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Evaluation of the use of banana pseudostem with thermoplastic corn starch for the elaboration of biodegradable dishes

Evaluación del uso del pseudotallo de plátano con almidón de maíz termoplástico para la elaboración de platos biodegradables

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Abstract

This project evaluated the use of fiber residues from the banana pseudostem (*Musa Paradisiaca* L.) with thermoplastic corn starch (*Zea Mays*) in the production of biodegradable dishes for food use. The homogenized mixture was gelatinized at 60 °C and thermopressed at 150 °C for 20 min. The amounts of thermoplastic starch and polyvinyl alcohol were varied. The raw material and the final product were characterized by physical-chemical, mechanical, and thermal analyses. The lignocellulosic fibers improved the tensile strength, modulus of elasticity, hardness, and viscoelasticity in the dish, also presented hydrophilic character. Degradation increased with the increase of thermoplastic starch. The unit cost per dozen plates was $1.63 dollars. It is concluded that the residues of fibers from the pseudostem of banana and thermoplastic starch turned out to be an alternative in the elaboration of biodegradable dishes.

Keywords: biodegradable dishes, waste, thermoplastic starch, fiber.

Resumen

El presente proyecto evaluó el uso de los residuos de fibra del pseudotallo del plátano (*Musa Paradisiaca* L.) con almidón de maíz (*Zea Mays*) termoplástico en la elaboración de platos biodegradables para uso alimentario. La mezcla homogeneizada se gelatinizó a 60 °C y procedió al termoprensado a 150 °C por 20 min. Se variaron las cantidades de almidón termoplástico y alcohol polivinílico. Se caracterizó tanto a la materia prima como al producto final mediante análisis físicos-químicos, mecánicos y térmicos. Las fibras lignocelulósicas mejoraron la resistencia a la tracción, módulo de elasticidad, dureza y viscoelasticidad en el plato, además, presentó carácter hidrofílico. La degradación se incrementó con el aumento de almidón termoplástico. El costo unitario por docena de platos fue de $ 1.63 dólares americanos. Se concluye que los residuos de fibras del pseudotallo de plátano y almidón termoplástico resultaron ser una alternativa en la elaboración de platos biodegradables.

Palabras clave: plato biodegradable, residuo, almidón termoplástico, fibra.

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1 Introduction

The world production of plastic for the year 2018 was 359 million tons and around 8 million tons of plastic waste are generated, which end up each year in the oceans, and added to its slow decomposition, they cause pollution to the ecosystems that surround. It should be noted for example, that a plastic bottle takes around 450 years to decompose and if it is not exposed to outdoor, it would take approximately 1,000 years (Miranda, 2020). In Ecuador, around 500,000 t of plastic waste is produced per year (Calero *et al*., 2021). These polymers also contain substances in their manufacture such as bisphenol A -$(CH_3)_2C(C_6H_4OH)_2$-, phthalates and lead that cause health damage and the environment. Various studies show that the way to reduce the problem of plastic waste is by controlling its production and consumption, coupled with awareness of waste management (Buteler, 2019).

Not forgetting that uncontrolled organic waste also causes pollution (Hernández-Neri *et al*., 2022). These globally represent 46% of the solid waste generated and come from domestic, agricultural and forestry activities (Chávez and Rodríguez, 2016). Ecuador is a highly agricultural country as it has more than 31 crops (Instituto Nacional de Estadistica y Censo [INEC-ESPAC], 2019), it generates a large amount of waste. Among the most important products is the banana with a global trade representation of 32%, which represents 50% of the national agricultural Gross Domestic Product (GDP) (Álvarez *et al*., 2020). This allows 17 million tons of *musa* crop residue to be generated per year (Roca-Pérez *et al*., 2017).

Around the entire country, 296,754 hectares of plantain and 230,000 hectares of bananas are produced per year (Instituto Nacional de Estadistica y Censo [INEC-ESPAC], 2019). In general, 17 million tons are produced per year of the residue of the banana crops (gender musas) (Roca-Pérez *et al*., 2017). The residues generated from banana production are left on the ground as fertilizer or taken to landfills in a 2:1 ratio with the respective fruit (Guerrero *et al*., 2015) and another part, are burned by the farmer to eliminate pests, reduce the amount of material and clean the area for cultivation. However, this action produces harmful effects on the environment due to its production of CO, CO_2 and particulate substances (Gómez *et al*., 2021).

These organic residues contain a large amount of cellulose, lignin and starch and therefore can become value-added products. With these characteristics, they can be used as raw material to produce biodegradable materials with the help of certain additives (Haro *et al*., 2017) and therefore, it can become a candidate for being a suitable potential substitute for plastic (Chávez and Rodríguez, 2016).

One such additive is thermoplastic starch (TPS) (Luna *et al*., 2009; Calderón *et al*., 2019), which is a modified starch to which a plasticizer is added under certain conditions. Then, to improve the own characteristics of the material combined with lignocellulosic fibers to the production of biodegradable products (Valero-Valdivieso *et al*., 2013). Another additive used in this research is polyvinyl alcohol (PVA), because it is a biodegradable synthetic polymer that is used as an emulsifier in the preparation of other polymers and as a lubricant (Calvo-Flores and Isac, 2013). Finally, the use of calcium carbonate ($CaCO_3$) is a common component in all formulations.

This work has the purpose of offering ideas on the added value to agricultural waste, reducing plastic pollution through the production of biodegradable materials and venturing into the circular economy. Due to the above, the objective of the project was to evaluate the use of fiber residues from the banana pseudostem (*Musa Paradisiaca* L.) with thermoplastic corn starch (*Zea Mays*) in the preparation of biodegradable dishes for food use. For this, different amounts of pseudostem fiber residues and TPS were taken. The different formulations were evaluated through mechanical, physical, chemical, thermal, and spectroscopic analysis, and their subsequent evaluation statistical analysis to determine the best formulation for the preparation of the biodegradable plate.

