Production, chemical, physical and technological properties of antioxidant dietary fiber from pineapple pomace and effect as ingredient in sausages

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ABSTRACT

In this study, fresh and steamed under pressure (SPP) pineapple pomace were used to produce dietary fiber concentrates (DFCs) dried by freeze-drying or hot-air drying. Chemical, physical and technological properties were determined to select one pineapple DFC (PDFD) and to evaluate its mixture effect with meats on characteristics of Vienna-type sausages. The PDFD produced from SPP and hot air-dried (SPDFD-HD) had the highest content of DF, carotenoids, polyphenols such as gallic, cinnamic and p-coumaric acids, antioxidant capacity and hydration properties. Microstructural analysis evidenced a cell wall disruption of the PDFD matrix by the effect of processing. The cubic model equations showed that with the increase in SPDFD-HD in the ternary mixture, a reducing effect on nitrates, moisture, shear force and shrinkage was obtained in sausages, while carotenoids and antioxidant polyphenols increased. This study demonstrated that SPDFD-HD was produced with characteristics to be used as ingredient in potential functional sausages.

INTRODUCTION

The processing of pineapple (Ananas comosus L.) is one of the most economically important tropical fruit industries. However, it generates a large amount of waste up to 30 tons per each 100 tons of processed fruit per day, which is destined for animal feed. Recently, these by-products has been suggested as source of dietary fiber (DF) and bioactive compounds such as carotenoids and polyphenols (Martínez et al., 2012; Selani et al., 2014), which has been recognized for their biological activity as powerful antioxidants (Haminiu, Maciel, Plata-Oviedo, & Peralta, 2012; Nayak, Liu, & Tang, 2015), while DF improves gastrointestinal and physiological functions and provides several human health benefits. Because physiological DF effects are related to their technological properties such as water holding (WHC), swelling (SWC), solubility and oil holding (OHC) capacities, DF has been proposed as functional ingredient (Sharma et al., 2016).

The preparation of DF concentrates (DFCs) from agro-industrial by-products as food ingredients is taken more research importance (Sharma et al., 2016). Some DFCs has been produced and characterized from several fruit and vegetable by-products (Akter, Ahmed, & Eun, 2010a; Boubaker, Omri, Blecker, & Bouzouita, 2016; Henríquez et al., 2010; López-Vargas, Fernández-López, Pérez-Álvarez, & Viuda-Martos, 2013; Martínez et al., 2012; Pantaleón-Velasco et al., 2014). These studies demonstrated that the properties of the DFC depend on the source and DF concentration method conditions. In addition, it has been...
observed that some heat pretreatment methods such as blanching or drying applied to by-products and DFCs could also influence its composition and properties (Chiewman, 2018; Heras-Ramírez, Quintero-Ramos, Camacho-Dávila, Barnard, & Talamás-Abbud, 2012). Therefore, utilization of agro-industrial by-products and the design of technological process to obtain DFCs with unique properties as food ingredients is underway (Sharma et al., 2016).

The meat products are commonly consumed foods; specifically, sausages such as Frankfurt, Bologna and mainly Vienna-type are popularly cooked meat products with high commercial significance. However, they contain high levels of saturated fatty acids, sodium chloride and curing salts (sodium nitrate – NaNO₃ and sodium nitrite – NaNO₂) which has been related to several chronic degenerative diseases. Therefore, enrichment of meat products with DF has been proposed as a way to improve the nutritional value of meat products, to contribute to the daily intake of DF recommended and to obtain potential functional products (Nisa et al., 2017). Some studies have documented the addition of DFCs into some types of emulsified cooked sausages (Kim, Jin, Mandal, & Kang, 2011; Li, Shao, Zhu, Zhou, & Xu, 2013; Sánchez-Zapata et al., 2011), and they showed that characteristics of the products were dependent on the properties of the DFC.

The aim of this work was to evaluate the chemical, physical and technological properties of pineapple antioxidant DFCs produced from fresh (FPP) and steamed under pressure (SPP) pineapple pomace, and then dried by freeze-drying or hot air-drying. After screening, one pineapple DFC was selected and produced to evaluate its effect in mixture with pork and turkey meats on the chemical and physical characteristics of Vienna-type sausages.

