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Effect of pretreatments and drying methods in the quality attributes of fortified yam flour (*Dioscorea rotundata*)

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Abstract

Yam is consumed in tropical regions because it is a good source of carbohydrates, proteins, fiber, and micronutrients, together with several alternatives of consumption such as cooked, boiled, roasted or fried. Its use for the development of flours and subsequent fortification has been considered as an alternative to address micronutrient deficiencies that have irreversible physical and cognitive consequences to child population. The aim of this study was to evaluate the effect of pretreatments (precooking and dipping) and drying methods (convection and vacuum) on the quality attributes of pretreated yam flour as well as the stability during storage after fortification with iron, calcium, and vitamin A. The results show that gelatinization temperature ranged from 79.2 to 86.0 °C and precooking led to changes on pasting properties where values of maximum viscosity and retrogradation diminished. The drying methods favored the protein concentration on the surface of the granules, reducing the solubility and hydration of the samples. With the fortification, the lightness decreased from 72.29 to 66.64 due to the addition of iron. The presence of molecular oxygen conditioned the oxidative degradation of vitamin A. Precooking caused greater colloidal stability and convection drying preserved on the nutritional quality of the flour.

Keywords: *Dioscorea rotundata*; flour; micronutrients; viscosity; stability.

Practical applications: Yam flour fortification can be a low-cost alternative to address micronutrient deficiencies.

1 Introduction

Yam (*Dioscorea spp.*) is a traditional consumption crop with cultural, economic and nutritional importance in many African, Americas and Oceania countries (Abiodun & Akinoso, 2015). According to the Food and Agricultural Organization, in 2019, global yam production accounted for 74.4 million tonnes. In America, Colombia is the largest producer with a production of 380 thousand tonnes being *D. rotundata* one of the most widely distributed species in the Caribbean region, due to both the area harvested and the demand for the tuber (Unidad de Plantificación Rural Aropecuaria, 2019; Food and Agriculture Organization of the United Nations, 2021). Nutritionally, it is a good source of starch, protein, fiber and minerals such as iron, calcium and phosphorus (Kayode et al., 2017; Zhou & Kang, 2019; Duan et al., 2020).

This tuber, as raw material, is marketed only for fresh consumption and, due to overproduction, it is necessary to seek strategies that reduce post-harvest or economic losses for producers by means of transformation and agroindustrialization (Adegunwa et al., 2011; Adejumo et al., 2013). To extend its useful life, processing technologies have been studied in flour obtention, such as pretreatments and drying methods that determine its nutritional and physicochemical quality (Akissoé et al., 2003; Correia & Beirão-da-Costa, 2012; Falade & Onyeoziri, 2012; Hemery et al., 2019). The pretreatments to minimize the action of the polyphenoloxidase enzyme include the exclusion of oxygen, the application of acidulants, thermal inactivation and the use of inhibitors such as sulfite (Salazar & Marcano, 2011; Harijono et al., 2013; Obadina et al., 2014; Suriya et al., 2016). Regarding dehydration processes, alternative methods to conventional convective have been evaluated, including vacuum-, freeze- and microwave-drying, and the use of these depends on factors such as energy, efficiency and cost, as well as those associated with the loss of nutrients and oxidation of the tuber (Hsu et al., 2003; Jimoh et al., 2009; Adegunwa et al., 2011; Chen et al., 2017; Li et al., 2019; Guan et al., 2019).

On the other hand, as it is regarded as staple food and is massively consumed, flour is considered one of the most suitable vehicles to reduce vitamin and mineral deficiencies when they are identified as public health problems (Akhtar et al., 2011; Hemery et al., 2018). One of the most effective alternatives to address this need has been a fortification, defined as the addition of one or more deficitary micronutrients to a food called transport or *carrier,* which must be selected based on the population's eating habits or population group considered as being at risk (Boccio & Monteiro, 2004; Awoyale et al., 2015). However, the stability of the fortifiers can be affected by uncontrolled conditions during processing, long storage times, exposure to light, type of packaging (oxygen and moisture permeable, or not), composition of the micronutrient premix and interaction between components of the premix (Hemery et al., 2019).

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Colombia is among the ten countries in the world with the highest yam production, however, there is a severe technological gap in terms of its level of agroindustrialization, and its production is concentrated in areas of high nutritional deficiencies (Food and Agriculture Organization of the United Nations, 2021). In addition, the development of new products has a strategic goal in the food industry, because consumers are increasingly demanding goods with a high nutritional component that provide health benefits, particularly to child population. Therefore, the objective of this study was to evaluate the effect of pretreatments (precooking and dipping) and drying methods (forced convection and vacuum) in the production of yam flour through proximal and physicochemical properties, including stability during storage after fortification with iron, calcium, and vitamin A.

2 Materials and methods

2.1 Yam flour processing

The flour was obtained from yam (*Dioscorea rotundata*) harvested in the municipality of San Juan Nepomuceno (Colombia/South America), located at average altitude of 200 meters above sea level with mean temperature of 27 ± 2 °C, mean annual precipitation of 750 mm and mean relative humidity of 80 ± 5%. The yam was selected free of bruises, bumps and microbiological alterations, following the Colombian Technical Standard – NTC 1269 (ICONTEC, 1976).