2 Materials and methods

2.1 *Obtaining residues from the fibers of the banana pseudostem*

The pseudostem of banana (*Musa Paradisiaca* L.) was obtained on the 5th day of December 2021 in winter (Naranjito, Guayas, Ecuador). It was cut into 4 sections of 50 cm each to facilitate transfer to the Laboratory of Analytical Chemistry at the Faculty of Chemical Engineering of the University of Guayaquil. The pseudostem leaves were manually separated from the central stem and those in good

condition were selected. The residue useful for the work was separated from the fibers with a metal spatula and placed in a 0.25% ascorbic acid solution (USP, Merck) to prevent oxidation, then washed 4 times with fresh water. It was dried at 60 °C in an air circulation oven for 18 h (Maldonado *et al*., 2013) and ground in a mill (Corona, Mexico). The residue was stored in sealed and identified plastic bags in a desiccator at 24 °C and 50% relative humidity (RH).

2.2 Obtaining thermoplastic starch (TPS)

Obtaining thermoplastic corn starch was carried out according to the methodology of Luna *et al*. (2009) with some modifications. Native corn starch (NS) (El Sabor, Alimensabor CIA. LTDA) was mixed manually with 30% glycerin (USP, Cevallos Laboratory) for 10 min. The mixture was placed in a sealed plastic bag and stored in a desiccator for 24 h. Then, the mixture was placed in an aluminum tray and placed in the oven at 155 °C for 15 min. It was stored in a desiccator at 24 °C and 50% RH until further characterization and use in the preparation of biodegradable dishes.

2.3 Manufacture of biodegradable dish

The manufacture of the biodegradable dish was obtained according to the methodology of Espina *et al*. (2016). The formulations were mixed with water until homogeneous and placed on an electric burner at 60 °C for 10 min with constant stirring. The mixture was introduced into the mold and spread out until it took the shape of the mold. Then, it was placed in the thermopress at a maximum temperature of 150 °C for 20 min and allowed to cool to room temperature. They were kept in a desiccator at 24 °C and 50% RH until use. These formulations were obtained based on results previously unpublished.

2.4 Experimental design and statistical analysis

Several formulations were evaluated to obtain the best answer from the hardness analysis. The residue and the $CaCO_3$ were kept constant, while the amounts of TPS and PVA varied. Three quantities of PVA and TPS were used with a total of 9 combinations and 3 repetitions for each of the samples, resulting in 27 experimental units, as detailed in Table 1. These formulations were obtained based on results previously unpublished.

A two-way analysis of variance, ANOVA, was performed to determine the interaction and effects at different amounts of TPS and PVA, at the 5% significance level. The normality test for the residuals was determined using the general linear model, Bartlett's test for homogeneity of variances, performing a combination of levels and multiple comparisons with Tukey's test. Statistical analyzes were performed with MINITAB ® 19 software.

2.5 Characterization of the raw material

2.5.1 Banana pseudostem

The yield with respect to the residues was carried out randomly at three stalks of the pseudostem, the fibers of the residue were weighed and separated. Calculated according to Eq. 1.

Table 1. Components for the formulation of biodegradable plates.

Treatments	TPS (g)	PVA (g)	Residue (g)	$CaCO_3$ (g)
T1	10	0.5	2.1	5
T2	5	0.5	2.1	5
T3	15	0.5	2.1	5
T4	10	1.0	2.1	5
T5	5	1.0	2.1	5
T6	15	1.0	2.1	5
T7	10	1.5	2.1	5
T8	5	1.5	2.1	5
T9	15	1.5	2.1	5

TPS = thermoplastic starch; PVA = polyvinyl alcohol and $CaCO_3$ = calcium carbonate.

$$Yield(\%) = \frac{Wr}{Wp} \times 100 \quad (1)$$

Where Wr, is weight of the residue; Wp, is weight of the pseudostem.

Humidity was determined according to Sluiter *et al*. (2008). A representative sample was taken from the entire pseudostem. For this, it was ground in a mill (Corona, Mexico). The determination was carried out in triplicate and was obtained according to Eq. 2.

$$Humitidy(\%) = \frac{Ma - Mb}{Ma - M} \times 100 \quad (2)$$

Where Ma is the mass of the capped capsule and sample; Mb, is the mass of the capped capsule and the dry sample; M is the mass of the capped capsule.

2.5.2 *Banana pseudostem fiber residue*

Humidity was determined according to Sluiter *et al*. (2008) drying the sample at 105 °C for 4 h in an oven (MLW, with air circulation), using Eq. (2) for this purpose.

Ash determination was performed according to Vargas *et al*. (2013), which consisted of calcining the sample at 500 °C in a muffle (Termoline) using Eq. (3) for such purpose.

$$Ashes(\%) = \frac{Mr - Mc}{Mm} \times 100 \quad (3)$$

Where Mr, is the weight of the crucible and the residue; Mc, is crucible weight y Mm, weight of the sample.

The determination of the amount of cellulose was carried out by the method of Kurschner and Hoffer (1931) as cited in Hessler and Merola (1949). To do this, 1 g of sample was weighed, 68% nitric acid and 96% ethanol (Laboratorio Cevallos) were added and heated to boiling under reflux for 30 min. Next, a second digestion was performed. It was washed and filtered to remove acid residues and the resulting mass was then dried and weighed. The percentage of cellulose was calculated according to Eq. (4).

$$Cellulose(\%) = \frac{Mf}{Mi} \times 100 \quad (4)$$

Where Mf, is the weight of the crucible and the final sample; Mi is the weight of the initial sample.

