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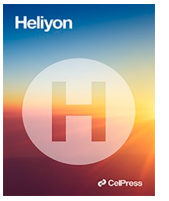

Nutritional composition and *in vitro* digestibility of two Plantain Cultivars (*Musa Paradisiaca* spp.) in Puerto Rico

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ABSTRACT

Plantain is a basic component in the Puerto Ricans' diet and one of the most economically important crops on the Island. Maricongo crops, the predominant cultivar, do not satisfy the demand for fresh and processed products. The objective of this study was to evaluate the nutritional composition and *in vitro* digestibility of Maiden and FHIA 20 plantains in stages 1 and 5 and compare these data to Maricongo. Estimated glycemic indexes (eGI) of cultivars under conventional cooking processes (i.e., boiling, fried, baked, and steamed) were performed as well. Baked Maricongo stood out because of its lowest rapidly available glucose value (22.06%), constituting a healthier and the first cooking alternative. eGI values were classified as medium and high, where frying and baking processes presented medium values, and boiling displayed the greatest eGI for both stages. In terms of nutritional profile, this research concludes that Maiden could constitute an option to substitute or supplement Maricongo.

1. Introduction

Plantain, classified scientifically as *Musa paradisiaca*, is used commonly to describe a banana group that must be put through a cooking process to be consumed due to its high starch content. Despite differences between existing and currently marketed plantain cultivars, carbohydrates prevail as the main nutrient in their proximal composition [1–5], and potassium as the predominant mineral [6].

In Puerto Rico, plantain and banana are among the most economically important crops, contributing between 2016 and early 2017, $ 76.2 million and $ 28.3 million, respectively [7]. However, after Hurricane Maria in the middle of the second half of 2017, most crops decreased substantially, including plantains. Gross production decreased from 78,071 tons in 2017 to 18,813 tons in 2018 [8]. Many efforts have been made to increase the availability of plantains on the island, including the introduction of new varieties to Puerto Rico. Currently, marketable cultivars include Maricongo, Enano común, Hartón, Super plátano, and Congo [9]. Maricongo is the dominant commercial cultivar in Puerto Rico.

Plantains are consumed through a variety of derived products. However, the trend in the consumption of processed plantain

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products on the Island cannot be supplied by local production [10]. It is necessary to satisfy the fresh and processed product markets with affordable prices [11]. New varieties of plantains are being evaluated for the Puerto Rican market to identify species that provide greater advantages in terms of productivity, resistance to pests, and nutritional value, without impacting the organoleptic characteristics.

Nutritional values, composition, and glycemic index play important roles in selecting plantain cultivars. The glycemic index is a parameter that allows food to be categorized according to its carbohydrate content and its relationship with the increase, in rate and magnitude, of blood glucose levels, compared to reference values under isoglucidic conditions [12]. This measurement is influenced by physical and chemical factors that interact with food, such as processing, heat treatments, type of starch present, and content of carbohydrates, fiber, and fat [13]. Since plantain is rarely eaten raw, it is also important to know if the cooking processes and maturity stage influence the glycemic index.

To date, many studies have investigated the effect of processing on the glycemic index of plantain meals using *in vivo* techniques. Results show that cooking processes significantly impact the glycemic index where fried foods have presented lower glycemic than roasted meals due to the lipid effect on the rate of starch digestion [14–16]. These studies show the effect of processing on the glycemic index but do not consider the potential effect of the maturity stage. Maturation influences the composition of plantains observed in the increase of fructose and decrease of starch content [2]. Therefore, the glycemic index, which is strongly influenced by the presence and type of carbohydrates, can be affected as well [17,18].

It is convenient to evaluate the characteristics of other varieties of plantain that can substitute or complement the production of Maricongo plantain for consumption in Puerto Rico without compromising quality and nutritional value. We hypothesized that other varieties of plantain are not significantly different from the predominant cultivar in Puerto Rico in terms of nutritional profile and *in vitro* digestibility, although there could be an effect of cultivar and maturity stage on the nutritional content of plantains. Thus, this study aimed to assess the nutritional composition and *in vitro* digestibility of Maiden and FHIA 20 plantains and compare them to Maricongo.

2. Materials and methods

2.1. Experimental design

A factorial experiment was carried out to evaluate the effect of cultivar and maturity stage on the nutritional content of plantains. This experiment consisted of two factors: Cultivars (i.e., Control: Maricongo, Maiden, and FHIA 20) and maturity indexes (i.e., Stage 1: Green, Stage 5: Yellow with green tips). Evaluation of the maturity index used the USDA-BAN-C-1 hedonic scale [19]. Chemical composition and sugar profiles were determined for this objective.

In addition, to evaluate the combined effect of cultivar, maturity stage, and cooking process on the glycemic index of plantains, a factorial experiment consisting of three factors: Cultivars, two maturity indexes, and four cooking processes (i.e., boiled, fried, steamed, baked) was implemented.

2.2. Materials

2.2.1. Sampling of plantains

To ensure adequate crop growth and development of the studied varieties, Maricongo, Maiden, and FHIA 20 cultivars were cultivated at the Juana Diaz Agricultural Experimental Station, according to the standard agronomic practices established in the *Conjunto Tecnológico para la Producción de Plátanos y Guineos* Guide, recommended by the Agricultural Experimental Station Mayaguez Campus. The soil was fertile, deep, and loose, with good drainage, and a pH between 4.5 and 5.5. For each variety, plantain trees were planted on four banks and two banks of free space were left between them. To guarantee plant uniformity, plants were left with bunches of six hands by removing hands when they were small to have enough room for the others to develop. Only complete plants were harvested, and marketable bunches were randomly selected across the field. Their appearance and size are the main criteria to exclude bunches from the randomized selection if they were cracked or stained.

Subsequently, bunches were taken from the plant by making a partial cut to the pseudo stem at half the height, so that the bunch slowly went down and thus, eliminate, or reduce the impact on the ground.

After collection, bunches were transported and processed in the pilot plant of the Food Science and Technology program of the University of Puerto Rico, Mayaguez Campus. Fruit production ranged from 58 to 62 fruits per bunch with an average weight of 213 to 314 g per fruit. All the fruits from bunches were selected and organized over wire shelving. Randomly, half of the fruits were selected and categorized as stage 1 of ripeness. To acquire plantains on stage 5 of ripeness, the rest of the samples in the green stage were stored unpacked over wire shelving at 20 °C until their peel reached a yellow skin (i.e., Maricongo, Maiden: 12–15 days; FHIA 20: 17–20 days).

The Ripeness of plantains was determined based on the banana ripening guide and color index numbers for banana ripening [19]. Stage 1 (Green) and stage 5 (Yellow with green tips) were selected because they are the most marketable and used stages for bananas and plantains in Puerto Rico. Most typical dishes in Puerto Rico such as “mofongo”, “tostones”, and “plátano hervido” are prepared from plantains at green stage; while “piñon”, “pastelón de plátano maduro” and “amarillitos” are made from fruits at stage 5.

2.2.2. Sample preparation

Flour preparation to evaluate the fruit composition followed the methodology described by Pérez-Donado et al. [20]. Samples were

dried in a forced-air dehydrator (Nesco Professional Food and Jerky Dehydrator, OH, USA) at 40 °C for 24 h. Dry samples were ground in a mill (Type C-1.5 hp, Glen Mills Inc, NJ, USA), sieved (600 μm and 1300 μm), and stored in packed bags at 5 °C prior to analysis.

Regarding the expected glycemic index determination, samples of each cultivar under the two stages of ripeness were subjected to each of the four cooking methods. For the sample preparation of this analysis, it is important that plantain was prepared as it is ingested. Therefore, the plantains were washed, the peel was removed, and they were cut into 3 cm-height pieces. Then, these pieces were subjected to the different cooking processes as follows.

2.2.2.1. Boiling process. Once the water reached boiling temperature, plantains were submerged for 10 min. Then, pieces were removed from the hot water, allowed to cool, and cut into slices of approximately 0.4 cm to be placed in a forced-air dehydrator (Nesco Professional Food and Jerky Dehydrator, OH, USA) at 40 °C. After 24 h of dehydration, slices were placed in an ultra-freezer (K221ULT K2 scientific, NC, USA) at −80 °C for 3 h (to cool them before the grinding process and prevent Maillard reaction) and then reduced in size in a coffee grinder (CBG110S, Black + Decker ®, MD, USA) to obtain a fine powder.