Materials and methods

Raw materials and conditioning

Pineapple pomace (PP) was provided by a processing industry of pineapple (Ananas comosus L. cv. Cayena Lisa) in Loma Bonita, Oaxaca (México). PP was mainly constituted by pulp, cores and a minimum of peel. One proportion of PP was conserved fresh, while another proportion was divided into portions of 500 g and packaged with a vacuum sealer (model VM-16; ORVED, Barcelona, Spain) into high-density polyethylene plastic food bags. Batches of three vacuum-packed PP portions were pretreated by saturated steam under pressure using autoclave (Felisa, FE 398, Ciudad de México, México) at 121°C and 1.03 bar for 5 min. After steaming, packaged samples were immediately chilled into cold water (5°C). The PP samples in FPP and SPP were monitored at 730 nm. Trolox was used for calibration and the results were expressed as μmol TE/g DW.

The soluble polyphenols were determined by sequential organic aqueous extraction using a solution of 16 mM hydrochloric acid in 50% aqueous methanol (50:50, v/v, 1 h at room temperature, constant shaking) and acetone/water mixture (70:30, v/v, 1 h at room temperature, constant shaking) according to the procedure described by Bravo and Saura-Calixto (1998). The polyphenols were estimated in the supernatants using Folin-Ciocalteu’s reagent at 750 nm with gallic acid as standard. The results were expressed as mg β-carotene equivalents/kg dry weight (DW).

Preparation of pineapple DFCs and selection

The pineapple DFCs (PDFCs) were prepared following the procedure described by Pantaleón-Velasco et al. (2014). Briefly, FPP and SPP were washed separately with water at 55°C for 5 min (water-to-pomace mass ratio of 2:1), pressed and dried. Four types of PDFCs were obtained: one from FPP (FPDFC-HD) and the second from SPP (SPDFC-HD), both dried by hot air-drying at 55°C for 9 h using a dryer of five trays (Poli Rep, Ciudad de México, México). The third PDFC (FPDFC-L) was prepared from FPP and the fourth from SPP (SPDFC-L), both were lyophilized using a freeze-drying equipment (Labconco Freeze Dry System/FreeZone 4.5, Kansas City, MO, USA) at 0.080 mbar and −48°C for 48 h. Each dried PDFC was milled and sieved through a No. 35-mesh screen (0.5 mm, U.S.A. standard test sieve ASTM E-11, Montinox, Ciudad de México, México). Finally, the powders of FPDFC-HD, SPDFC-HD, FPDFC-L and SPDFC-L were vacuum-sealer packaged into polyethylene plastic food bags and stored at 6 ± 1°C.

The four PDFC powders were chemically characterized and screened according to their content in bioactive compounds and antioxidant capacity. Later, the selected PDFCs were again screened according to their DF content, technological and morphological characteristics, and determination of phenolic acids.

Chemical composition, technological and microstructural characterization of PP and PDCF samples

The content of moisture, crude protein (N × 6.25), fat and ash were determined according to the 934.01, 960.52, 948.22 and 942.05 methods, respectively (AOAC, 2005). Insoluble (IDF), soluble (SDF) and total (TDF) DF contents were determined according to the enzymatic-gravimetric (32-07.01) method of AACC (2009). The carbohydrate content was determined by the subtraction from the total sum value of the before components.

The carotenoids were determined according to Ortega et al. (2013). Extraction with acetone/petroleum ether 80:20 (v/v) and MgCO₃ further recovering with NaCl (20%) and dilution with petroleum ether of the samples was carried out. The content of carotenoids was obtained by measurement at 448 nm using a β-carotene as standard. The results were expressed as mg β-carotene equivalents/kg dry weight (DW).

The antioxidant standard (AOX) of the polyphenolic extracts was evaluated by two in vitro methods. The capacity to scavenge the free radical cation 2,2'-azino-bis-(3-ethylbenzothiazoline-6-sulfonic acid) (ABTS⁺) was assessed by the assay of Re et al. (1999). The decrease of radical ABTS⁺ preformed by oxidation with potassium persulfate, was monitored at 730 nm. Trolox was used for calibration and the results were expressed as μmol TE/g DW.