Crude fiber content was made according to AOAC 978.10 regulations as cited in VELP Scientifica (2019). 1.25% sulfuric acid at 98% and sodium hydroxide 1.25% by weight were used. 2 g of the sample were taken and boiled first with the acid and then the hydroxide. Subsequently, it was placed in an oven where the percentage of crude fiber obtained was determined by gravimetry using Eq. (5). These determinations were carried out in triplicate.

$$Crudefiber(\%) = \frac{W_1 - W_2}{Ws} \times 100 \quad (5)$$

Where W_1 is the weight of the crucible plus the dry sample; W_2 is the weight of the crucible + ash and Ws is the weight of the initial sample.

2.5.3 *Native starch (NS) and thermoplastic starch (TPS)*

The determination of humidity was carried out according to the INEN 1666 (2014) regulation applying Eq. (2).

2.6 *Characterization of biodegradable dishes*

2.6.1 *Hardness test*

Hardness was determined according to the ASTM D2240-15 (2017) standard with the Shore D Durometer equipment (0 ?100HD, 0.5HD) under environmental conditions of 22.6 °C and 56.3% RH. 10 repetitions were taken for each specimen.

2.6.2 *Tensile strength*

The tensile strength followed the indications of the ASTM D 3039M-14 (2014) standard. Nine specimens were made (according to the treatments) of 165 mm long and 19 mm wide. The test was performed under ambient conditions of 21.9 °C and 58.6% RH. A Metrotec 50 KN universal testing machine, model MTE-50, series 8802M002 was used. The test speed was 1 mm/min and a preload of 0.01 N.

2.6.3 *Rheological analyzes*

The test was carried out in accordance with the procedure described by Velásquez-Barreto and Velezmoro (2018). For this, suspensions of NS, TPS and T2 at 4% w/w were prepared. The samples were placed in a water bath at 90 °C for 30 min with magnetic stirring. Subsequently, the samples were placed in the Rheometer (Malvern Kinexus PRO) at 25 °C with a speed of 1 to 100 Hz. The geometry was plate-plate and a diameter of 20 and 65 mm.

2.6.4 *Differential Scanning Calorimetry (DSC)*

The tests using DSC Thermograms were carried out according to Sikora *et al*. (2020) on an Instrument DSC Q200 V24.11 Build 124 device, DSC Standard Cell FC module. Samples of NS, TPS and T8 were taken between 7.0 and 8.5 mg, hermetically sealed in aluminum trays. Nitrogen atmosphere 50 mL/min and a mass flow of 40 mL/min were used. Samples were heated from room temperature to 170 °C at a rate of 10 °C/min.

2.6.5 *Fourier Transform Infrared Spectroscopy (FT-IR)*

According to Jiménez *et al*. (2019), the structural analysis by means of FTIR to NS, TPS and T1 was carried out for the elaboration of the dish. Infrared spectra were recorded in a spectral range between 7800 and 349 cm^{-1} and a spectral resolution of 4 cm^{-1}. A Jasco equipment, model FT/IR 4200, series C083661018 was used.

2.6.6 *Thermogravimetric analysis (TGA)*

Thermogravimetric analyzes were carried out according to Ghanbari *et al*., (2018) with modifications. The equipment used was an Instrument SDT Q600 V20.5 Build 15, Model DSC-TGA Standard. Samples NS, TPS and T8, weighing approximately 7.5 mg, were placed in alumina crucibles. Measurements were carried out at a heating rate of 10 °C/min in a nitrogen atmosphere of 100 mL/min from 25 °C to 600 °C.

2.6.7 *Thickness*

The thickness of the plates was measured with a digital micrometer (0-12.7 mm with a sensitivity of 0.001 mm). Three random replicates were performed at different points on each plate (Anchundia *et al*., 2016).

2.6.8 *Humidity test*

The humidity of the plates was determined according to Sluiter *et al*. (2008). This was milled in a mill (Corona, Mexico) and calculated according to Eq. 2.

2.6.9 *Contact angle test*

For the contact angle test, a drop of water was deposited on the biodegradable plate and after 20 seconds, with a camera, the angle formed between the drop and the plate was recorded, according to Yin *et al*. (2020) and Salgado-Delgado *et al*. (2022). Its hydrophobic character was determined. The hydrophobicity was determined according to the value of the angle; if it is less than 90°, it is considered a hydrophilic material and if it is greater than 90°, it would be hydrophobic (ASTM D 7334-08, 2013).

2.6.10 *Biodegradability test*

Biodegradability analysis was performed according to Schröpfer *et al*. (2015). Samples were cut to 1 cm x 3 cm sizes and aerobically buried. Samples were placed in the middle of a 177 mL beaker and filled with more soil. After 30 days, the samples were extracted from the soil, carefully cleaned with a brush, and weighed every 7 days until the analysis was completed. Biodegradability percentage was determined with Eq. 6.

$$Biodegradability(\%) = \frac{Mf}{Mi} \times 100 \tag{6}$$

Where Mf is the final weight and Mi is the initial weight.

2.7 *Evaluation of the costs of biodegradable dishes*

2.7.1 *Research instrument, population and target group*

A questionnaire was carried out using the Google Forms survey administration software, structured by 18 questions in order to establish the potential demand for the dish. Three national sectors were taken: Guayaquil, Durán and Samborondón with a population of 2,723,665, 315,724 and 102,404 respectively (Instituto Nacional de Estadística y Censos [INEC], 2013), which was taken as the total population.