The vegetal material was washed, peeled and chopped into approximately 3.0 mm thick slices and pretreated by two ways: the first consisted of heating the material at 75 °C for 10 min (precooking) in a thermostatic bath (Memmert WNB 14, Schwabach, Germany), and the second, of a dipping process using 1% (w/v) citric acid monohydrate (≥99.5%, Sigma-Aldrich) aqueous solution for 10 min, as performed by Abiodun et al. (2014) and Salazar & Marcano (2011), respectively.

The pretreated samples (400 g total weight) were subjected to two drying processes: one by way of tunnel type forced convection at 50 °C, with an air speed of 1.0 m/s and drying area of 1080 cm^2, and another by way of vacuum oven (Memmert VO 200, Schwabach, Germany), at 40 °C, 10 mbar and drying area of 885 cm^2. Subsequently, a grinding process under cooling (liquid nitrogen) was carried out, using a hammer micro-mill (Willye TE-650, Piracicaba, Brazil) and sieving until a particle size of 180 µm was achieved. The unpretreated samples (native flour) were used as control.

2.2 Flour fortification

Fortification was defined, following the daily intake requirements for children above six-month age and younger than four years, established in Resolution 333 of 2011 by the Colombian Ministry of Health and Social Protection. The mixing of the fortifiers with the flour was carried out according to the procedure suggested by Hemery et al. (2018), with slight modifications. Ferramin (Ferrous Fumarate) with a concentration of iron at 13% (w/w), vitamin A with a minimum concentration of 250000 IU/g and tricalcium phosphate with a concentration of calcium at 40% (w/w) were used. All of these were supplied by Tecnas S.A., Medellín, Colombia.

2.3 Fourier transform infrared spectroscopy (FT-IR)

The formation of the crystals was done by mixing 1.0 mg of flour with KBr in a ratio of 1:200 (flour: KBr), using a pressure of 220.63 bar. A Fourier transform infrared spectrometer (Shimadzu IRTracer-100, Kyoto, Japan) was operated a 20 scanner/s in the range of 4000 to 500 cm^{-1}. Thirty-two readings were made at a resolution of 8 cm^{-1} and the spectra were processed with the PerkinElmer Spectrum ™ program., version 9.0.

2.4 Scanning Electron Microscopy (SEM)

The morphological features of the flour samples were examined with a scanning electron microscope (JSM-6490LV, Jeol, Japan), using the method reported by Chen et al. (2017). The samples were fixed on a sample holder with electro-conductive carbon tape and covered with gold alloy. The observation conditions were established at 20 kV and 30 mA. The images of the flour granules were captured at a magnification of 1000X.

2.5 Determination of pasting properties

The viscosity profile of the yam flour dispersions was determined according to the methodology proposed by the American Association of Cereal Chemistry (2000) using a rheometer (MCR 302, Graz, Austria). 2.0 g of sample on a dry basis, dissolved in 25 mL of distilled water, were deposited in an aluminized sample holder. The temperature at 50 °C was maintained for one minute, then gradually increased up to 95 °C for 7.5 min, kept at 95 °C for 5.0 min, cooled to 50 °C after 7.5 min and finally, it was kept at 50 °C for 2 min. The rotational speed of the spindle (ST24-2D/2V, Graz, Austria) was 960 rpm during the first 10 s, allowing the starch suspension to be uniformly dispersed, and then was reduced to 160 rpm for the rest of the experiment (Montoya et al., 2012). Values of gelatinization temperature, peak viscosity, final viscosity, breakdown and setback were analyzed from viscoamilograph and used to define the optimum fortification.

2.6 Determination of thermal properties

The analysis was performed using a differential scanning calorimeter (DSC Q2000, New Castle, USA) similar to that developed by Yu et al. (2021). In an aluminum capsule with a capacity of 40 µL (Tzero Hermetic Lids 100/PK - Tzero Pans 100/PK), 3.5 mg of the sample was weighed, and distilled water was added to obtain a suspension at 70% (w/v). The capsules were hermetically sealed, allowed to stand for 4 hours at 25 °C, and subjected to a heating rate of 10 °C/min from 25 to 100 °C. The thermograms obtained were analyzed using the Universal Analysis Advanced E-Training 2000 software, TA Instruments. The gelatinization temperatures including onset temperature (To), conclusion temperature (Tc), and enthalpy of gelatinization (ΔHgel) were recorded from each endotherm.

2.7 Proximal and physicochemical properties

The quantification of the minerals was performed by atomic absorption spectrophotometry as proposed by Oyeyinka et al. (2018). The protein, fiber and crude fat content of the yam flour were established under the protocols of the American Association of Cereal Chemistry (2012), as well as the moisture content (X_w) and ash of the fortified treatments. The water activity (a_w) was determined with a dew point hygrometer at 25 °C (AquaLab 4TE, Washington, USA) (Cortés et al., 2007) and the color measurement (CIELAB method) was performed by using a spectrophotometer (Minolta CR-400, New Jersey, USA) integrated with the SpectraMagic NX software, considering the illuminant D65 and the 2° observer angle, where the values of the coordinate system were expressed as L* (luminosity), a* (green-red chromaticity) and b* (blue-yellow chromaticity) (Hunter Associates Laboratory, 2001). The water solubility index (WSI), water absorption index (WAI) and swelling power (SP) were calculated as suggested by Salcedo et al. (2016) and the water absorption capacity (WAC), according to the method described in the Association of Official Agricultural Chemists (2012).