Ferric reducing antioxidant power (FRAP) assay was carried out as described by Pulido, Bravo, and Saura-Calixto (2000). FRAP reagent (containing 10 mM TPTZ in 40 mM HCl, 20 mM FeCl₃·6H₂O and 0.3 M acetate buffer, pH 3.6) was used and the absorbance readings were taken at 595 nm. The results were expressed as μmol TE/g DW.
The partial identification of phenolic acids of FPP, SPP and selected PDFCs was performed using an HPLC system (Agilent Technologies 1260 Infinity, Waldbronn, Germany) that was equipped with a photodiode array detector and a C18 reverse-phase column (Thermo Scientific®, 5 μm particle size, 4.6 mm in diameter and 250 mm of length, Sunnyvale, CA, USA). The mobile phases were acidified water with 2% acetic acid (A eluent) and acidified water (0.5% acetic acid): methanol in ratio 10:90 (B eluent). Standards and sample extracts were analyzed using a gradient program of 0% B; 0–35 min, 35% B; 35–55 min, 75% B; 55–60 min, 100% B, 60–70 min 0% B, with a flow rate of 0.4 mL/min. The peak areas were detected at 280 and 320 nm for the samples, and a calibration curve (0.5–300 μg/mL) of gallic, chlorogenic, caffeic, cinnamic and p-coumaric acids (Sigma-Aldrich, Inc., St. Louis, MO, USA) was used to identify and quantify the polyphenols (Jiménez, Gruschwitz, Schweiggert, Carle, & Esquivel, 2014).

Technological properties of PP samples and selected PDFCs were determined by analysis of WHC, SWC and OHC capacities according to the methods of Robertson et al. (2000).

A microstructural analysis by scanning electron microscopy (SEM) was made in the powdered samples. Each sample was mounted and sputter-coated with a thin layer of gold–palladium alloy. SE micrographs were obtained using a JEOL Scanning Electron Microscope (Model JSM-7600F, Schottky Field Emission Scanning Electron Microscope, Jeol Inc., Peabody, MA, USA) equipped with an integrated program for digital image capture. Each sample was observed with 200-, 1500-, 2000- and 3000-fold magnification at an accelerating voltage of 1.5 kV and 9.6 × 10⁻⁵ Pa.

**Vienna-type sausage preparation**

The pork and turkey meats (loin and leg, respectively) were of Federal Inspection Type from Tuxtepec, Oaxaca (México). Meats were assessed to have a pH of 5.4–5.7 as a good technological quality parameter. Vienna-type sausages were manufactured using a fixed formula (grams for each 100 g of meat) composed by 20% crushed ice (w/w), 15% pork backfat, 3% starch potato, 2% potassium chloride, 1% sugar, 0.3% cure salt (composed by 94% sodium chloride and 6% sodium nitrite), 0.1% garlic powder, 0.1% humus flavor powder, 0.05% polyphosphates and 0.05% ascorbic acid powder. On the other hand, pork and turkey meats were ground (Moulinex ME-625, Moulinex, Celaya, México) and mixed with the PDFC powder according to the experimental design (Table 1). The mixture was homogenized with the sausage formula in a proportion of 1:0.416 (w/w), stuffed into artificial Viscofan casing (25.4 mm diameter and 170 mm length) and linked at both ends into portions of 34 g. The sausages were submerged in a water bath at 80–85°C and internal temperature of 73°C. The cooked sausages were cooled at room temperature and vacuum packed in high-density polyethylene plastic food bags and refrigerated at 5°C overnight until analysis.

**Effect of the mixture of meats and PDFC on the characteristics of Vienna sausages**

A simplex mixture design with three factors and one center centroid (3,1) was used to study the effect of the proportions of pork meat, turkey meat and PDFC powder on the chemical and physical characteristics of Vienna sausages (Table 1). Experimental results of the 13 formulations were related with pork meat ($x_1$), turkey meat ($x_2$) and selected PDFC powder ($x_3$) components in a ternary mixture by a special cubic model:

$$y = b_1x_1 + b_2x_2 + b_3x_3 + b_{12}x_1x_2 + b_{13}x_1x_3 + b_{23}x_2x_3 + b_{123}x_1x_2x_3$$

(1)

Equation (1) was fitted to experimental data using ordinary linear regression to estimate model parameters $b_1$, $b_2$, $b_3$, $b_{12}$, $b_{13}$, $b_{23}$ and $b_{123}$ for each one of the responses. Following data fitting, an analysis of variance (ANOVA) was performed for each equation to identify significant predictor variables ($p < 0.05$). The fitness quality of the linear regression models was quantified by the determination coefficient ($R^2$). Linear regression procedures were performed with the Matlab R2012a software and its Statistics Toolbox 7.5 (MathWorks Inc., Natick, MA, USA).