2.7.2 *Sample size*

A total population of 3,141,793 inhabitants was considered. To determine the number of surveys, a degree of confidence and a margin of error were established, according to Eq. 7 (Aguilar-Borjas, 2005):

$$N = \frac{Z^2 * P * q * n}{(n-1) * E^2 + Z^2 * p * q} \tag{7}$$

Where N is the number of surveys to be carried out; Z, 1.96 confidence level; P, 0.50 probability of success; q, 0.50 probability of failure; n, is the size of the population; E, 5% margin of error.

Table 2. Proximal content of the residue on a wet and dry base.

Register	Residue in w.b. (%)	Residue in d.b. (%)
Humidity	95.32 (0.36)	8.62 (0.5)
Cellulose		51.79 (2.25)
Ash		5.71 (0.36)
Crude fiber		27.26 (0.05)

()=standard deviation; w.b.= wet base; d.b.= dry base

2.7.3 *Determination of the costs of the biodegradable plate*

The cost per dozen of the biodegradable plate was determined from direct costs (raw material and direct labor) and indirect costs. In addition, the retail price was calculated based on a 30% profit.

3 Results and discussion

3.1 *Banana pseudostem characteristics*

The banana stem (*Musa Paradisiaca* L.), harvested after its useful life, had a total weight of 16.3 kg and a length of 2.7 m, with a lower diameter (attached to the corm) of 17 cm and an upper diameter of 11 cm. Of the banana stem, 623 g were disposable matter, 2.4 kg were from the central trunk and 13.3 kg were from the pseudostem, where 12.8 kg were useful residue and 0.5 kg were fiber. The pseudostem cut into 4 sections had a few stalks between 11 and 17 because they decreased towards the upper part of the pseudostem. The weight of the leaves ranged between 153 and 244 g. The moisture content of the pseudostem was 91.81% (S=0.68%) similar to 90% and 90.75%, data found by Díaz *et al*. (2021) and Khan y Perveen (2010) respectively.

3.2 *Characterization of banana pseudostem fiber residue*

The wet base pseudostem (w.b.) presented a yield of 96.31% (S=0.27%) with respect to residues and 4% (S=0.27%) of fiber. According to Díaz *et al*. (2021), the values were similar with 94% residues. The proximal content for the banana pseudostem fiber residue on a wet basis and on a dry basis (d.b.) is shown in Table 2. The reported values were not compared with other investigations, due to the scarce information regarding the use and characterization of this residue.

3.3 *Corn starch characterization*

The corn NS presented a humidity of 11.13% (S=0.06%), a value that was between 9.82% (S=0.07%) and 12.3% described by the authors Bianco *et al*. (2014) and Zhang *et al*. (2021). While the TPS had a humidity of 21.41% (S=0.29%) for 30% plasticizer, a lower value than that reported by Barrios *et al*. (2015) of 29.4% with 35% plasticizer. The increase in humidity in the TPS was given by the presence of the plasticizer because the higher its concentration, the higher the humidity value.

3.4 *Characterization of biodegradable dishes*

3.4.1 *Hardness test*

The shore D hardness values were higher in treatments T2, T5 and T8 with a lower percentage of TPS (5 g) where no significant differences were found according to Table 3. Values corresponded to 30.55, 32.40 and 33.30 shore D. According to Ibrahim *et al*. (2020), with 20% fiber, a hardness of 43.00 shore D was obtained. A value higher than that of this research, which had 15.4% fiber with a hardness of 33.30 shore D. The aforementioned is corroborated by what was stated by Ibrahim *et al*. (2020) and Ibáñez *et al*. (2020) by indicating that the greater the amount of fiber, the harder it increases.

3.4.2 *Thickness*

Regarding thickness (Table 3), the dishes with the smallest measurements were T2 and T7 and the rest of the treatments did not present a significant difference between them. The difference of the obtained values was between 0.2 and 0.6 mm. Similar values were obtained by Salmerón (2019) and Bátori (2019). The thickness variation could be related to the difficulty of controlling the pressure exerted in the thermopress.

3.4.3 *Humidity test*

The dishes presented a humidity range (Table 3) between 6.7 and 12.6%. The treatments with the lowest humidity were those that contained the least amount of TPS in the formulation. The T6 and T9 treatments had a higher amount of TPS, so their humidity was higher. Therefore, the humidity of the

dishes varied in relation to the amount of TPS added because the greater the plasticizer, the more moisture absorption increases (Almario *et al*., 2018; Kuciel and Liber-Knec, 2009, as documented by Barrios *et al*., 2015).

3.4.4 Contact angle test

Regarding the contact angle (Table 3), the treatments T3, T5, T6, T7 and T8 did not present significant differences. The highest value was 79.33°, like those reported by Marichelvam *et al*. (2019), Surya *et al*. (2021) and Yin *et al*. (2020), they indicate that the material is impermeable when it has a contact angle between the drop and the surface of the material greater than 90°. Therefore, the material of this research has a permeable surface.

3.4.5 Tensile strength

The tensile properties are shown in Fig. 1. The tensile strength (Fig.1a) is the maximum stress that the material supports for its breakage. The maximum value was 2.26 MPa, which corresponded to T7, presenting non-significant differences with most of the treatments. This value was lower than the one reported by Barrios *et al*. (2015), who obtained values between 5 and 6 MPa with ash fibers and TPS. They concluded that increasing the amount of lignocellulosic fiber improves the mechanical performance of the composite material, being confirmed by (Cheng, 2019) that by increasing the amount of TPS, the resistance decreases.

Young's modulus (Fig. 1b) -which indicates the stiffness of a material-, showed higher values for treatments T1, T4 and T6 with values between 142 and 164 MPa, presenting non-significant differences, which may be related to a higher dispersion of the fibers in the polymeric matrix (Cheng, 2019) which in turn act as reinforcement in the biocomposites with TPS (Ibrahim *et al*., 2020).