2.2.2.2. Steaming process. When the water reached a boil, plantains were exposed to hot steam for 15 min. Then, allowed to cool, and cut into slices of approximately 0.4 cm to be placed in a forced-air dehydrator at 40 °C. After 24 h of dehydration, slices were placed in an ultra-freezer at a temperature of −80 °C for 3 h and reduced in size in a coffee grinder to obtain a fine powder.

2.2.2.3. Frying process. When the oil reached a temperature of 180 °C, plantains were immersed in the hot vegetable oil (canola) for 3 min. When the time was up, pieces were removed from the oil, drained, allowed to cool, cut into slices of approximately 0.4 cm, and placed in a forced-air dehydrator at 40 °C. After 24 h of dehydration, slices were placed in an ultra-freezer at a temperature of −80 °C for 3 h before reducing their size in a coffee grinder to obtain a fine powder. This powder was defatted with ether in a Soxhlet system for 7 h.

2.2.2.4. Baking process. Plantains are placed on a tray in an oven forced-air mode (ECO2D, Vulcan, MD, USA) at 180 °C for 40 min. When the time was up, they were removed from the oven, allowed to cool, and cut into slices of approximately 0.4 cm to be placed in a forced-air dehydrator at 40 °C. After 24 h of dehydration, slices were placed in an ultra-freezer at a temperature of −80 °C for 3 h and reduced in size in a coffee grinder to obtain a fine powder.

All samples passed through a sieve to guarantee a particle size of less than 600 μm.

2.3. Methodology

2.3.1. Composition

Protein, fat, crude fiber, ash, and moisture contents were determined according to standard methods of AOAC [21]. The remaining carbohydrate fraction or non-nitrogen extract (i.e., other carbohydrates) was estimated by difference.

Starch content was determined according to a hydrolysis method [22]. Briefly, 50 mg of the sample was dispersed in 6 mL of 2 M KOH and incubated at room temperature. After 30 min, the dispersed sample was hydrolyzed using 60 μL of amyloglucosidase A7095 and incubated at 60 °C for 45 min with constant shaking. After incubation, samples were stored at 5 °C overnight to facilitate residue precipitation. 1.0 mL of supernatant was taken, and its glucose content was determined by the phenol-sulfuric acid method [23]. An aliquot was ten-fold diluted, and 1 mL of 5% phenol solution and 5 mL of concentrated sulfuric acid was added. The mixture was vortexed and incubated at room temperature for 20 min. The absorbance of the samples was read at a wavelength of 490 nm in a spectrophotometer (UV–3100PC VWR®, Matsonford, PA, USA). The starch content was calculated by equation (1):

$$Starch(\%) = \left(\frac{G \times 6 \times 100}{M} - G_i\right) \times 0.9 \quad (1)$$

Where G is glucose content in the supernatant, G_i is the initial sugar content of the sample, M is the weight of the sample and 0.9 is the conversion factor from glucose to starch.

Glucose content was determined using a standard calibration curve, prepared from standard glucose solutions. The regression coefficient of the equation used to calculate the sugar contents was 0.9994.

Mineral content (Ca, Mg, K, B, Mn, and P) was measured according to the method of Perkin Elmer [24] using an inductively coupled plasma-optical emission spectrometer (PE 7300 DV, MA, USA). For this purpose, samples were dried for 5 days at 60 °C, powdered, and placed in an open digestion system (DigiPrep Jr, SCP Science, Canada) with 3 mL of plasma pure 67–70% HNO_3 and diluted to 50 mL with Millipore water. Method validation was performed using a NIST 1570a certified reference material (95% recovery). A blank and a standard were read every 10 samples for QC/QA purposes.

2.3.2. Sugars profile of cultivars

Fructose, glucose, and sucrose content were determined using the ethanolic extraction method with some modifications [25]. Samples were subjected to extractions with different percentages of ethanol (0%, 40%, 50%, 60% & 70%: v/v) to guarantee the maximum extraction of sugars. Ethanol 50% showed the highest percentage of extraction (>99.78% of sugars extracted after four rinses in 50% ethanol; the number of rinses performed was five).

Samples of 0.5 g were placed in 50 mL centrifuge tubes, and 3.0 mL of ethanol 50% were added. Subsequently, tubes were vortexed

for 30 s, sonicated for 15 min, and centrifuged to 5000 rpm for 15 min. Supernatants were transferred to 15 mL centrifuges tubes. The extraction procedure mentioned above was done until reaching a volume of 15 mL. The supernatant was filtered through a 0.45 μm nylon filter for High-Performance Liquid Chromatography (HPLC) analysis.

Quantification of fructose, glucose, and sucrose achieved by HPLC equipment (Waters Corp., MA, USA) with a binary pump (Waters Model 1525), differential refractometer detector (40 °C) (Waters Model 410), and a Water Sugar Pack column at 90 °C conditioned with CaEDTA (50 mg/L) for 24 h. The mobile phase (CaEDTA, 50 mg/L) was previously filtered with a 0.45 μm Nylon filter and degassed under vacuum for 30 min with ultrasound. The temperature of the column was 90 °C, the elution method was isocratic, a flow rate of 0.5 mL/min, and a sample injection time of 20 min. Fructose, glucose, and sucrose content were determined using standard calibration curves, prepared from standard solutions of the studied sugars in the extractor solution (50% ethanol). The regression coefficient of the equation used to calculate the sugar contents was 0.9995. Two standard solutions of the studied sugars at 2500 and 25000 ppm in the extracting solution (50% ethanol) were read every 10 samples for QC/QA purposes.

2.3.3. In vitro *digestibility and determination of estimated glycemic index (eGI)*

Digestibility of samples was carried out according to a method that involved two hydrolysis processes: free glucose (FG), rapidly available glucose (RAG), and slowly available glucose (SAG) [26].

Reaction kinetics were described by equation (2):

$$C = C_{\infty}\left(1 - e^{-kt}\right) \tag{2}$$

Where C, C_{∞}, k, and t are the concentration at time t, the equilibrium concentration, the kinetic constant, and the chosen time, respectively.

These values were used to determine the hydrolysis index (HI), dividing the area under the curve (AUC) of samples between the AUC of white bread described theoretically. Subsequently, eGI was estimated using equation (3) [27]:

$$eGI = 39.71 + (0.54 \times HI) \tag{3}$$

The quantification of hydrolyzed glucose was achieved by HPLC as described for the profile of the sugars.

2.3.4. *Statistical analysis*

Analysis of variance (ANOVA) was applied with a 95% confidence level ($\boldsymbol{\alpha} = 0.05$). Significance and comparison of means were performed using Tukey's test with a maximum probability of rejection of 5% ($p < 0.05$). Additionally, Principal Component Analysis (PCA) was applied to analyze relationships among parameters. ANOVA was performed using InfoStat 2019 software (Cordoba, Argentina) and PCA using Microsoft Excel integrated with the Analyze-it® tool.

3. Results and discussion

3.1. *Composition*

Table 1 shows the proximal composition of the three cultivars under the two stages of ripeness. Regardless of cultivar and maturity index, the non-nitrogen extract was the major component while ash and crude fat were the lowest. Moisture content for both maturity

Table 1
Nutritional profiles of Maricongo, Maiden, and FHIA 20.