**Specific analysis in Vienna-type sausages**

The residual nitrite content was determined in each formulation by triplicate according to the NOM-213-SSA1-2002 (Norma Oficial Mexicana, 2002). The fresh sample was homogenized with water and heated at 80°C for 1 h. After addition of mercuric chloride, the mixture was filtered and Griess reactive was added. The pink chromophore compound was detected at 520 nm using sodium nitrite as standard. The results were reported as NaNO₂ mg/kg fresh weight (FW).

The color parameters $L^*$, $a^*$ and $b^*$ were determined in three sausage samples for formulation using a colorimeter (CR-400 Konica Minolta Sensing Americas, Inc., Ramsey, NJ, USA). Each sausage was cross cut in three sections and each flat part was used for the nine flash lectures for formulation taken with the colorimeter.

The shear force was determined using a Tester EZTest EZ-S Shimadzu Universal Texturometer (Shimadzu Corporation, Kioto, Japan). Each sample of 3 cm length was placed on the rig and sheared in the direction of the axis of the sausage using a Warner–Bratzler probe. The full scale load was set at

| Blend | $x_1$ (pork) | $x_2$ (turkey) | $x_3$ (PDFC) |
|-------|-------------|---------------|--------------|
| A     | 1           | 0             | 0            |
| B     | 0           | 90            | 10           |
| C     | 0           | 90            | 10           |
| D     | 0           | 100           | 0            |
| E     | 47.5        | 47.5          | 5            |
| F     | 95          | 0             | 5            |
| G     | 0           | 95            | 5            |
| H     | 45          | 45            | 10           |
| I     | 50          | 50            | 0            |
| J     | 67.5        | 25            | 7.5          |
| K     | 25          | 67.5          | 7.5          |
| L     | 72.5        | 25            | 2.5          |
| M     | 25          | 72.5          | 2.5          |

Table 1. Mixture design for studying the ternary mixture (% proportion) of pineapple dietary fibre concentrate (PDFC), pork meat and turkey meat in Vienna sausage formulation.

Table 1. Diseño de mezclas para el estudio de la mezcla ternaria (% de proporción) del concentrado de fibra dietaria de piña (PDFC), carne de cerdo y carne de pavo en la formulación de salchichas tipo Viena.
0.4903 kN with the cross-head speed set at 120 mm/s. The shear force (N) value was the mean of the maximum cutting force.

The shrinkage was determined by cooking the sample at 150°C in an oven (Felisa) to an internal temperature core of 72°C (thermocouple, Oakton thermometer, Vernon Hills, IL, USA). The diameter and length of sausage were measured before and after cooking using a vernier (Trupper, Ciudad de México, México). Dimensional changes (shrinkage) were determined considering that sausage is a right circular cylinder according to the following equation.

\[
Shrinkage \% = \left( \frac{(D_o \times L_o - D_f \times L_f)}{(D_o \times L_o)} \right) \times 100
\]

where \(D_o\) is the uncooked sausage diameter, \(L_o\) is the uncooked sausage length, \(D_f\) is the cooked sausage diameter and \(L_f\) is the cooked sausage length.

### Statistical analysis

Results of each analysis were recorded as the mean of three replicates ± standard deviation. A one-way ANOVA was run, followed by a Fisher’s Least Significant Difference post-hoc test at a confidence level of 95% using the Statgraphics Plus 5.1 statistical software (Statpoint Technologies, Inc., Warrenton, VA, USA).