Stability during storage was estimated for 30 days under controlled conditions of temperature and relative humidity (25 ± 1 °C, 75 ± 2%). The product was packed in low-density polyethylene bags with zip-lock closure and stored in a stability chamber (ICH 260, Schwabach, Germany). Variables such as X_w, ash, a_w, color, WSI, WAI, SP and WAC, were measured on days 0 and 30 of storage. The analyzes were performed in triplicate for the control treatment and the fortified resulting optimum.

2.8 Statistical analysis

The results of the pasting properties of yam flour were compared under a categorical multifactorial design, considering the applied pretreatment (precooking and dipping) as the first factor and as the second factor, the drying method (forced convection and vacuum), with a total of 4 treatments. All treatments were performed in triplicate (12 runs). The analysis of variance (ANOVA) and the mean comparison (Fisher's test) at 5% significance level were performed using the Statgraphics Centurion XVI software (Version 16.1.18).

3 Results and discussion

3.1 FT-IR spectroscopy

Since the main component of flour is starch, FT-IR spectroscopy has been used to identify localized arrangements of the polymeric chains. In Figure 1 it is observed that both the shape, position, and intensity of the absorbance bands of the pretreated yam flours were similar to their respective controls (native flour). The typical region of 3600 to 3100 cm^{-1} reflects the stretching vibrations of (O-H) hydroxyl groups and indicates the hydration of the samples (Salcedo et al., 2016). Because changes in intensity were not visualized in the pattern of the band, it is induced that the loss of water molecules during the drying process is not influenced by the applied pretreatments. Also, in the 1620 cm^{-1} signal assigned to the amide I group (predominantly C=O), no alterations revealing the denaturation of the protein contained in the flour were detected (Kong & Yu, 2007; Amador-Rodríguez et al., 2020; González et al., 2021).

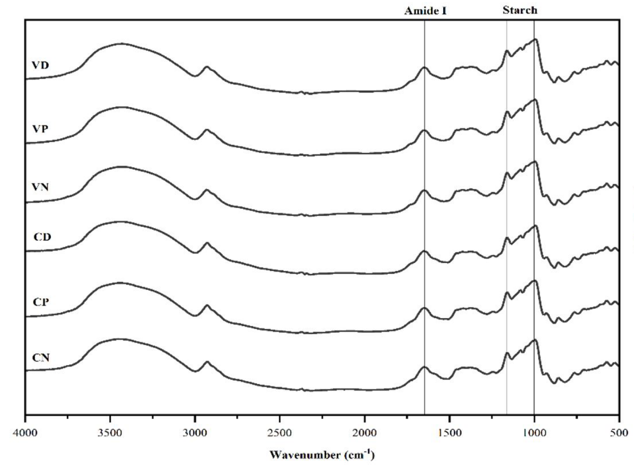

Figure 1. Fourier transform infrared spectroscopy of yam flour. (CN) Native - convective, (CP) Precooking - convective, (CD) Dipping - convective, (VN) Native - vacuum, (VP) Precooking - vacuum, (VD) Dipping - vacuum.

The absorption peaks from 1150 to 800 cm^{-1} associated with the symmetric stretching of C-C, C-OH and C-H allow the identification of the starch fingerprint and to monitor the variations in amylose and amylopectin molecules (Li et al., 2019). The low intensity band at 845 cm^{-1} corresponds to the C-1-H(α) configuration and has been ascribed to the skeletal mode involving the α-D-(1→4) glycosidic bond (Wiercigroch et al., 2017). The peak at 991 cm^{-1} is attributed to the single helix crystal structure of starch, accompanied by bands at 928, 1076 and 1149 cm^{-1} that show the ring and bending modes of COH, [β(COH)], and [ν(COC), ν(CC)] in glycosidic linkages, respectively (Chen et al., 2017). The above suggests that, although it is possible to detect the carbohydrate region in the flours obtained, there are no appreciable changes in the spectroscopic patterns that indicate the modification of the external molecular order of the granules by the applied treatments.

3.2 Granule morphology

With the SEM micrographs, the morphology of the yam flour particles (Figure 2) was observed, being oval, ellipsoidal and, to a lesser extent, ovoidal (Moorthy, 2002; Zhou & Kang, 2019). Most of the flour granules (native and pretreated) presented a material adhered to their surface associated with the migration of the surfactant protein favored by the drying process, as a result of the concentration of high molecular weight compounds with less diffusivity in the crust of it (Bhandari, 2013).