Component	Stage 1 - Green			Stage 5 - Ripe		
	Maricongo	Maiden	FHIA 20	Maricongo	Maiden	FHIA 20
Moisture (%)	59.60 ± 1.46^{a}	60.64 ± 0.81^{a}	70.05 ± 0.44^{b}	60.85 ± 2.51^{a}	62.21 ± 0.75^{a}	70.92 ± 2.21^{b}
Ash (%)	1.47 ± 0.13^{a}	1.72 ± 0.01^{b}	1.98 ± 0.07^{c}	1.96 ± 0.09^{a}	2.11 ± 0.12^{b}	2.48 ± 0.07^{c}
Crude Fat (%)	0.47 ± 0.04^{a}	0.32 ± 0.02^{b}	0.47 ± 0.05^{a}	0.54 ± 0.09^{ab}	0.56 ± 0.08^{a}	0.46 ± 0.05^{b}
Crude Protein (%)	2.62 ± 0.22^{a}	1.86 ± 0.32^{b}	3.01 ± 0.41^{c}	3.45 ± 0.41^{a}	2.72 ± 0.36^{b}	3.06 ± 0.00^{b}
Crude Fiber (%)	0.89 ± 0.07^{a}	0.93 ± 0.18^{a}	1.01 ± 0.23^{a}	0.64 ± 0.04^{a}	0.80 ± 0.06^{b}	0.75 ± 0.04^{b}
Non-nitrogen extract (%)	94.55	95.17	93.53	93.41	93.81	93.26
Starch content (%)	89.70 ± 1.65^{a}	93.40 ± 2.77^{ab}	91.40 ± 1.47^{b}	43.92 ± 1.74^{a}	60.82 ± 1.97^{b}	28.48 ± 1.84^{c}
Reducing sugars (%)	0.60	0.50	0.66	18.74	13.53	20.15
P (%)	0.06 ± 0.01^{a}	0.06 ± 0.00^{a}	0.06 ± 0.01^{a}	0.07 ± 0.01^{a}	0.08 ± 0.01^{a}	0.08 ± 0.02^{a}
K (%)	0.69 ± 0.05^{a}	0.79 ± 0.03^{a}	0.79 ± 0.10^{a}	0.88 ± 0.03^{a}	0.87 ± 0.05^{a}	1.01 ± 0.14^{a}
Mg (%)	0.09 ± 0.01^{a}	0.07 ± 0.00^{a}	0.08 ± 0.01^{a}	0.10 ± 0.01^{a}	0.09 ± 0.01^{a}	0.10 ± 0.02^{a}
Ca (%)	0.06 ± 0.01^{b}	0.04 ± 0.00^{a}	0.05 ± 0.00^{ab}	0.06 ± 0.01^{a}	0.06 ± 0.01^{a}	0.06 ± 0.01^{a}
Mn (μg/g)	2.83 ± 0.38^{b}	4.12 ± 0.09^{c}	1.77 ± 0.21^{a}	2.33 ± 0.15^{a}	4.40 ± 0.17^{b}	2.47 ± 0.42^{a}
B (μg/g)	7.33 ± 0.25^{b}	4.56 ± 0.03^{a}	7.63 ± 1.00^{b}	9.30 ± 0.95^{b}	5.93 ± 0.40^{a}	9.83 ± 1.12^{b}

Component percentages are expressed on a dry basis, except for moisture.
Values are means ± standard deviation.
Means with different letters in the same row and maturity stage differ significantly ($p < 0.05$).
Starch content at stage 1 was previously reported by Pérez-Donado et al. [20].

stages was within values heretofore reported, which ranged from 52.0 to 75.0% [1–3,6]. Maricongo and Maiden presented similarities in this parameter being their percentages in stage 1, 59.60% and 60.64%, respectively. FHIA 20 presented the highest moisture content in both stages, being this difference significant compared to Maricongo and Maiden values. Such differences could be attributed to variations in soil, climate, fertilization, and harvest conditions [28]. However, evaluated samples came from the same plot and received the same agricultural practices. Thus, under the same conditions, FHIA 20 has a significantly higher moisture content than Maricongo and Maiden. Ash contents at the green stage were in concordance with data reported in the literature (i.e., FHIA 20 1.98%, Maiden 1.72%, and Maricongo 1.47%). At stage 5, ash values were higher than at the green stage.

Plantains showed low crude fat content (i.e., 0.32–2.48%) depending on maturity stage and cultivar type. Protein content ranged from 1.86 to 3.01% for the green stage and 3.06 to 3.45% for the yellow stage. Similar values were reported for green and yellow stages for the Agbagba variety, 3.21 and 3.50%, respectively [3]. Meanwhile, other studies reported superior values for each stage (i.e., 5.09–5.18% for the green stage and 4.76–5.13% for the yellow stage) [4]. Comparing genotypes, FHIA 20 presented the greatest protein content (3.01%), followed by Maricongo (2.62%) and Maiden (1.86%). However, the maturity process implied an increase in the protein content for Maricongo and Maiden, but not for FHIA 20.

The content of reducing sugars was low at maturity stage 1 (i.e., 0.50–0.66%). However, content increased significantly at the yellow stage, FHIA 20 being the cultivar with the highest content (20.15%), followed by Maricongo (18.74%) and Maiden (13.53%). This increment is the result of the maturity process, which involves the activity of several enzymes responsible for starch breakdown and sugar formation [29].

Reducing sugars do not represent the total sugar content but reflect those sugars that possess an available carbonyl group to react with other oxidant molecules [30]. Also, this parameter could indicate the susceptibility level of starch to chemical or enzymatic hydrolysis [31]. FHIA 20 cultivar showed the greatest amount of reducing sugar and moisture content in the mature stage, thus, it is the most susceptible to enzymatic browning of the three cultivars. FHIA 20 had the appropriate conditions for browning, including the presence of polyphenol oxidase, a precursor of this type of reaction.

Starch was the most abundant carbohydrate and ranged from 89.70 to 93.40% and 28.48 to 60.82%, for stages 1 and 5, respectively (Table 1). In the green stage, the highest starch percentage corresponded to the Maiden cultivar (93.40%). For the mature stage, starch percentages decreased drastically, displaying values of 60.82, 43.92, and 28.84% for Maiden, Maricongo, and FHIA 20, respectively. The decrease in starch content is attributed to the ripening process, where the ethylene generated in respiration induces the activation of enzymes that catalyze the synthesis of glucose and fructose from starch [32]. Starch granules abundant in the first ripening stages experienced changes in their structure, from smooth to surfaces with striations, becoming deeper as maturity progresses [33]. The degradation of starch is initiated by the addition of phosphate groups catalyzed by the enzyme glucan water dikinase to disturb the glucans packing at the granule surface [34]. According to Smith, Zeeman & Smith [35], these groups may influence the packing of glucose polymers within the granule, therefore, the susceptibility of the granule's surface to be degraded by enzymes such as α-amylase and invertase. The latter is the main process responsible for starch breakdown at the late phases of fruit ripening and has been reported to increase during postharvest ripening. Subsequently, sucrose phosphate synthase is considered the determinant enzyme responsible for sucrose synthesis during ripening [36].

Mineral contents are depicted in Table 1. Potassium was the most abundant mineral in plantains (0.69–1.01%) regardless of maturity and cultivar, followed by magnesium (0.07–0.10%). Manganese had the lowest values (1.77–4.40 μg/g). This is in concordance with data observed in the literature [6]. Maricongo had higher values of potassium and boron at the yellow stage than at the green stage.

Similarly, Maiden exhibited an increase in phosphorous, magnesium, calcium, and boron contents from the unripe to the ripe stage. This behavior could be explained by the migration of minerals from the peel to the pulp when ripening [2]. In contrast, no mineral in FHIA 20 increased significantly from the unripe to the ripe stage.

3.2. Sugars profile

Sugars found in Maricongo, Maiden, and FHIA 20 appear in Table 2. Glucose, fructose, and sucrose were present in samples, agreeing with previous studies using alcoholic extractions of plantain and bananas [37]. At the green stage, the sugar content was lower (0.6–2.2%). Sugar content increases significantly during the maturity process [1]. FHIA 20 presented higher values for glucose and fructose contents than the other two cultivars in stage 1, while Maricongo exhibited the highest sucrose content in this stage. At the mature stage, FHIA 20 had the highest values for all analyzed sugars followed by Maricongo. Maiden exhibited the lowest values.

Table 2
Sugar profiles of Maricongo, Maiden, and FHIA 20.

Component	Stage 1 - Green			Stage 5 - Ripe		
	Maricongo	Maiden	FHIA 20	Maricongo	Maiden	FHIA 20
Glucose (%)	0.27 ± 0.00^{a}	0.24 ± 0.00^{b}	0.30 ± 0.00^{c}	9.02 ± 0.08^{a}	6.44 ± 0.28^{b}	9.65 ± 0.47^{a}
Fructose (%)	0.32 ± 0.01^{a}	0.25 ± 0.02^{b}	0.36 ± 0.01^{c}	9.72 ± 0.17^{a}	7.10 ± 0.30^{b}	10.51 ± 0.45^{a}
Sucrose (%)	0.67 ± 0.00^{a}	0.63 ± 0.00^{b}	0.49 ± 0.01^{c}	2.32 ± 0.09^{a}	0.94 ± 0.01^{b}	8.06 ± 0.26^{c}

Values are means ± standard deviation.
Means with different letters in the same row and maturity stage differ significantly ($p < 0.05$).