### Results and discussion

#### Proximate chemical composition of PP and PDFC samples

The chemical composition of PP and PDFCs is shown in Table 2. The starting raw materials (FPP and SPP) had the highest moisture content with no significant differences between them, but they showed differences in ash, protein and fat contents (\(p < 0.05\)). There was an increase of 148.48% and 50.54% in protein and fat contents, respectively, after steaming. The \(p<0.05\) values for differences between samples are shown in Table 2. The Fast heat penetration into cell is the cooked sausage diameter. There was an increase of 148.48% \(p<0.05\).

There were significant differences in carotenoid content (\(p<0.05\)). The SPDFC-HD had the highest carotenoid content followed by its raw material (SPP) and the lyophilized DFCs (FPDFC-L and SPDFC-L), while FPP and FPDFC-HD were the samples with the lowest carotenoid content (\(p<0.05\)). Therefore, steaming pretreatment and hot air-drying had a synergistic effect and contributed to enhance the carotenoid content in the PDFCs, maybe by a release of them from the disrupted cell PP matrix modified by the hot treatments (Nayak et al., 2015). On the other hand, freeze-drying samples are more susceptible to oxygen degradation than hot air-drying samples due to the highly porous structure of the first, which make them susceptible to high lipid oxidation levels because of the hydrophobic nature of carotenoids (Kapoor & Aggarwal, 2015).

#### Polyphenol content and AOX of PP and PDFC samples

As shown in Table 2, the SPP showed the highest polyphenol content, followed by FPP and the PDFCs (\(p<0.05\)). Regarding the starting raw materials, SPP showed 39.03% higher polyphenol proportion than FPP, which was related to its AOX (\(p<0.05\)). The fast heat penetration into cell matrix of FPP by the steaming can cause inactivation of browning enzymes and opening up the cell food matrix, which in turn could increase the polyphenol extraction.

| Parameter               | FPP            | SPP            | FPDFC-HD       | SPDFC-HD       | FPDFC-L       | SPDFC-L       |
|-------------------------|----------------|----------------|----------------|----------------|----------------|----------------|
| Moisture (g/kg FW)      | 825.4 ± 15.4\(^a\) | 825.5 ± 1.10\(^b\) | 36.0 ± 0.32\(^c\) | 29.3 ± 0.36\(^c\) | 48.5 ± 0.16\(^d\) | 46.3 ± 0.15\(^d\) |
| Ash (g/kg DW)           | 28.6 ± 0.6\(^a\)   | 18.9 ± 0.08\(^b\)   | 8.9 ± 0.08\(^c\)   | 15.6 ± 0.01\(^d\)   | 15.6 ± 0.04\(^d\)   | 20.6 ± 0.27\(^d\)   |
| Proteins (g/kg DW)      | 19.8 ± 0.2\(^a\)   | 49.2 ± 0.11\(^b\)   | 18.7 ± 0.04\(^c\)   | 34.2 ± 0.10\(^d\)   | 43.8 ± 0.11\(^d\)   | 46.0 ± 0.24\(^d\)   |
| Fat (g/kg DW)           | 93.0 ± 0.3\(^a\)   | 14.1 ± 0.19\(^b\)   | 18.6 ± 0.14\(^c\)   | 5.1 ± 0.23\(^d\)   | 7.1 ± 0.23\(^d\)   | 2.1 ± 0.07\(^d\)   |
| Carbohydrates (g/kg DW) | 358.9 ± 0.24\(^a\)  | 310.4 ± 0.31\(^b\)  | 70.5 ± 0.07\(^c\)  | 8.8 ± 0.62\(^d\)  | NC             | 121.5 ± 0.24\(^d\)  |
| Polyphenols (g GAE/kg DW)| 6.42 ± 0.22\(^a\)  | 8.92 ± 0.18\(^b\)  | 4.92 ± 0.17\(^c\)  | 5.80 ± 0.89\(^d\)  | 4.07 ± 0.36\(^d\)  | 5.45 ± 0.21\(^d\)  |
| Antioxidant capacity    | 45.10 ± 1.43\(^a\) | 45.97 ± 1.88\(^b\) | 35.69 ± 1.07\(^c\) | 43.15 ± 1.32\(^d\) | 35.0 ± 0.89\(^d\) | 43.48 ± 1.25\(^d\) |
| FRAP assay (µmol TE/g DW)| 7.50 ± 0.73\(^a\)  | 8.63 ± 0.30\(^b\)  | 7.42 ± 0.02\(^b\)  | 8.12 ± 0.01\(^d\)  | 1.57 ± 0.20\(^d\)  | 8.78 ± 0.02\(^d\)  |
| ABTS\(^+\) assay (µmol TE/g DW)| 4.4 ± 0.01\(^a\) | 6.30 ± 0.09\(^b\) | 4.37 ± 0.00\(^c\) | 11.33 ± 0.02\(^d\) | 5.52 ± 0.01\(^e\) | 5.01 ± 0.01\(^d\) |