In fact, an irregular structure was evidenced by the possible melting of the starch crystallites attributed to incipient gelatinization during precooking or by thermal fracture in response to the higher drying temperature used by convection (Figure 2 CP, CD) and with a rough appearance due to the aggregation of some granules that were cemented by the protein matrix, as well as by the presence of fiber and fat (Figure 2 VP, VD), analogous

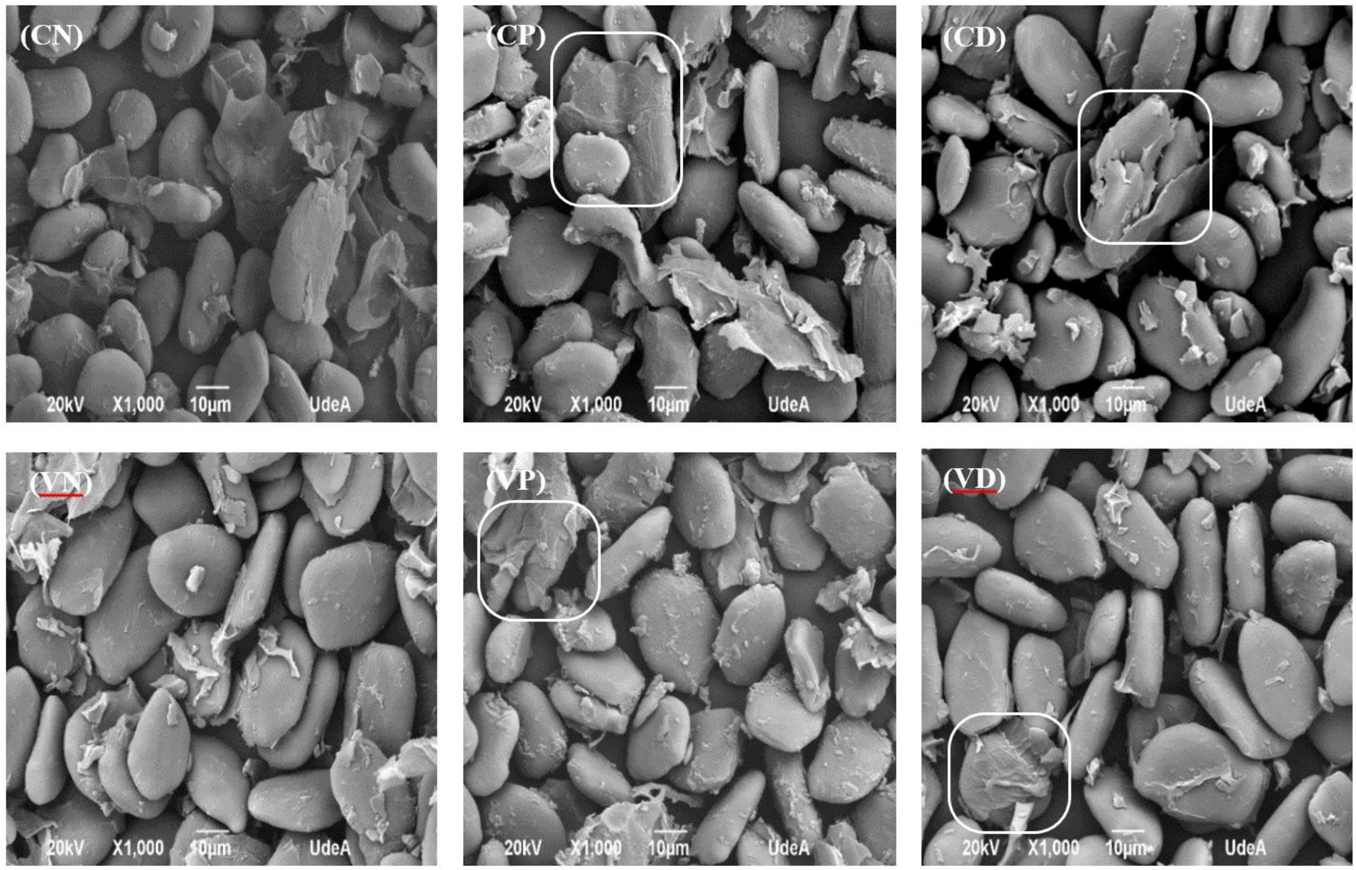

Figure 2. Granular appearance of yam flour under scanning electron microscope: (CN) Native - convective, (CP) Precooking - convective, (CD) Dipping - convective, (VN) Native - vacuum, (VP) Precooking - vacuum, (VD) Dipping - vacuum.

to previous reports by Suriya et al. (2016), Chen et al. (2017), González et al. (2021), Yu et al. (2021). These minimal differences in the degree of protein wrapping give the flours variations in emulsifying and viscosity characteristics that are attractive for their application in food matrices (Otegbayo et al., 2014; Zou et al., 2021). Nevertheless, the SEM images suggest that the applied treatment conditions did not change the shape of the granules in contrast to their respective natives (Figure 2 CN, VN).