3.3. In vitro *digestibility and determination of estimated glycemic index (eGI)*

FG, RAG, and SAG of cultivars at two maturity stages and four cooking processes are depicted in Table 3. Comparing FG values among stages but within the same cooking process, it was observed that these values were lower at the green stage (0.43–0.96%) than at the yellow stage (5.15–18.80%) for all cultivars. At stage 1, FHIA 20 presented the highest FG values (0.70–0.96%) in each cooking process. Meanwhile, results were different at stage 5, where Maricongo had the greatest FG values (10.39–13.34%), except for the frying process where FHIA 20 showed a higher value (18.80%).

Examining FG data for cooking processes at the same maturity stage, the highest values at maturity stage 1 were observed for the boiling and steaming processes, ranging between 0.51 and 0.96%. In contrast, the same behavior was not observed at maturity stage 5. With few exceptions, FG values were superior for Maricongo (10.39–13.34%) and FHIA 20 (8.47–18.80%). It was not possible to establish a dependence of FG data on the cooking process.

Regarding RAG, stage 1 values were higher than for stage 5 within the same cooking process, ranging between 48.02 - 68.68% and 20.40–50.49%, respectively. Plantains at the mature stage have lower starch and higher simple sugars (glucose and fructose) contents than at the green stage. Consequently, RAG values will be lower (glucose from starch hydrolysis) and FG values higher for ripe plantains, as observed in this study. During stage 1 and within the same cooking process, RAG values were similar among cultivars for boiling (64.18–67.43%), frying (48.02–49.38%), and steaming (63.91–68.68%). However, baked Maricongo exhibited lower RAG (52.04%) compared to FHIA 20 and Maiden. These values are higher than reported for a snack elaborated with plantain flour, where the RAG value was 34.69% [38]. It is important to mention that the snack was cooked in a microwave oven at different times and conditions as herein described, which could explain the minor RAG content of the snacks.

At stage 5, significant differences were found within each cooking process, observing the highest RAG values in Maiden and FHIA 20 for boiling (48.79–50.49%) and baking processes (41.74–43.44%); Maricongo and Maiden for frying (46.15–46.79%); and Maiden for steaming (29.86%). Considering RAG values among the different cooking processes at the same stage, it was observed that the frying process exhibited the lowest value at the green stage. Meanwhile, these values were similar among cooking processes at the mature stage.

There were no significant differences among SAG values within each stage and the same cooking process. Neither were there significant differences in the SAG values of cultivars among the different cooking processes at the same stage of ripeness.

Figs. 1 to 8 depict the hydrolysis graphs of cooked cultivars at the two maturity stages. In general terms, similar hydrolysis patterns were observed for the green stage. In the first 20 min, the curve presented a higher slope, which indicates a greater amount of released glucose. From 20 to 60 min of hydrolysis, there is a slower release. After 60 min, curve flattening becomes evident. This 60-min hydrolysis pattern agrees with the one observed for the plantain-flour snack [38]. A similar pattern was observed at the ripe stage. Considerable glucose release is observed during the first 20 min. Between 20 and 120 min, glucose release slows down and flattens after 120 min.

Observing hydrolysis curves of samples corresponding to stage 1, it is inferred that there were similarities among the glucose release rhythms of cultivars in the process of boiling (Fig. 1), frying (Fig. 3), and steaming (Fig. 7). In contrast, Maricongo exhibited a

Table 3
In vitro digestibility of Maricongo, Maiden, and FHIA 20.

Cooking process	Maturity stage	Cultivar	FG (%)	RAG (%)	SAG (%)
Boiled	1 - Green	Maricongo	0.51 ± 0.01^{a}	67.43 ± 1.60^{a}	12.20 ± 3.67^{a}
		Maiden	0.75 ± 0.05^{b}	66.73 ± 1.31^{a}	12.02 ± 3.66^{a}
		FHIA-20	0.88 ± 0.07^{b}	64.18 ± 2.61^{a}	10.98 ± 1.17^{a}
	5 - Ripe	Maricongo	11.65 ± 0.16^{a}	39.73 ± 2.32^{a}	18.03 ± 8.47^{a}
		Maiden	7.20 ± 0.33^{b}	48.79 ± 0.70^{b}	12.41 ± 6.05^{a}
		FHIA-20	8.47 ± 0.31^{c}	50.49 ± 1.47^{b}	11.35 ± 1.29^{a}
Fried	1 - Green	Maricongo	0.43 ± 0.03^{a}	49.38 ± 0.95^{a}	20.36 ± 4.20^{a}
		Maiden	0.60 ± 0.05^{b}	48.09 ± 1.07^{a}	15.03 ± 2.05^{a}
		FHIA-20	0.70 ± 0.05^{b}	48.02 ± 4.19^{a}	19.97 ± 4.33^{a}
	5 - Ripe	Maricongo	5.15 ± 0.13^{a}	46.15 ± 2.12^{b}	9.84 ± 2.23^{a}
		Maiden	8.94 ± 0.23^{b}	46.79 ± 0.82^{b}	17.49 ± 1.19^{a}
		FHIA-20	18.80 ± 0.19^{c}	20.40 ± 2.71^{a}	12.37 ± 5.54^{a}
Baked	1 - Green	Maricongo	0.51 ± 0.02^{a}	52.04 ± 6.67^{a}	20.19 ± 8.08^{a}
		Maiden	0.47 ± 0.07^{a}	66.01 ± 2.35^{b}	19.46 ± 1.02^{a}
		FHIA-20	0.88 ± 0.02^{b}	64.86 ± 0.97^{b}	10.46 ± 0.87^{a}
	5 - Ripe	Maricongo	13.34 ± 0.34^{a}	22.06 ± 4.59^{a}	18.00 ± 4.81^{a}
		Maiden	8.93 ± 0.07^{b}	43.44 ± 1.20^{b}	11.40 ± 1.84^{a}
		FHIA-20	9.70 ± 0.24^{c}	41.74 ± 3.61^{b}	9.26 ± 3.78^{a}
Steamed	1 - Green	Maricongo	0.62 ± 0.01^{a}	68.68 ± 0.50^{a}	10.41 ± 0.86^{a}
		Maiden	0.66 ± 0.03^{a}	65.02 ± 1.04^{a}	11.99 ± 2.16^{a}
		FHIA-20	0.96 ± 0.01^{b}	63.91 ± 5.12^{a}	12.35 ± 7.54^{a}
	5 - Ripe	Maricongo	10.39 ± 0.18^{a}	41.75 ± 1.81^{c}	10.02 ± 1.92^{a}
		Maiden	7.95 ± 0.13^{b}	47.55 ± 0.88^{b}	13.73 ± 3.99^{a}
		FHIA-20	15.04 ± 0.25^{c}	29.86 ± 1.99^{a}	9.46 ± 3.90^{a}

Values are means ± standard deviation.
For each cooking process, means with different letters in the same column and maturity stage differ significantly ($p < 0.05$).

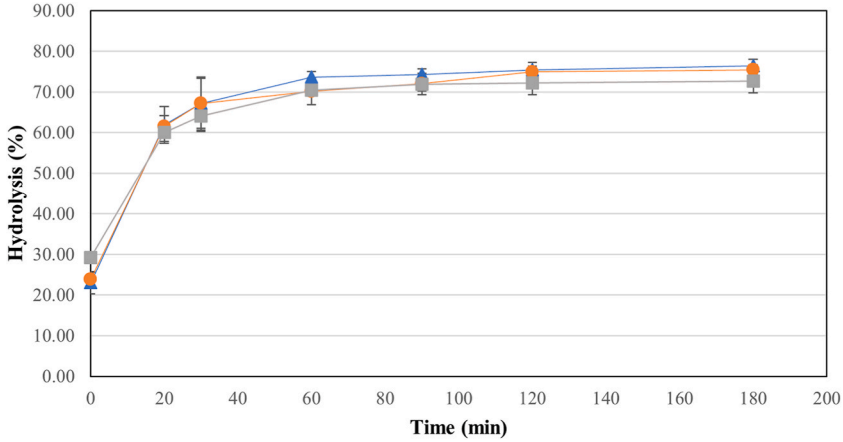

Fig. 1. *In vitro* hydrolysis curves of boiled plantains (▲) Maricongo (■) FHIA 20 (●) Maiden – Stage 1.