Data expressed as mean ± standard deviation of three independent experiments. Means in a column followed by different superscript letters are significantly different (\(p<0.05\)). FPDFC-HD: PDFC from fresh pomace and hot air-dried; SPDFC-HD: PDFC from pressure-steamed pomace and hot air-dried; FPDFC-L: PDFC from fresh pomace and lyophilized; SPDFC-L: PDFC from pressure-steamed pomace and lyophilized. NC = No calculated.

Datos expresados como la media ± desviación estándar de tres experimentos independientes. Promedios en una columna seguido de diferentes letras en súper índice son significativamente diferentes (\(p<0.05\)). FPDFC-HD: CFTP de bagazo fresco seco y aire caliente; SPDFC-HD: PDFC de bagazo tratado con vapor a presión y secado con aire caliente; SPDFC-L: CFDP de bagazo tratado con vapor a presión y liofilizado. NC = No calculado.
yield and related AOX (Nayak et al., 2015). Heras-Ramírez et al. (2012) have also reported an increase in polyphenol proportion (20.19%) after steaming at atmospheric pressure of apple pomace, which was attributed to the release of polyphenols by the effect of steaming.

There was a loss of polyphenols up to 54.41% of PDFCs after the DF concentration of FPP and SPP (p < 0.05) (Table 1). This could be due to the conditions of DF concentration (hot water washing with mechanical agitation) and drying. The PDFCs pretreated by steaming under pressure (SPDFC-HD and SPDFC-L) had no significant differences in AOX (ABTS) with respect to their raw material (SPP) (p > 0.05), which indicates that polyphenols with scavenging-free radical property were maintained after application of these treatments.

The PDFCs pretreated by steaming (SPDFC-HD and SPDFC-L) showed higher polyphenol content and AOX than PDFCs without pretreatment (FPDFC-HD and FPDFC-L) (p < 0.05) (Table 2). This suggest that steaming pretreatment enhanced the antioxidant polyphenols of PP despite the drying method used to dry the fresh PDFC, maybe by structural changes in the tissue and the release of some of them from the cell plant matrix, which resulted in an increase in its measure value (Akter, Ahmed, & Eun, 2010b; Heras-Ramírez et al., 2012; Nayak et al., 2015).

The SPDFC-HD had the highest polyphenol content with high AOX (Table 2), which indicates a synergy effect of steaming and hot air-drying. Kessy, Hu, Zhao, and Zhou (2016) reported similar findings after steam blanching and drying with hot air at 60°C of litchi pericarp. This behavior can be attributed to an enhanced release of the phenolics from the cell matrix pericarp by the effect of these heat treatments.

The PDFCs prepared in this work had higher polyphenol content and Fe³⁺ chelating AOX by FRAP (Table 2) than those reported (1.29–5.46 g GAE/kg and 6.2–19.1 μmol TE/g, respectively) for DFCs prepared from pineapple (mainly peel and heart), passion fruit, guava and mango juice processing co-products (Martínez et al., 2012). In addition, PDFCs had higher polyphenol content than those reported (2.98–4.31 g GAE/kg) for DFCs from yellow passion fruit co-products (López-Vargas et al., 2013).

According to the results in polyphenol content, AOX and carotenoid content, the PDFCs pretreated by steaming and dried by traps (FPDFC-HD, SPDFC-HD and SPDFC-L) were selected to evaluate their DF content, microstructural characteristics, phenolic acid profile and technological properties.