3.3 Pasting properties

According to Figure 3A, the precooked flours samples presented higher initial gelatinization temperature values concerning the flours pretreated with citric acid ($p < 0.05$), reflecting greater resistance to swelling and loss of intragranular order (Paternina et al., 2016). The peak viscosity (Figure 3B) was significantly higher for the CD and VD samples (approx. 4700 - 6100 cP) compared to the CP and VP (approx. 1400 - 3200 cP). These differences are associated with the lower water absorption capacity of the precooked samples (Table 1) and the amylose content as suggested by Oyeyinka et al. (2018). In the cooling phase, the viscosity of the flours decreased, presenting a significant effect between the drying methods of the precooked samples (Figure 3C); this characteristic is due to a high degree of shear-thinning of the cooked pasta. The values achieved ranged from 866 to 1459 cP for CP and VP, respectively. Adu-Kwarteng et al. (2021) mention that low viscosity values (< 1000 cP) could be very suitable in baby food production and soups. Consequently, the suspensions show greater stability (Figure 3D) and less retrogradation (Figure 3E) when precooking was applied. Given the low setback ratios in the pasting profiles for CP and VP, they could be suggested for the development of breads and the other baked goods. It is known that a high retrogradation of a starchy material impacts the quality when it is used as an additive in a food favoring characteristics such as syneresis or hardening-hardness (Suriya et al., 2016). For the above, the stability study with fortified flour was carried out by selecting the CP and VP treatments.

3.4 Thermal properties

The similarity in the values of the onset (T_o) and conclusion (T_c) gelatinization temperature for VP and CP that were found between 80.81 and 81.32 °C and from 84.95 to 85.11 °C, respectively, indicated that the drying methods ($p > 0.05$) did not condition the degree of crystallinity that determines its phase transition been this result according to suggested by Amador-Rodríguez et al. (2020). These temperatures, associated with the endothermic reaction due to the dissociation of the amylopectin double helices, coincided with those given in Figure 3A and higher than those obtained for the native yam flour reached at 79.5 °C. Yu et al. (2021) suggest that the high values recorded could be attributed to the interactions between the components of the