The elongation (Fig. 1c) measures the increase in length before it breaks with a tensile stress. In this case, a range of values between 1.1% and 2.3% was obtained. Treatments T8 and T9 presented non-significant differences and corresponded to the highest results, however, they were the lowest in modulus of elasticity. In 2015, Barrios *et al*. concluded that by incorporating lignocellulosic material, elongation causes a restriction to the mobility of starch chains, obtaining values above the one reported in this research of 8% in thermal treatment of TPS and ash fiber at 5 %.

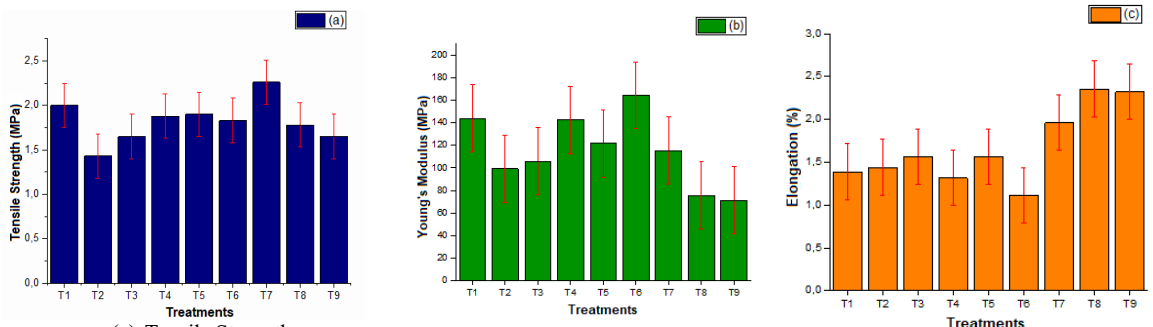
3.4.6 Fourier Transform Infrared Spectroscopy (FT-IR)

FT-IR spectroscopy was performed to determine the interactions between NS, TPS and the dish. The samples are represented in the spectra of Fig. 2. The most evident characteristic peaks were identified according to the corresponding literature. The broad band at approximately 3400 cm^{-1} corresponds to the OH groups linked by hydrogen bonds, which had greater intensity in the TPS. The band attributed in the 2930 cm^{-1} band is associated with the CH_2 groups due to their axial deformation (Arik and Us, 2014). The signals around 1000 cm^{-1}, with less pronouncement in T1, belong to stretching of C-O bonds (Goheen and Wool, 1991, as cited in Torres *et al*., 2017) and bending vibration of C-O-H groups (Barrios *et al*., 2015).

Table 3. Properties of the biodegradable dishes.

Treatments	Combinations TPS*PVA (g)	Hardness (shore D)	Thickness (mm)	Humidity (%)	Contact angle (°)
T1	10*0.5	24.55^{cd} (3.411)	3.24^{abc} (0.337)	7.53^{cd} (0.039)	50.33^{bc} (0.577)
T2	5*0.5	30.55^{ab} (1.833)	2.65^{bc} (0.274)	6.66^{d} (0.183)	18.00^{d} (15.87)
T3	15*0.5	11.90^{e} (1.390)	4.01^{a} (0.431)	8.42^{c} (0.703)	79.33^{a} (0.577)
T4	10*1.0	22.25^{d} (5.035)	3.25^{abc} (0.236)	10.10^{b} (0.232)	50.33^{bc} (8.387)
T5	5*1.0	32.40^{a} (3.542)	2.89^{abc} (0.221)	9.82^{b} (0.618)	62.00^{ab} (3.606)
T6	15*1.0	20.25^{d} (2.841)	3.85^{ab} (0.620)	12.62^{a} (0.706)	67.00^{ab} (2.000)
T7	10*1.5	27.25^{bc} (2.908)	2.57^{c} (0.425)	10.74^{b} (0.572)	65.00^{ab} (3.000)
T8	5*1.5	33.30^{a} (5.627)	3.14^{abc} (0.391)	10.28^{b} (0.222)	71.33^{a} (1.528)
T9	15*1.5	20.20^{d} (1.947)	3.96^{cd} (0.685)	12.43^{a} (0.354)	41.00^{c} (9.539)

() = standard deviation. Different letters indicate a significant difference for $p \leq 0.05$.



(a) Tensile Strength (b) Young's Modulus (c) Elongation

Fig 1. Mechanical properties of the nine dish treatments: (a) Tensile Strength; (b) Young's Modulus and (c) Elongation.

In the spectrum corresponding to NS, similar to the one obtained by García-Cruz *et al.* (2020), characteristic absorption signals of the anhydroglucose ring with stretching of the C-O bonds in the C-O-C and C-O-H groups are observed for wavelengths between 1149 and 760 cm^{-1} (Arik and Us, 2014). In addition, a signal of absorbed water was observed at 1630 cm^{-1} with more pronounced peaks in NS and TPS with respect to T1. This may be due to the formation of intermolecular forces by hydrogen bonding between the starch and the fibers (Barrios *et al.*, 2015).

Remembering that the mixture of the dish contains lignin, cellulose, and other components. Thus, in T1 the presence of lignin was observed between 1328 and 1619 cm^{-1} (Bodîrlău *et al.*, 2014; Jiménez *et al.*, 2019) corresponding to the CH_3O and benzene ring groups respectively. At 3327 cm^{-1}, the OH group was generated, which shows the presence of cellulose (Ibáñez *et al.*, 2020). The peak attributed to 1795 cm^{-1} corresponds to stretching vibrations of C=O groups in the plate sample, which unlike NS is not shown. The appearance of this group is given by the thermocompression process that produced a slight decomposition due to the temperature and processing time, without affecting the physical-mechanical properties (Wu, 2005, as cited in Barrios *et al.*, 2015).