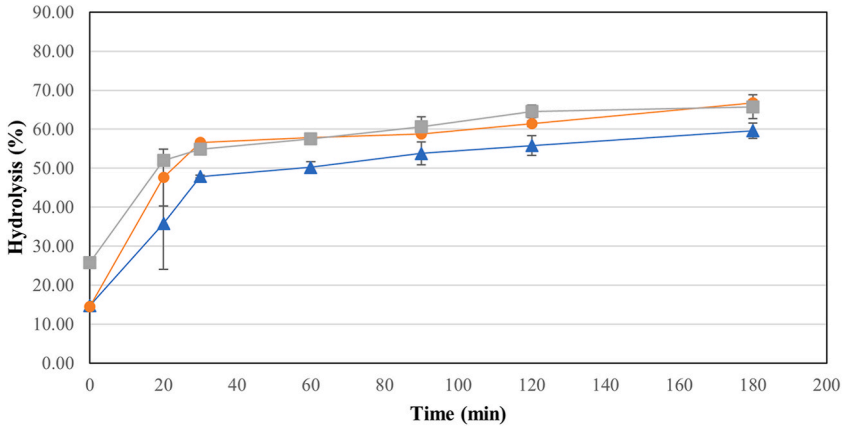

Fig. 2. *In vitro* hydrolysis curves of boiled plantains (▲) Maricongo (■) FHIA 20 (●) Maiden – Stage 5.

lower glucose release than the other cultivars when baked at stage 1 (Fig. 5). This behavior was also observed for stage 5 fried FHIA 20 (Fig. 4) and baked Maricongo (Fig. 6).

It is pivotal to consider that samples in this study were not starches, but dehydrated, defatted, and ground plantain pulp samples. Thus, a hydrolysis value close to the starch content of plantains presented in Table 1 cannot be reached. This pattern agrees with a study where the degree of starch hydrolysis for cooked flour plantain reached a value no higher than 50% [39]. The purpose of hydrolysis curves is to compare the hydrolysis ratio of starch present and the released glucose during *in vitro* digestion. To that end, hydrolysis curves were analyzed to determine the variation in the degree of hydrolysis concerning time. As result, equilibrium concentration (C_∞), kinetic constant (k), and hydrolysis index (HI) could be obtained to determine eGI. These values are depicted in Table 4.

Food can be classified into three categories: low glycemic index (<55), medium glycemic index (56–69), and high glycemic index (>70) [40]. Table 4 displays eGI values for each treatment. These values ranged from 58.54 to 90.72, falling into the medium and high glycemic index categories.

At stage 1, eGI medium values were observed in the fried plantain. This result agrees with a previous study where fried plantain showed the lowest glycemic index values, despite differences in methodology [16]. These results can be explained due to the oil interaction with food at high temperatures, resulting in complex hard-to-digest macromolecules from free carbonyl groups of sugars [41]. The highest eGI values were observed for the boiling process. A previous study presented different eGI values for cooked plantain at stage 1, where boiled, baked, and fried plantain presented values of 64.94, 56.87, and 64.93, respectively [14]. These differences can

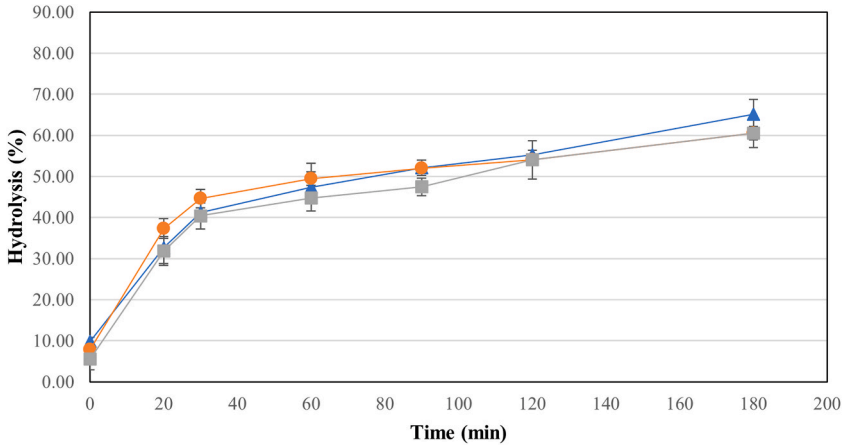

Fig. 3. *In vitro* hydrolysis curves of fried plantains (▲) Maricongo (■) FHIA 20 (●) Maiden – Stage 1.

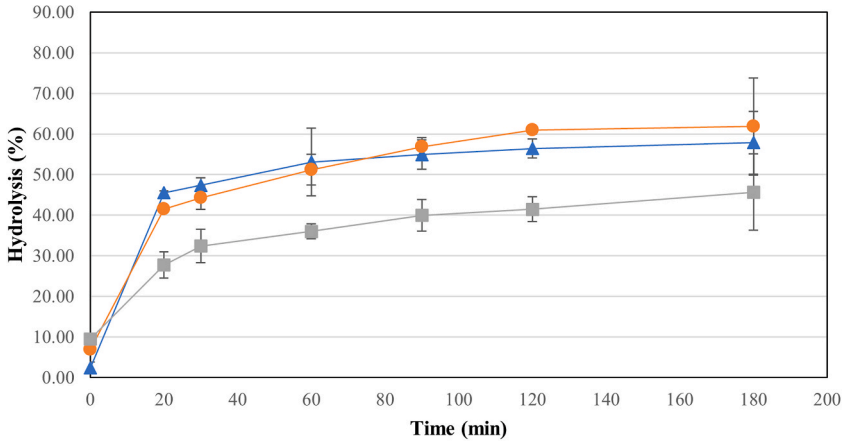

Fig. 4. *In vitro* hydrolysis curves of fried plantains (▲) Maricongo (■) FHIA 20 (●) Maiden – Stage 5.

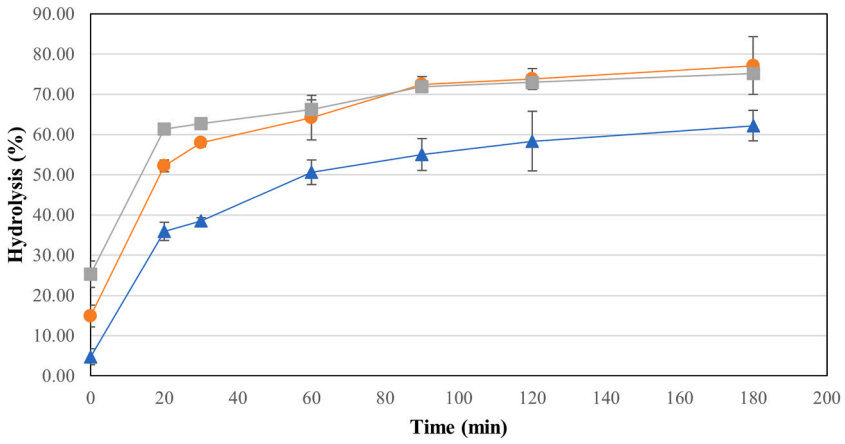

Fig. 5. *In vitro* hydrolysis curves of baked plantains (▲) Maricongo (■) FHIA 20 (●) Maiden – Stage 1.

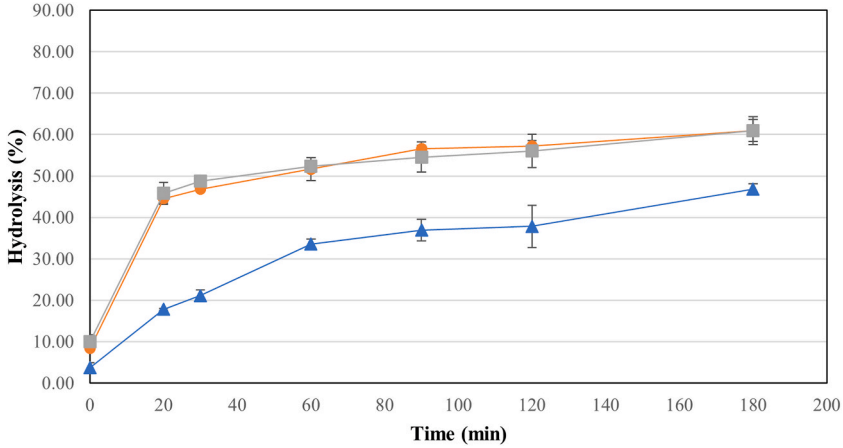

Fig. 6. *In vitro* hydrolysis curves of baked plantains (▲) Maricongo (■) FHIA 20 (●) Maiden – Stage 5.