Characterization of PP and selected PDFC samples

DF content and microstructure

The DF contents of FPP, SPP and PDFCs are given in Table 3. The SPP sample showed higher contents of TDF and SDF than FPP (p < 0.05). Heat treatments by saturated steaming above atmospheric pressure provide an efficient and fast heat penetration into vegetal cell matrix structure (Chiewchan, 2018). This fact may cause a microstructural modification of the cell matrix of PP as shown in SEM images of FPP and SPP samples (Figure 2). These SEM micrographs showed that cell matrix structure of FPP particles was whole with irregular shape and regular surface (Figure 2(a)), but after steaming (SPP), the surface structure was porous presenting a breakdown of the primary and secondary cell wall structures evidenced by the exposed lignin trachel elements of helical thickness type, which many of whom were broken (Figure 2(b)). This breakdown may release some IDF and mainly SDF components, which in turn, may increase their extractability and measured values. The FPP and SPP had higher TDF, IDF and SDF than those of PP reported by Selani et al. (2014).

Considering the dry basis DF composition of each sample, the content of TDF, IDF and SDF of PDFCs increased up to 56.85, 50.76 and 169.16%, respectively, with respect to the starting raw materials (FPP and SPP) (p < 0.05) (Table 3). This demonstrated the advantage of the DF concentration processing. SPDFC-HD was the PDFC that shows the highest TDF and SDF values followed by FPDFC-HD and SPDFC-L (p < 0.05). It can be noted that SDF was the fraction with the largest increase until proportion up to 18.46% (p < 0.05), which represents a potential human physiological benefit because the intake of SDF may promote growth and proliferation of beneficial bacterial colonic flora with several health benefits ( Sharma et al., 2016). Related to these results, SEM image of SDFC-L (Figure 3(a)) showed a more irregular and pitted surface than SPP sample (Figure 2(b)), with deep areas and dug holes which evidenced the broken primary and secondary walls without their components (microfibril cellulose, hemicelluloses and pectins). In this regard, plus the effect of the steaming pretreatment, the hot water washing and mechanical agitation of DF concentration method of the PP samples, could have caused the cell disruption and release of DF components from the cell wall matrix, resulting in extraction of DF components and increase in their

### Table 3. Dietary fiber content and technological properties of fresh (FPP) and pressure-steamed (SPP) pineapple pomace and selected pineapple dietary fiber concentrates (PDFCs).

| Parameter                  | FPP       | SPP       | FPDFC-HD  | SPDFC-HD  | SPDFC-L  |
|----------------------------|-----------|-----------|-----------|-----------|-----------|
| Total dietary fiber (g/kg) | 583.6 ± 8.0³ | 607.4 ± 8.4² | 883.3 ± 5.2³ | 936.3 ± 8.0³ | 809.8 ± 7.9³ |
| Insoluble dietary fiber (g/kg) | 552.1 ± 7.0² | 590.3 ± 10.3³ | 750.8 ± 7.6³ | 763.5 ± 3.9³ | 767.9 ± 13.1³ |
| Soluble dietary fiber (g/kg) | 642.0 ± 11.0³ | 98.1 ± 2.3³ | 1325.0 ± 17.4³ | 1728.2 ± 6.9³ | 420.0 ± 1.9³ |
| WHC (g water/g)            | 14.03 ± 3.4³ | 14.45 ± 0.66³ | 14.84 ± 1.05³ | 17.68 ± 2.43³ | 14.63 ± 1.26³ |
| SWC (ml water/g)           | 9.97 ± 0.48³ | 6.94 ± 0.39³ | 13.96 ± 0.01³ | 16.49 ± 0.07³ | 10.14 ± 0.30³ |
| OHC (g oil/g)              | 0.08 ± 0.01³ | 0.04 ± 0.01³ | 0.01 ± 0.00³ | 0.01 ± 0.00³ | 0.005 ± 0.00³ |

Data expressed in dry weight as mean ± standard deviation of three independent experiments. Means in a column followed by different superscript letters are significantly different (p < 0.05). FPDFC-HD: PDFC from fresh pomace and hot air-dried; SPDFC-HD: PDFC from pressure-steamed pomace and hot air dried; SPDFC-L: PDFC from pressure-steamed pomace and lyophilized.