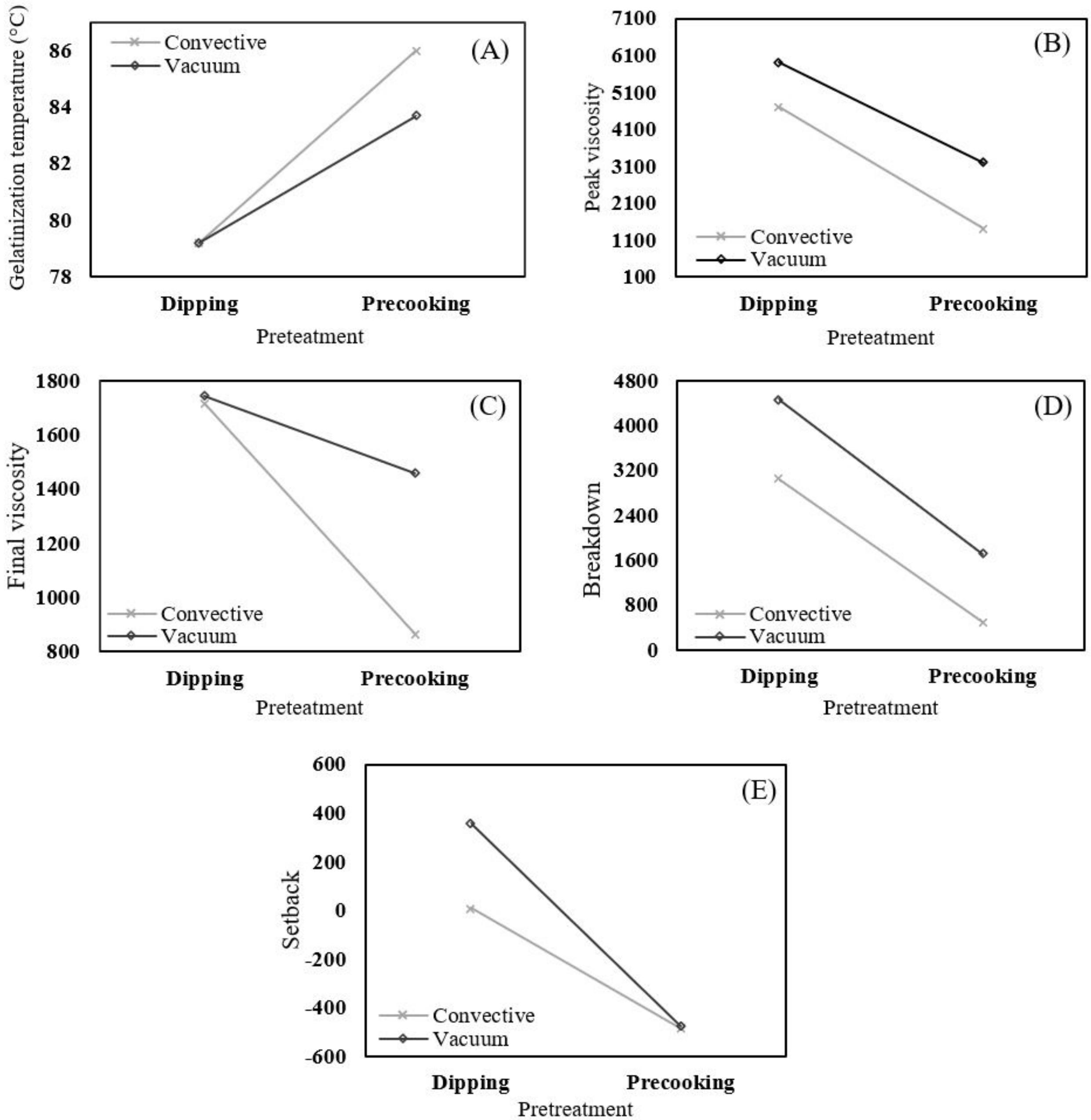

Figure 3. Pasting properties of yam flour. (A) Gelatinization temperature (°C), (B) Peak viscosity (cP), (C) Final Viscosity (cP), (D) Breakdown (cP), (E) Setback (cP).

granule (amylose-amylose, amylose-amylopectin, starch-lipid), acting as a barrier and reducing the amount of heat emitted for gelatinization (Wang et al., 2020). In terms of enthalpy, the CP and VP results were 12.85 and 11.93 J/g, respectively, showing a small variation according to the applied drying conditions ($p < 0.05$). This response could be due to the increase in the concentration of the protein on the surface of the granule by CP, following that mentioned by Martínez et al. (1999), who argue that the higher the protein denaturation temperature, the higher is the variation in enthalpy (energy requirement) associated with the loss of molecular order within it.

3.5 Proximal and physicochemical properties

The results of the protein content of the pretreated yam flour indicated statistically significant differences between the drying conditions evaluated ($p < 0.05$), although it is induced that the drying temperatures, when they caused loss of water molecules, did not disrupt the order of protein arrangements, as identified in Figure 1. For the dry samples obtained by CP and VP, the values changed between 4.6 ± 0.7 and 4.3 ± 0.3 g/100 g, being lower than those of wheat flour (10%), commonly used as a vehicle for the fortification of micronutrients (Akhtar et al., 2011). Other

Table 1. Proximal and physicochemical properties of yam flour.

Properties	Treatments			
	CP	VP	FCP	FVP
Proximal (%)				
X_w (d.b)	7.09 ± 0.46**	9.86 ± 0.59**	7.68 ± 0.29**	11.00 ± 0.1**
Ash	1.49 ± 0.01*	1.26 ± 0.01*	3.10 ± 0.03*	3.07 ± 0.09*
Physicochemical				
a_w	0.27 ± 0.01**	0.50 ± 0.01**	0.30 ± 0.04**	0.51 ± 0.09**
Color				
(L*)	70.33 ± 2.27**	72.29 ± 2.67**	67.85 ± 1.37**	66.64 ± 1.74**
(a*)	-0.20 ± 0.01*	-0.29 ± 0.01*	-0.26 ± 0.02*	-0.26 ± 0.04*
(b*)	5.56 ± 0.26*	6.37 ± 0.22*	4.58 ± 0.08*	4.11 ± 0.06*
WSI (g soluble/g sample)	0.06 ± 0.01*	0.06 ± 0.03*	0.06 ± 0.01*	0.06 ± 0.03*
WAI (g gel/g sample)	3.20 ± 0.01*	3.21 ± 0.03*	3.22 ± 0.03*	3.18 ± 0.02*
SP (g gel/g insoluble)	3.22 ± 0.11*	3.31 ± 0.03*	3.31 ± 0.04*	3.27 ± 0.04*
WAC (%)	157.94 ± 0.28*	163.9 ± 2.07*	164.58 ± 0.59*	164.78 ± 2.92*

Arithmetic mean ± standard error. Means in the same row with an asterisk (*) do not differ significantly at 5%. (CP) Precooking - convective, (VP) Precooking - vacuum, (FCP) Fortified flour obtained by precooking - convective, (FVP) Fortified flour obtained by precooking - vacuum. X_w (moisture content), a_w (water activity), L* (CIELAB coordinate of luminosity), a* (CIELAB coordinate green-red), b* (CIELAB coordinate degree blue-yellow), WSI (water solubility index), WAI (water absorption index), SP (swelling power), WAC (water absorption capacity).

studies report protein contents below those obtained, arguing that higher temperatures or other drying methods cause the weakening of the three-dimensional conformation of the proteins (Danso-Boateng, 2013; Obadina et al., 2014; Chen et al., 2017).

The drying conditions did not significantly affect the contents of fiber, fat and ash to yam flours ($p > 0.05$). The fiber content was the same for the evaluated samples (1.3 g/100 g) and coincided with the results reported by Abara et al. (2003) in *D. bulbifera*, Wu et al. (2016) in *D. alata* and Oyeyinka et al. (2018) in *D. dumetorum*. The fat component for both treatments was less than 0.50 g/100 g, which responds to the nature of the tuber (Harijono et al., 2013; Techeira et al., 2014). The ash content values (Table 1) were comparable with those reached by Adegunwa et al. (2011) and Nina et al. (2017), who evaluated flours from different yam genotypes as well as their evolution during the postharvest conservation of the tubers.