3.4.7 Thermogravimetric Analysis (TGA)

The TGA and first derivative (DTG) curves were used to evaluate the thermal stability and degradation profile of NS, TPS and T8 as shown in Fig. 3. The TGA curve belonging to NS corresponds to Fig. 3a. For the TPS to Fig. 3b and T8 to Fig. 3c, it is observed that the degradation start temperature was presented

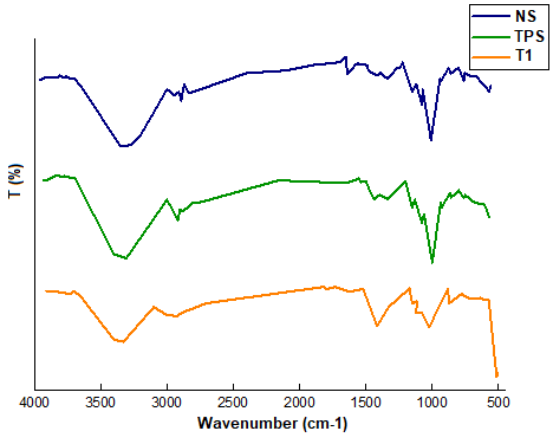


Fig. 2. ATR-FTIR spectra: (NS) native starch, (TPS) thermoplastic starch and (T1) biodegradable dish mixture.

at 297.47, 299.35 and 279.47 °C respectively. The three samples indicated a first thermal event at approximately 100 °C, which is related to the loss of water and volatile components (Yin *et al.*, 2020; Guleria *et al.*, 2017) with 11.97% for NS, 4.18% for TPS and 6.37% for T8.

The second thermal event of the TPS and T8 belonged to the decomposition of the glycerin phase (Santos and Spinacé, 2021) with initial and final temperatures between 150 and 200 °C. The third thermal event of the TPS arose with temperatures between 299.35 and 327 °C and a weight loss of 58.87% due to the partial oxidation of the decomposed starch where the hydrogen bonds increase between the glycerin molecules and the hydroxyl groups of the starch chains.

Consequently, the intra and intermolecular forces of the starch-starch chains decrease, which allows

the thermal degradation of TPS (Santos and Spinacé, 2021). Carbonization is found around 500 °C, being lower for T8 with 0.89% weight loss, probably due to the presence of calcium carbonate compared to NS and TPS with 1.33 and 1.064% respectively.

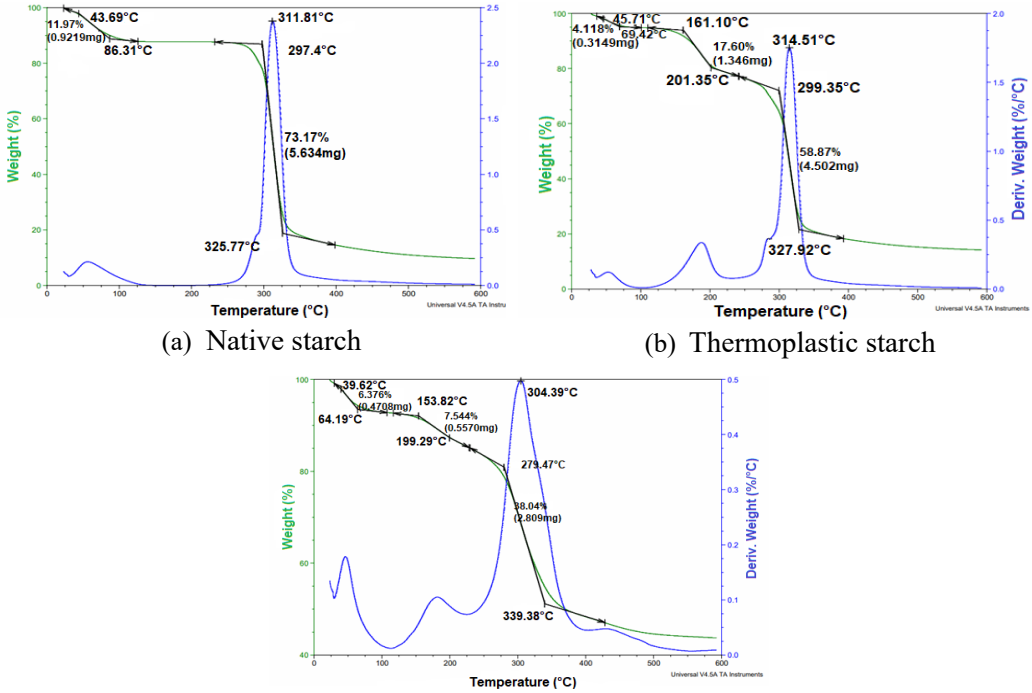
Additionally, this technique was also used for the evaluation of the different components present in the biomass, such as lignin and cellulose. According to Alvarado and Rutiaga (2018), the presence of cellulose occurs at degradation temperatures between 275 and 380 °C, not showing a visible event in Figure 8c. However, from 400 °C the author states that the slow decomposition is due to lignin, as observed in Fig. 3c, at 430 °C.

The DTG curve shows the decomposition rate of the previously analyzed samples, observing the maximum degradation temperature. Values were maintained between 300 and 315 °C. The compound that presented the best thermal stability was T8 with a total weight loss of 55.72%, while for TPS and NS, a loss of 85.25 and 90.76% was observed, respectively.