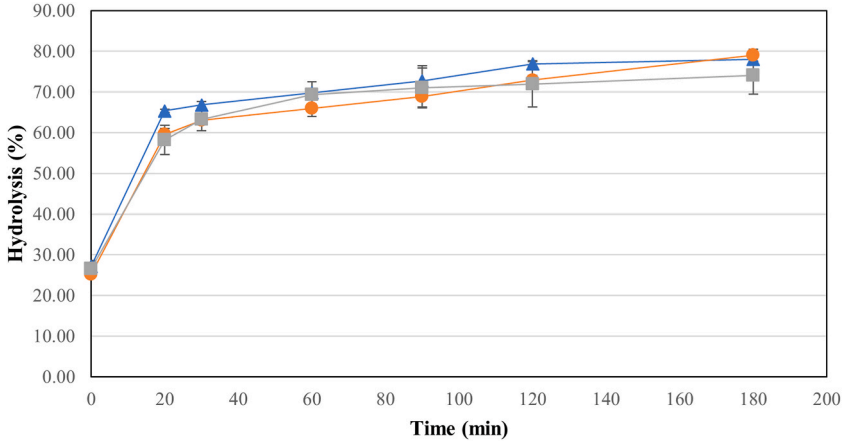

Fig. 7. *In vitro* hydrolysis curves of steamed plantains (▲) Maricongo (■) FHIA 20 (●) Maiden – Stage 1.

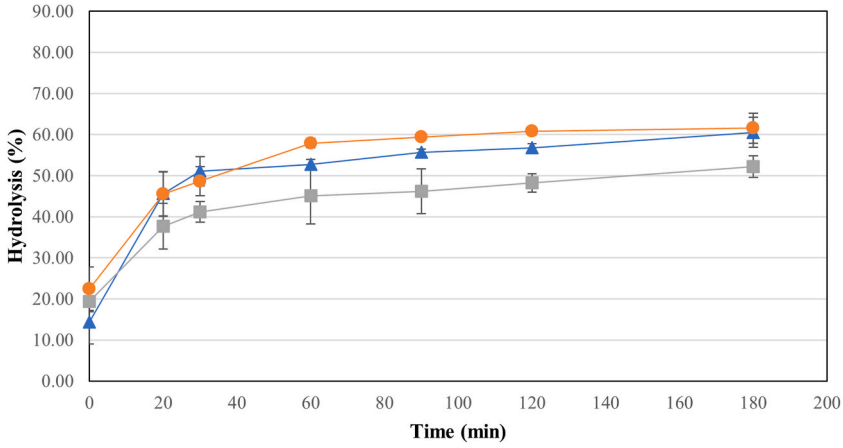

Fig. 8. *In vitro* hydrolysis curves of steamed plantains (▲) Maricongo (■) FHIA 20 (●) Maiden – Stage 5.

Table 4
Equilibrium concentration, kinetic constant, hydrolysis index, and estimated glycemic index of Maricongo, Maiden, and FHIA 20.

Cooking process	Maturity stage	Cultivar	C_∞ (%)	k	HI	eGI	eGI Classification
Boiled	1 - Green	Maricongo	76.43	0.028	90.76	89.54	High
		Maiden	75.42	0.033	92.91	90.72	High
		FHIA-20	72.63	0.034	89.88	89.06	High
	5 - Ripe	Maricongo	59.60	0.018	59.54	72.40	High
		Maiden	66.70	0.016	62.08	73.79	High
		FHIA-20	65.75	0.020	68.91	77.54	High
Fried	1 - Green	Maricongo	65.10	0.013	49.64	66.97	Medium
		Maiden	60.51	0.016	56.09	70.50	High
		FHIA-20	60.51	0.014	49.21	66.73	Medium
	5 - Ripe	Maricongo	57.85	0.023	63.70	74.67	High
		Maiden	61.85	0.023	68.79	77.48	High
		FHIA-20	45.67	0.016	41.23	62.35	Medium
Baked	1 - Green	Maricongo	62.16	0.016	56.88	70.94	High
		Maiden	77.12	0.021	81.78	84.61	High
		FHIA-20	75.14	0.019	75.28	81.04	High
	5 - Ripe	Maricongo	46.90	0.015	34.30	58.54	Medium
		Maiden	60.97	0.015	53.45	69.06	Medium
		FHIA-20	60.97	0.015	53.73	69.21	Medium
Steamed	1 - Green	Maricongo	78.08	0.020	80.65	83.99	High
		Maiden	79.03	0.013	60.27	72.80	High
		FHIA-20	74.11	0.024	82.82	85.18	High
	5 - Ripe	Maricongo	60.51	0.018	60.44	72.89	High
		Maiden	61.53	0.014	49.04	66.63	Medium
		FHIA-20	52.20	0.015	45.77	64.84	Medium

be attributed to cultivar type, food morphology, cooking parameters, and implemented methodology. Despite differences, in both studies, the highest glycemic index values were for the boiling process.

The lowest eGI values were exhibited at the mature stage. Remarkable low eGI values include Maricongo in the frying process (eGI 58.54), FHIA 20 in the frying process (eGI 62.35), and FHIA 20 in the steaming process (eGI 64.84). At the mature stage, the boiling process had the highest eGI values as well. It is noticeable that the boiling process exhibits the greatest eGI values for both stages. This could be attributed to the use of water in the cooking process that allows a higher degree of starch gelatinization which makes it more susceptible to enzymatic attack and a higher glucose release rate.

Frying showed the lowest eGI values overall. This corroborates with previous findings where food processed by frying displayed lower values of *in vivo* GI for plantain, sweet and Irish potatoes, despite differences in methodologies [42]. However, it is important to consider the implications of consuming fried products due to the high-fat content, which represents higher calorie intake in the diet.

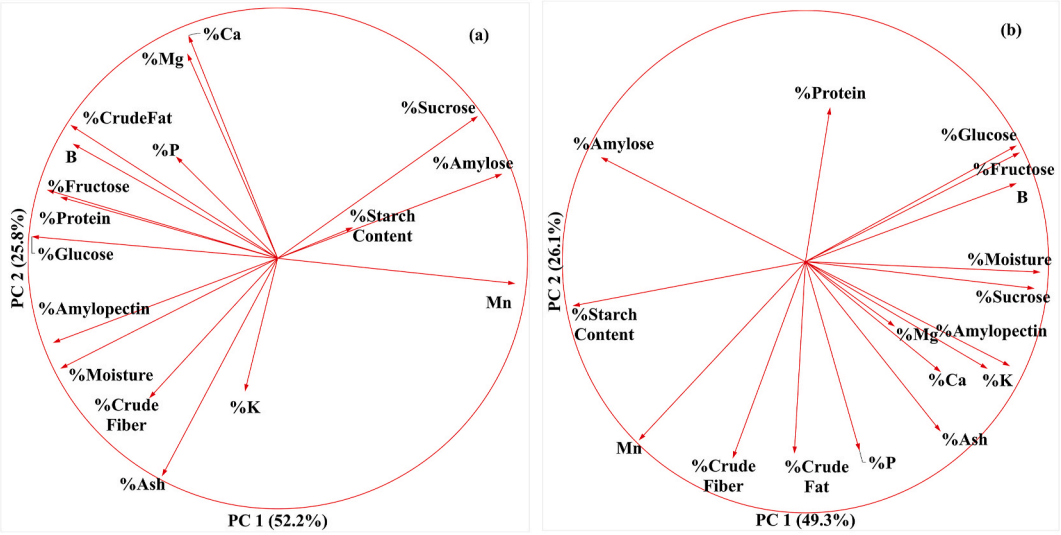

Fig. 9. Principal Components Analysis of the composition of plantain cultivars – (a) Stage 1; (b) Stage 5.

3.3.1. Pearson's correlation coefficients and PCA

A Pearson correlation matrix was determined to identify which variables were most highly correlated with others (Supplementary material). Considering the nutritional composition of cultivars, significant correlations were presented. Strong negative correlations between starch content and sucrose ($r = -0.945$), glucose ($r = -0.928$), and fructose ($r = -0.941$) were observed at stage 5 while this trend was not observed at stage 1. This can be explained by the fact that starch is metabolized and degraded as maturity progresses, which is reflected in the increment and synthesis of sugars such as glucose and fructose. In contrast, fructose and glucose displayed a high positive correlation ($r > 0.942$) between them regardless of the maturity stage.