Regarding the content of vitamin A, Fe and Ca, the values for CP and VP ($p > 0.05$) were 138 - 130 IU, 10 - 4.5 and 134 -112 mg/Kg, respectively, showing that yam flours do not achieve the reference standard of vitamin A (1332 IU), Fe (12 mg) and Calcium (385 mg) defined for child population between six months and four years of age, according to the Resolution 333 of 2011 of Colombian Ministry of Health and Social Protection. Omohimi et al. (2018) and Oyeyinka et al. (2018) have reported a higher concentration of these, probably as a consequence of the elemental composition, pH and mineral fertilization of the ground, the species treated, or the post-harvest time of the tubers, as well as the processing conditions for the production of flour (Wu et al., 2016; Nina et al., 2017; Maziya-Dixon et al., 2016). In this case, the lower micronutrient content obtained for vacuum drying may be due to the longer residence time of the yam slices in the dryer rather than to exposure to the higher temperature used by convection, also reported by Alibas et al. (2021).

The pretreated flours reached an X_w that varied depending on the drying conditions ($p < 0.05$), being lower for the process carried out by convection completed in 270 min, while the vacuum drying was longer and continued for 510 min (Table 1). According to with Sharma et al. (2015), in addition to the fact that precooking leads to a faster elimination of water due to the rupture of the tissues of the cell wall, the temperature used in the dehydration process favors the drying speed. Likewise, the movement of moisture through the product depends on both the formation of capillaries and the interactions of moisture with the food matrix (Tagodoe & Nip, 1994). With fortification, the moisture of the flours increased. A possible explanation for this could be the capacity of the calcium salt to cause the ordering of the water around it, producing a change in the hydration properties of the protein molecules present on the surface of the granule and in the structuring of the water-protein interface (Dergal, 2006; Khushbu et al., 2019); nevertheless, the values found were below the permissible limits established in the Codex Standard 176 - 1989, where it is described that the maximum humidity percentage should not be greater than 13% (w/w). The same occurs with the water activity (a_w), where the fortified samples show a statistically significant increase ($p < 0.05$), although the values reached are less than 0.65 where microbiological stability is guaranteed and contributes to the decrease in the relative speed of Vitamin A's autooxidation (Shishir et al., 2017).

CP and VP presented similar values of L*, reflecting that precooking probably favored the inactivation of the polyphenoloxidase responsible for enzymatic browning (Harijono et al., 2013); in particular, the VP sample exhibited a higher L* ($p < 0.05$) due to the anaerobic conditions managed during vacuum drying that prevented the Maillard reaction (Li et al., 2019). After fortification, there was a decrease in L* for both treatments ($p < 0.05$), which responds to the addition of iron in the samples (Table 1), giving them a less light reflection (Cortés et al., 2007). This effect could limit the addition of these flours in food production, based on considerations of Anyasi et al. (2015), who affirm that flour with high whiteness can improve nutritional characteristics without changing the color of food. It should be noted that L* values higher than 90 indicate a satisfactory degree of whiteness/purity in starches, and that the differences with flour can be explained by the presence of anthocyanins and carotenes (Wang et al., 2020). Concerning the green-red (a*) and blue-yellow (b*) chromaticity, the fortification did not produce a statistically significant effect (p>0.05), although the mixtures exhibited slight shades of grayish-green and yellow, associated with the presence of iron and vitamin A, respectively.

WAC responds to the hydrophilic character of starch granules (Alcázar-Alay & Meireles, 2015). Both CP and VP presented close WAC values (p>0.05), being consistent with the formation of the amylose-lipid complex that reduces their ability to bind water molecules (Zou et al., 2021). Something similar occurs with the WSI obtained, for which no significant differences were found between CP and VP or after fortification (p > 0.05). Mimouni et al. (2010) mention that the concentration of protein on the surface produced during drying makes the dispersion of the granules difficult, showing low solubility and inhibiting the hydration of the particles. Besides, it is induced that, due to the registered values, a high degree of intragranular association of amylose and amylopectin prevails, a behavior contrary to that achieved by Chen et al. (2017), who affirm that the effect of the drying method contributes in the partial destruction of the surface structure of starch granules. In contrast, Hutasoit et al. (2018) who evaluated sweet potato flour, mention that precooking can cause gelatinization of the starch and, consequently, it will break the starch granule and favor the starch-water interaction, which would increase the WAI and SP values. This corroborates that both the precooking and the drying methods evaluated did not cause a significant effect on the WAI and SP values (p>0.05) of the vehicle food used for fortification, arguing that it is mainly due to the content of amylose and the presence of other components such protein, fat and fiber on the surface of the particles (Suriya et al., 2016).