3.4.8 Differential Scanning Calorimetry (DSC)

The DSC curves were used to obtain the main thermal transactions in the analyzed samples (Fig. 4). The three samples analyzed presented endothermic peaks with similar melting temperatures (Tm). NS had a Tm of 124.04 °C corresponding to the range defined by Yingfeng *et al*. (2012) and Orue *et al*. (2016). The TPS presented a higher Tm with 135.78 °C that corresponds to Sikora *et al*. (2020) and higher than those of Cheng, (2019) and Ghanbari *et al*. (2018) with 63.4 and 86.99 °C respectively. The glass transition temperature (Tg) corresponds to 37.27 °C. Ghanbari *et al*. (2018) they indicate that above this temperature, the material softens.

The mixture of the T8 dish presented a lower Tm 121.72 °C due to the addition of fibers creating adherence compatibility with the TPS interface. However, the addition of calcium carbonate did not indicate a significant effect on Tg (Gerezgiher *et al*., 2020). The energy absorbed in the diagrams was lower for T8 with 78.91 J/g, increasing in TPS and NS with 106.3 and 261.0 J/g, respectively.

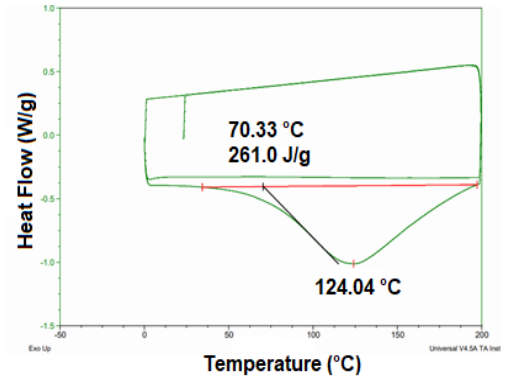


(a) Native starch

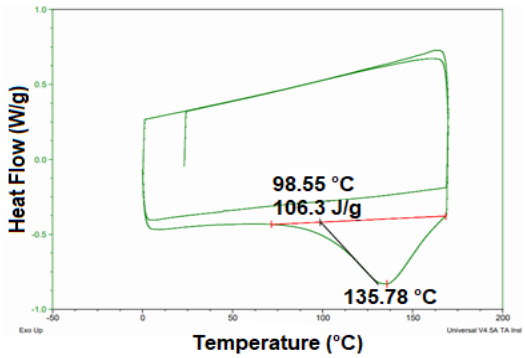
(b) Thermoplastic starch

(c) Biodegradable dish mix

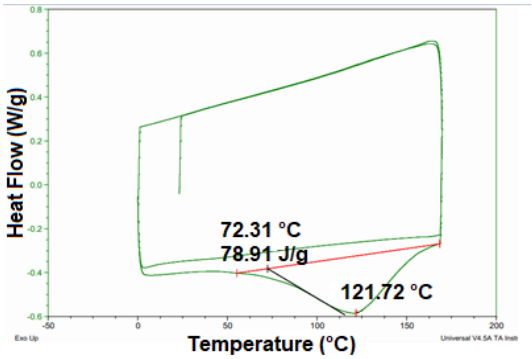
Fig. 3. TGA and DTG thermograms of (a) native starch, (b) thermoplastic starch, and (c) biodegradable dish mix.



(a) Native starch



(b) Thermoplastic starch



(c) Biodegradable dish mixture

Fig. 4. DSC curves of (a) native starch, (b) thermoplastic starch and (c) biodegradable dish mixture.

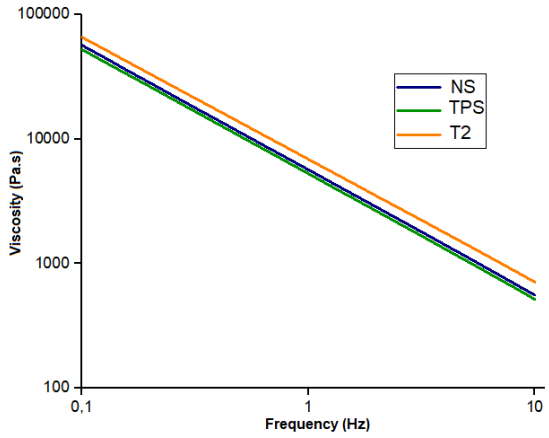


Fig. 5 Complex viscosity of (NS) native starch, (TPS) thermoplastic starch and (T2) biodegradable dish mixture.

3.4.9 Rheological tests

The viscoelastic properties of the three samples are represented in Fig. 5. It was observed that according to the viscosity as a function of frequency, the flow behavior is non-Newtonian (Ma *et al*., 2019). Their viscosities are very similar to each other, unlike the mixture that increases slightly, probably due to the addition of lignocellulosic fibers (Cheng, 2019).

The ratio of G" and G' reflects the viscoelastic behavior of the samples (Karim *et al*., 2000). The G' modulus is a measure of storage or recoverable energy per elastic cycle, while G" is the loss or viscosity modulus (Hussain *et al*., 2020). The G' values for the 3 samples analyzed (Table 4) presented significant differences with values lower than those reported by Torres *et al*. (2018) around 1.6×10^5 Pa.

In relation to G" there was no significant difference between the NS and TPS samples with values lower than those indicated in Guzmán and Murillo (2018). However, T2 shows values close to 3×10^3 Pa. Comparing G' and G", the former was much higher than the latter, evidencing the prevalence of elastic properties over viscous ones, indicating a dominant solid behavior (Heydari and Ali, 2021).

Table 4. Viscoelastic properties of NS, TPS and T2.