After reducing the dimensionality of the data, PC1 and PC2 accounted for 78.0% and 75.5% of the variability of stage 1 and stage 5 datasets, respectively. For stage 1, glucose, and fructose content, as well as moisture, protein, ash, and fat contents are the main parameters contributing to the PCA, while starch P, K, and starch contents influenced the least (Fig. 9). For stage 5, glucose, fructose, moisture, and starch contents contributed the most to data variability. In contrast, protein and most minerals were minor contributors at this maturity stage.

PCA biplots were built to understand the similarities between observations and establish which of the studied cultivars presented more similarities with Maricongo based on their nutritional composition (Fig. 10). In this figure, parameters were represented as axes, cultivar means as points, and distances between points represent the similarity between them. When comparing cultivars at the same maturity stage, distances among their mean points are noticeable. However, some remarks were noted when making orthogonal projections upon the axes.

In stage 1, parameters such as glucose, Mn, fructose, and protein contents mostly defined the distances among cultivars (Fig. 10a). Since these variables were responsible for the major contributions to PCA determination and differed among cultivars, the location of means points in the graph was distantly located. In variables such as starch, amylose, and sucrose, Maricongo and Maiden projection upon their axes were closely situated.

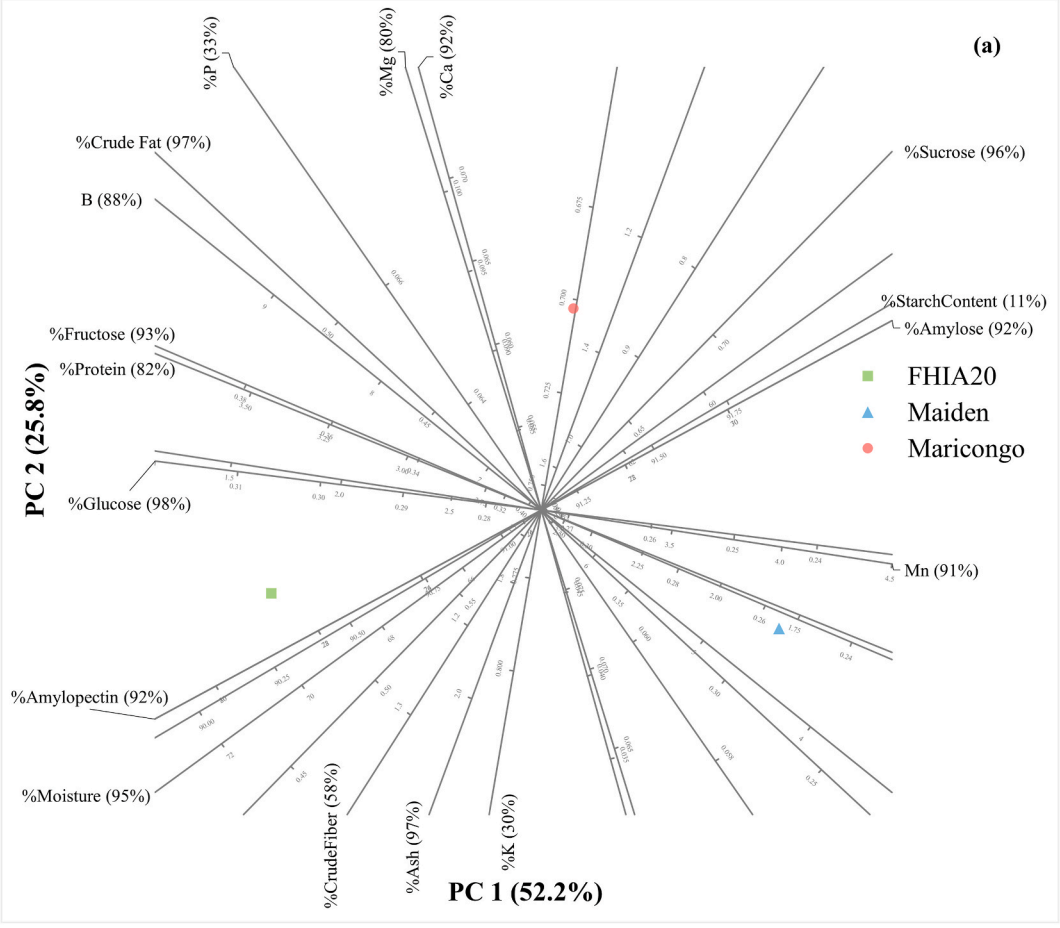

Fig. 10. PCA biplot of the nutritional composition of plantains (●) Maricongo (■) FHIA 20 (▲) Maiden – (a) Stage 1; (b) Stage 5; (c) Both stages.

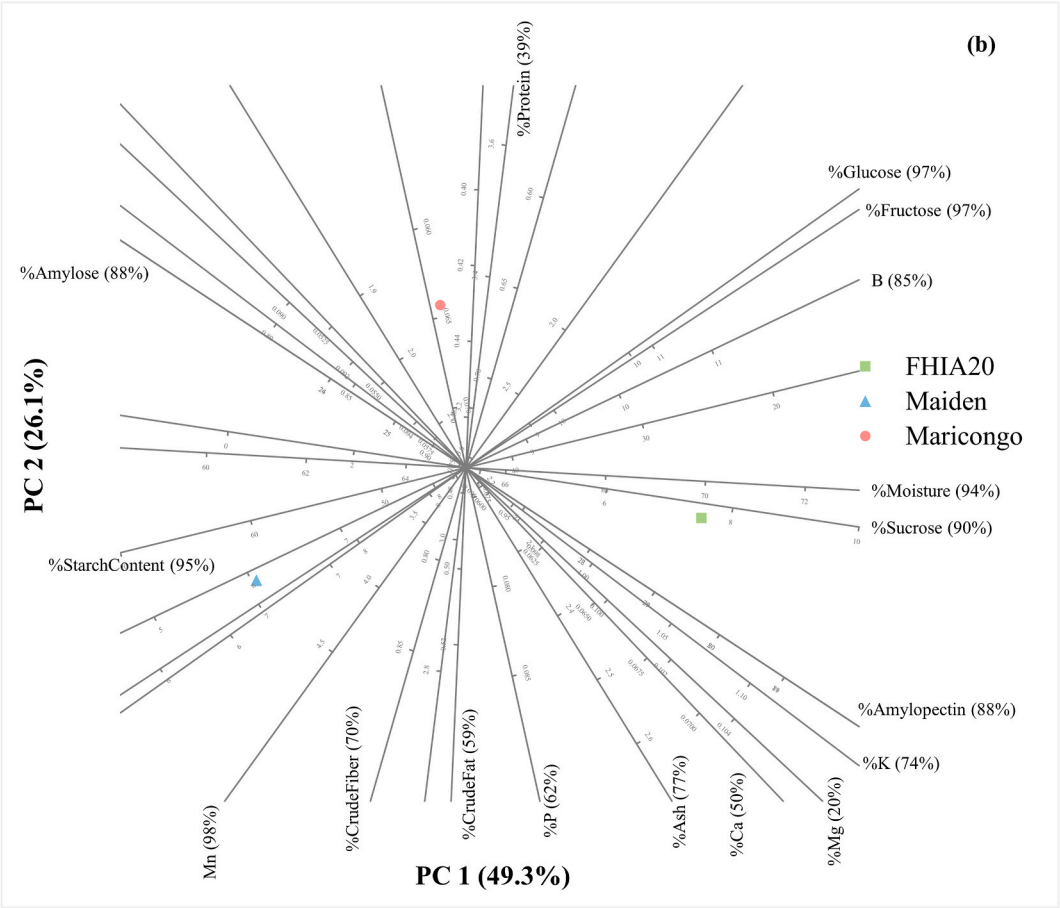

Fig. 10. (*continued*).