3.6 Storage during stability

When yam flours fortified with vitamin A, iron and calcium were packaged in low density polyethylene bags, variables such as ash, L*, WSI, WAI, SP and WAC, do not present statistically significative differences related to the drying method and storage time. In contrast, X_w and a_w (Figure 4A, B) showed a significant tendency to increase at day 30 of storage (p < 0.05). This situation

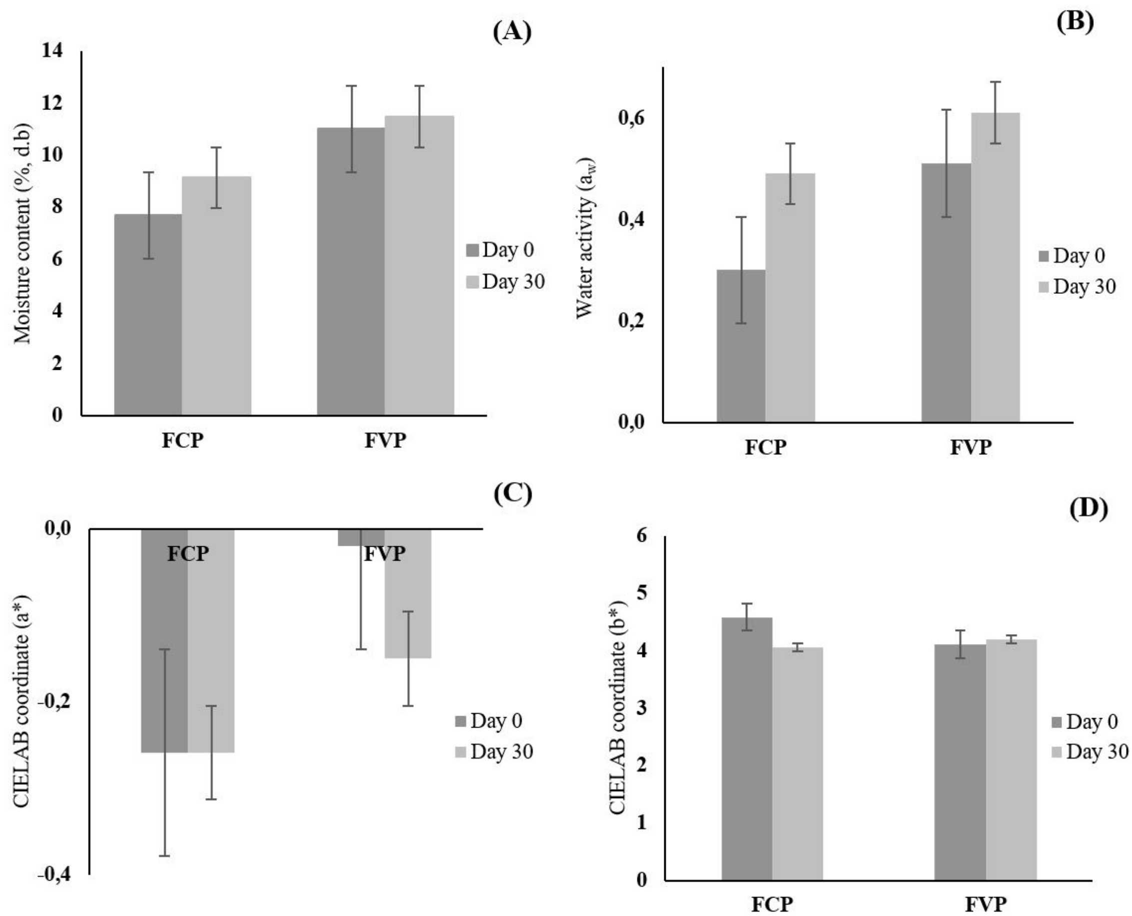

Figure 4. Evaluation of the stability of fortified yam flour during storage. (A) Moisture content (X_w), (B) Water activity (a_w), (C) CIELAB coordinate green-red (a*), (D) CIELAB coordinate blue-yellow (b*).

can be attributed to the higher vapor pressure experienced by the surface water adsorbed on the samples through the packaging used (Cortés et al., 2007). Similar behaviors have been mentioned by Khamila et al. (2020) and Lucas (2017), where it is considered that the water sorption kinetics is influenced by the temperature and relative humidity of the environment as well as by the microstructure of the granules. Considering the above, the permeability of the packaging material used can adversely affect the stability of the product during longer storage times (Hemery et al., 2018); however, Akhtar et al. (2008) argue that mineral fortification has been shown to impart an inhibitory effect on mold growth during storage in fortified flour for 60 days.

Regarding the coordinates a* and b*, both for the storage time and for the drying method there were significant variations ($p < 0.05$) between the fortified treatments. The differences found may be derived as a consequence of the oxidative degradation of vitamin A (Figure 4C, D), possibly caused by the catalytic action of iron since its encapsulation structure can be weakened during storage or by autooxidation of retinyl esters and carotenoids in presence of molecular oxygen, reactions that increase their speed with increment of the a_w (Akhtar et al., 2011; Hemery et al., 2019).

4 Conclusions

Precooking had a significant impact on the thermal and pasting properties of yam flour, reflecting greater colloidal stability. Furthermore, it was found that the forced convection drying method preserved, to greater degree, the content of proteins and micronutrients (Fe, Ca and vitamin A), compared to vacuum drying. In general, the presence of protein, fiber, and fat (non-starch components) condition the hydration and solubility properties of the samples. With fortification, the moisture content and water activity of the flours increase during storage time, which suggest reviewing the characteristics of packaging used (non-permeable to humidity and oxygen) to avoid oxidation reactions. Finally, yam flour could be a good alternative as a vehicle in food fortification.

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