Parameters	NS	TPS	T2
G'(Pa)	3.6×10^{4b} (158.5)	3.3×10^{4c} (180.3)	4.3×10^{4a} (1077)
G''(Pa)	3.5×10^{2b} (78.9)	2.2×10^{2b} (89.7)	3.3×10^{3a} (433.9)
η*(Pa.s)	1.3×10^{4a} (16044)	1.2×10^{4a} (14850)	1.5×10^{4a} (18674)
δ (°)	0.5971^{b} (0.1292)	0.3738^{b} (0.1584)	4.415^{a} (0.467)

() = standard deviation. Different letters indicate significant difference for $p \leq 0.05$. NS= native starch; TPS= thermoplastic starch; T2= treatment corresponding to 5 g of TPS, 0.5 g of PVA, 2.1 g of residue and 5 g of $CaCO_3$.

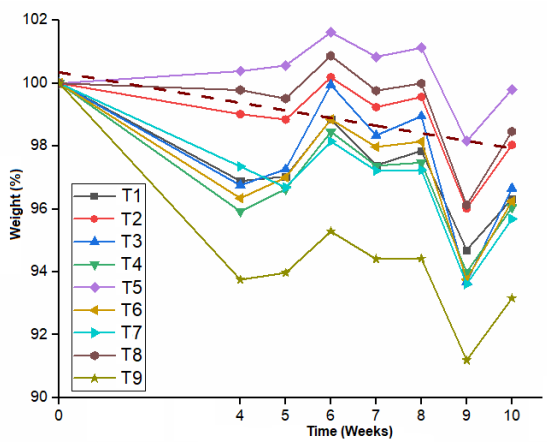


Fig. 6. Biodegradation of dish treatments.

The tangent (tan δ) is used to study changes in amylose aggregation of corn starch (Li *et al*., 2016). Tan δ values for NS and TPS were less than 1, like Cheng (2019). The T2 treatment indicated higher values with the other treatments presenting significant differences. The elevation of tan δ values according to Tang *et al*. (2013) improves the viscous characteristics and decreases the elastic characteristics.

3.4.10 Biodegradability test

The biodegradability of the dishes is shown in Fig. 6. Treatment T9, with 15 g of TPS, exhibited a higher degradation rate of 7% at 10 weeks. According to Encalada *et al*. (2018), the increase in starch favors biodegradability, and it also states that starch together with PVA does not degrade easily under environmental conditions. However, the addition of fibers enhances PVA degradation.

Treatments with a higher amount of TPS increased their hydrophilicity and water absorption, which favored microbial attack (Fitch-Vargas *et al*., 2019). The lowest degradation rate corresponded to the treatments T5 with 1%, T8 and T2 with 2%. This minimal loss is justified by the lower amount of starch present in said formulations.

3.5 Determination of product costs

The survey of 384 people made it possible to determine the demand for this type of biodegradable dishes in the three selected cantons with a total of 3,141,793 inhabitants. These data were filtered according to the results obtained in the survey. Initially, only 0.5% of this demand was considered based on the capital to be invested, which represents 3,026 dozen plates per month.

The determination of the costs of the plate was given by the costs of raw materials, direct labor, and indirect costs. The labor cost per dozen was determined from the monthly salary established for the operator (Table 5). The indirect costs that were taken were the administrative expenses that were not directly related to production (Table 6). The unit cost of production (Table 7) had a value of $1.63 and the retail price was $2.12 dollars (Table 8), which was adjusted to what people were willing to pay according to the survey carried out. A profit margin of $0.49 dollar per dozen was evidenced.

Table 5. Direct cost estimation results.

RH	Price ($) /kg	Qty/ dozen	Price per dozen ($)	Price per dozen per month ($)
NS	3.14	0.084	0.26	798.14
Glycerin	5.60	0.036	0.20	610.04
PVA	11.20	0.018	0.20	610.04

Residue	0.02	0.0252	0.00050	1.53
$CaCO_3$	6.04	0.06	0.36	1,096.62
Ascorbic acid	2.30	0.001	0.00230	6.96
Total			1.09	3,123.33
Direct Labor (Gross Salary)				
		Raw material (RH)		
Operator1				425.00
Total direct costs per dozen				3,548.89

Table 6. Indirect costs for the elaboration of the product.

Indirect costs per month	
Administrative expenses	**Price ($)**
Rental of the premises	350
Payment of communal rates	40
Legal paperwork	230
Phone Service	60
Electric power	150
Potable water	120
Internet	45
Office supplies	100
Water bottles	24
Cleaning tools	30
Gallon alcohol in antibacterial gel glycerin hands	10
White industrial toilet paper x4 jumbo rolls	13
Web page design and creation	150
Social networks	5
Signage: canvas sign: Full color. Measurement: 4 m x 1.5	55
Total	**1,382.00**

Table 7. Cost of production.

Cost per dozen	**Cost ($)**
Total direct cost	3,548.89
Indirect cost	1,382.00
Production cost	4,930.89
Unit cost of production	1.62951

Table 8. Determination of the retail price (RRP) of the dozen biodegradable plates.

Product	**Unit cost of production**	**Utility (30\%)**	**RRP**
Dishes	$1.63	1.3	$2.12

Conclusions

The residues of the fibers of the banana pseudostem and the thermoplastic corn starch turn out to be a sustainable alternative in the elaboration of biodegradable dishes for food use. The high amount of this waste allowed its use in materials that contribute positively to the environment. The biodegradable dish formulations demonstrated different characteristics depending on the amounts of TPS and PVA used. Likewise. the presence of lignocellulosic fibers allowed to improve the properties of tensile strength. elasticity modulus. hardness. and viscoelasticity in the biodegradable plate. Treatment T8 with 5 g of TPS was considered the best formulation for its high hardness value. The production costs of the dozen biodegradable plates were competitive with those existing in the market. Its unit cost per dozen was $1.63 and a retail price of $2.12 dollars.

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