of 1.5%, as additives in the production of bioplastics. With palm oil, they obtained a tensile strength of 2MPa, while with epoxidised palm oil, the strength was slightly higher at 0.5MPa. The authors indicated that the epoxidation of the oil negatively affected the interaction between the starch molecules, due to the alteration of their chemical properties, which reduced the structural cohesion of the material. On the other hand, Chong *et al.* [35] demonstrated that the use of banana lignocellulosic fibre as reinforcement in bioplastics generated a significant improvement in tensile strength, reaching a value of 3.8 MPa. In line with these findings, Nur *et al.* [36] evaluated the effect of starch and glycerol in corn-based bioplastics. They observed that by increasing the starch concentration to 20%, the tensile strength reached 1.28 MPa; however, by increasing the starch content to 40%, the strength decreased to 0.5 MPa. This reinforces the importance of starch in the structure of bioplastics, while glycerol, as a plasticiser, facilitates molecular interaction and improves the flexibility of the material. Additionally, Aeysha *et al.* [18] employed a combination of potato starch, glycerol and acetic acid, achieving a tensile strength of 11.6±0.15 MPa, suggesting that acetic acid may have a synergistic effect by promoting stronger bonds between the starch chains, significantly improving the mechanical properties of the bioplastic. According to this research, it has been shown that bioplastics with good strength can be obtained from starches derived from various products, which is consistent with our approach, since in our research, using broad bean pod starch and glycerol, we achieved a tensile strength of 2.41 MPa. This shows that the combination of these additives significantly improves the mechanical properties of the material. Although some studies report higher tensile strength values, this is due to the incorporation of additional materials. Although we only used glycerol las a plasticiser, we obtained a considerable improvement, and this value is within the tensile strength range of LDPE, which varies between 0.9 and 2.5 MPa.

According to Aeysha *et al.* [18], in their research on potato bioplastics, they observed peaks at 3500 and 1800 cm^{-1} in FTIR, corresponding to stretching vibrations of -OH (hydroxyl) groups and the presence of esters or interactions with other functional compounds. In our investigation, we obtained similar peaks at 3484.849 and 1951.515 cm^{-1}, confirming the presence of -OH and C≡C groups. The peak at 1951.515 $cm\text{-}^{1}$ is related to the vibration of the C≡C bond, which indicates interactions between glycerol and starch, contributing to the structure of the bioplastic.

Thermal behavior also distinguishes starch bioplastics from LDPE. Starch-based films, such as those made from fava bean shells, begin to gelatinize at around 72°C, a relatively low temperature compared to LDPE, which can withstand temperatures of 82–100°C without significant deformation [37]. This lower thermal resistance of starch bioplastics limits their practical use in environments where greater thermal stability is required. However, the ability of these films to degrade under ambient conditions is a clear advantage over LDPE, which remains a non-biodegradable material, contributing to long-term environmental problems [38].

In terms of solubility and permeability, starch bioplastics are hydrophilic, meaning they are water-soluble and more permeable than LDPE. This characteristic makes them more biodegradable, but also limits their use in wet conditions, where LDPE performs better due to its water resistance. For example, studies have shown that starch bioplastics have water solubility rates ranging from 2.35% to 51.97%, depending on the formulation, while LDPE is completely insoluble in water [39]. The permeability of starch bioplastics also varies significantly, with some formulations offering moderate resistance to gases and liquids, but do not match the superior barrier properties of LDPE [40].

The environmental impact of starch-based bioplastics is a significant advantage over LDPE. These films are biodegradable, break down more quickly in soil, and reduce long-term pollution compared to LDPE, which can persist in the environment for decades. This makes starch bioplastics a more sustainable option, especially in applications such as food packaging, where environmental concerns are increasing. Research has shown that the degradation of starch-based plastics occurs relatively quickly in natural environments, leading to less environmental pollution compared to LDPE [38, 41]. In addition, starch-based films are a promising alternative in packaging applications, particularly when combined with natural additives such as oils, which enhance their functionality without compromising their biodegradability [42].

Overall, although starch-based bioplastics have some limitations, such as lower thermal stability and permeability compared to LDPE, they offer clear environmental advantages, particularly in their biodegradability. Ongoing research to improve the mechanical and thermal properties of these films through additives and formulation adjustments could make them viable substitutes for LDPE in a variety of applications. In addition, studies on the microbial degradation of starch-based films suggest that these materials could offer an environmentally sustainable alternative to traditional plastics, particularly in short-term use cases [31, 40].

VI. Conclusion

In conclusion, bioplastics made from starch extracted from broad bean pod (Vicia faba) have great potential for sustainable applications due to their favorable characteristics, such as their biodegradability. The starch obtained showed a gelatinization temperature of 72.18°C and a solubility of 7.32%, which made it an excellent option for the production of biodegradable bioplastics.

As for the bioplastics, FTIR analysis revealed that they contained key functional groups such as O-H, C-H, C=O and C≡C, which indicated interactions between starch and glycerol. These interactions were essential to form a structural network that improved mechanical properties. Thus, broad bean pod starch bioplastics exhibited tensile strength comparable to LDPE (1.37–2.41 MPa vs. 0.9–2.5MPa for LDPE), making them suitable for the manufacture of edible films and food coatings, providing an environmentally friendly and safe option in the food industry. Their lower elongation (46.67%–186.67%) makes them ideal for applications where higher stiffness and lower flexibility are required, such as in biodegradable labels or protective wrappings.

Unlike LDPE, which is not biodegradable and contributes to the accumulation of plastic waste, broad bean pod starch bioplastics are biodegradable, representing a more environmentally friendly and sustainable alternative. This feature is crucial for the reduction of plastic waste and the promotion of nature-based solutions.

Further research on the properties of broad bean pod starch bioplastics is recommended, especially to improve their mechanical strength and water solubility through formulation and processing modifications. It would also be useful to evaluate their feasibility for specific applications, such as biodegradable packaging in dry conditions, and to analyze their long-term behavior in natural environments to confirm their effectiveness in reducing plastic waste.

Conflict of Interest

The authors declare no conflict of interest.

Author Contributions

Jiomaira del Cielo Cotache Mercado participated in the design of the study, as well as in the interpretation and organisation of the experimental data, which were fundamental for the preparation of the results section. Keila Leslie Basaldua Papuico was in charge of the experimental development, carried out the literature review, and led the writing of the initial version of the manuscript, especially the introduction and the materials and methods section. Jhon Alex de la Cruz Perez collaborated in the validation of the data and contributed to the writing of the results, discussion, and conclusion sections. Steve Dann Camargo Hinostroza provided critical observations and made substantial revisions that improved the coherence and quality of the manuscript. All team members actively participated in the study design and methodology development and approved the final version of the article.

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