In stage 5, point projections of Maricongo and Maiden mean values upon moisture, sucrose, amylopectin, and amylose content axes (data already published but considered for this analysis) are closely placed in the biplot while projections upon glucose and fructose axes were distantly located (Fig. 10b) [20]. When all data were considered regardless of stages, Maiden and Maricongo were closer together than FHIA 20 (Fig. 10c). Despite differences in the proximal composition of cultivars, Maiden and Maricongo have displayed similarities in terms of starch properties according to the results obtained in the first part of this research [20]. Plantain is a starchy crop, and parameters such as amylose, and amylopectin contents, thermal properties, and morphology of the starch granules influence its functional properties and cultivar behavior during food processing.

Regarding the *in vitro* digestibility properties, PCA biplots of the FG, RAG, and SAG fractions were built and presented in Fig. 11. Distances among boiled cultivars at stage 1 of ripeness were reduced, while Maricongo boiled at stage 5 was visibly separated from the others in this same cooking process. Baked Maricongo and Maiden were closely located in the graph while FHIA 20 was more distant at stage 1. Fried green cultivars were close to each other although Maricongo and Maiden were more closely located in the PCA biplot, and steamed cultivars at stage 1 were similar based on their digestibility. In contrast, fried stage 5 cultivars were separated across the plot. Trends varied between cultivars across maturity stages and cooking methods. However, Maiden and Maricongo were closely located for most treatments (Stage × Cooking method).

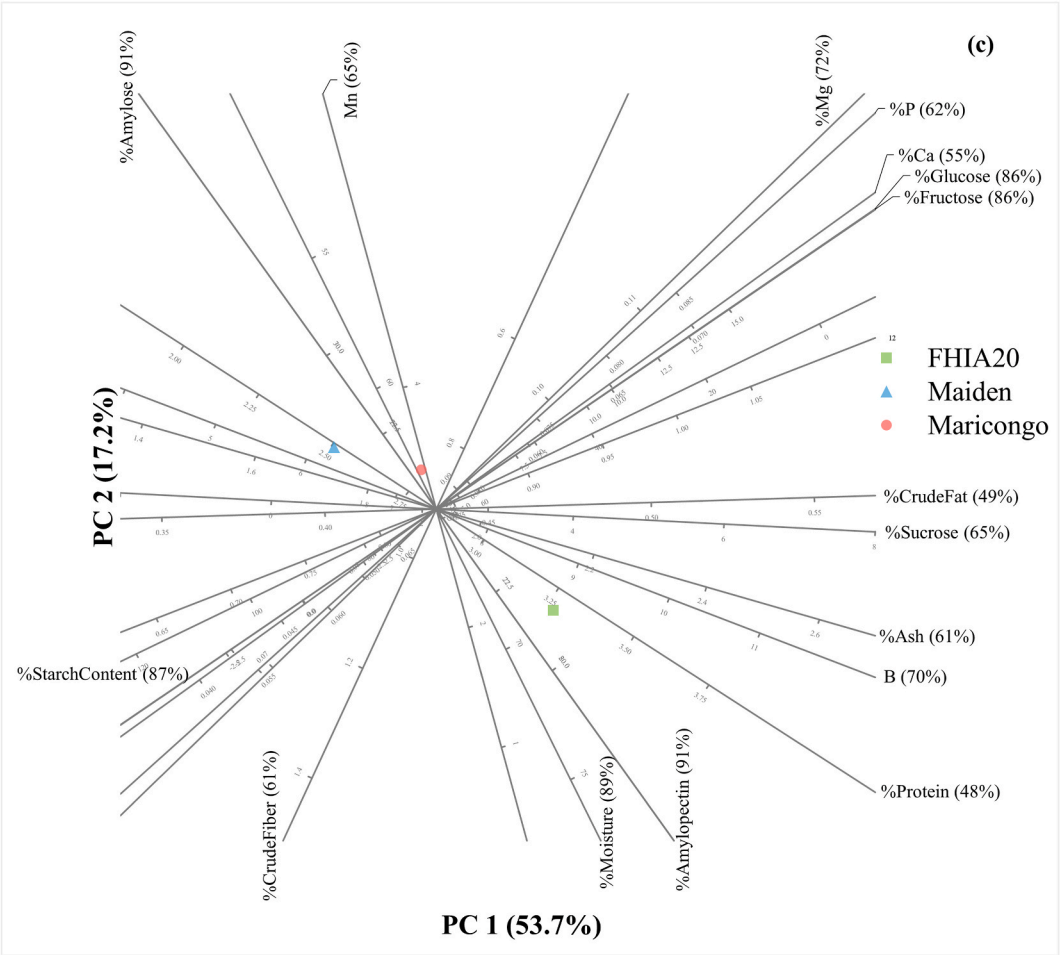

Fig. 10. (*continued*).

4. Conclusion

The physicochemical characterization of the different cultivars studied allowed us to identify possible varieties that could substitute Maricongo. The maiden cultivar had some similarities with Maricongo in terms of nutritional content. FHIA 20 showed differences with the other two varieties studied.

Regarding starch digestibility properties and glycemic index, eGI values were similar between varieties for the same cooking process. However, differences were observed between the stages studied, where stage 5 showed lower eGI values due to its lower starch content. In terms of cooking processes and maturation stages, it is important to highlight the baking process as the first cooking alternative. It presented properties that reflect a lower glycemic impact and, therefore, constitutes a healthier option to include in the diet.

According to the results of the present investigation, Maiden could constitute a potential option to replace Maricongo, since similarities were found in composition and nutritional properties. Other aspects such as non-microbiological shelf life, processing characteristics, and sensorial evaluation of the cultivars also need to be considered, given that nutritional profile is not the only factor that determines the acceptability of cultivars in the Puerto Rican market. However, these aspects are outside the scope of the present work.

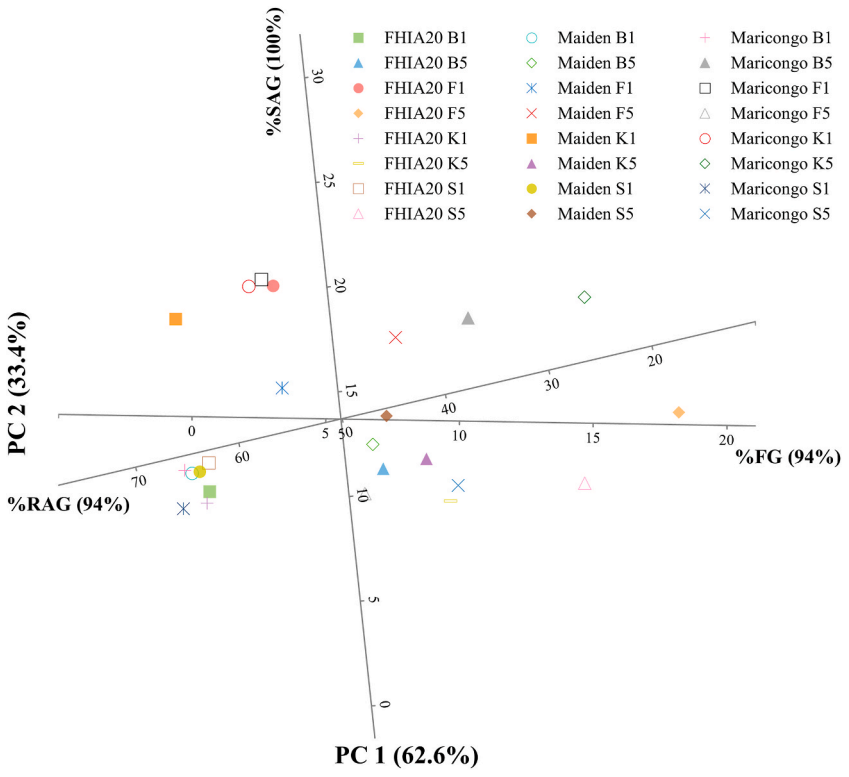

Fig. 11. PCA biplot of *in vitro* digestibility properties of Maricongo, FHIA 20, and Maiden. B: Boiled; F; Fried; K; Baked; S: Steamed.

Declarations

Author contribution statement

Carmen E. Pérez-Donado: Conceived and designed the experiments; Performed the experiments; Analyzed and interpreted the data; Wrote the paper. Fernando Pérez Muñoz, Rosa N. Chávez-Jáuregui: Conceived and designed the experiments; Contributed reagents, materials, analysis tools or data; Wrote the paper. Data availability statement: Data will be made available on request.

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Additional information

No additional information is available.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Fernando Perez Munoz reports financial support was provided by National Institute of Food and Agriculture.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.heliyon.2023.e17563.

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