**Tabla 3.** Contenido de fibra dietaria y propiedades tecnológicas del bagazo de piña fresco (BPF) y tratado con vapor a presión (BPV), y concentrados de fibra dietaria de piña seleccionados (CyFDP).

| Parámetro                  | FPP       | SPP       | FPDFC-HD  | SPDFC-HD  | SPDFC-L  |
|---------------------------|-----------|-----------|-----------|-----------|-----------|
| Fibra dietética total (g/kg) | 583.6 ± 8.0³ | 607.4 ± 8.4² | 883.3 ± 5.2³ | 936.3 ± 8.0³ | 809.8 ± 7.9³ |
| Fibra no disoluble (g/kg) | 552.1 ± 7.0² | 590.3 ± 10.3³ | 750.8 ± 7.6³ | 763.5 ± 3.9³ | 767.9 ± 13.1³ |
| Fibra soluble (g/kg)      | 642.0 ± 11.0³ | 98.1 ± 2.3³ | 1325.0 ± 17.4³ | 1728.2 ± 6.9³ | 420.0 ± 1.9³ |
| WHC (g agua/g)            | 14.03 ± 3.4³ | 14.45 ± 0.66³ | 14.84 ± 1.05³ | 17.68 ± 2.43³ | 14.63 ± 1.26³ |
| SWC (ml agua/g)           | 9.97 ± 0.48³ | 6.94 ± 0.39³ | 13.96 ± 0.01³ | 16.49 ± 0.07³ | 10.14 ± 0.30³ |
| OHC (g aceite/g)          | 0.08 ± 0.01³ | 0.04 ± 0.01³ | 0.01 ± 0.00³ | 0.01 ± 0.00³ | 0.005 ± 0.00³ |

Datos expresados como la media ± desviación estándar de tres experimentos independientes. Promedios en una columna seguido de diferentes letras en súper índice son significativamente diferentes (p < 0.05). CFDPBF-SC: CFDP de bagazo fresco secado con aire caliente; CFDPBV-SC: CFDP de bagazo tratado con vapor a presión y secado con aire caliente; CFDFBP-SC: CFDP de bagazo tratado con vapor a presión y liofilizado.
measured values. The same changes in microstructure were also observed in the SPDFC-HD but with greater effect as is shown in Figure 3(b), where the cellulose microfibrils are shown broken, maybe by the action of hot air-drying, according to the report by Chiewchan (2018).

The powder of SPDFC-HD had higher TDF, SDF and IDF contents (Table 2) than those reported for DFC powders from pineapple (758, 6 and 752 g/kg, respectively), guava (691, 111 and 577 g/kg, respectively) juice-processing co-products (Martínez et al., 2012), ripe persimmon peel (749.5, 52.3 and 698.7 g/kg, respectively) (López-Vargas et al., 2013). The proportion (18.46%) of SDF with respect to the TDF of SPDFC-HD powder was similar to those reported for DFCs from carambola pomace (20.68%) (Pantaleón-Velasco et al., 2014) and artichoke stems (20.3%) (Boubaker et al., 2016) and slightly lower than that reported for DFC from passion fruit albedo (27.09%) (López-Vargas et al., 2013).

**Partial identification of polyphenols by HPLC**

The second most important group of phenolic compounds are phenolic acids, which account for almost the remaining third of the dietary polyphenols, and which are present in fruits in a bound form (Haminiuk et al., 2012). The profile of phenolic acids of raw materials (FPP and SPP) and the PDFC subjected to hot air-tray-drying (SPDFC-HD and FPDFC-HD) (Figure 1 and Table 4) showed that hydroxycinnamic acids as cinnamic acid followed by p-coumaric acid, chlorogenic acid and cafeic acid were the most abundant phenolic acids in the raw material (FPP), while gallic acid (hydroxybenzoic acid) showed the lowest level. However, after pressure steaming of FPP, the gallic acid content increased ($p < 0.05$), showing SPP the highest content of this polyphenol, maybe by a release from its derivative and bounded chemical structures (sugar derivatives and hydrolysable tannins) (Nayak et al., 2015) caused by the heat steaming under pressure; this could be related with the partial disruption of cell wall matrix, as can be seen in the microstructure micrography of Figure 2(b). After the concentration process and drying, the content of gallic acid decreased in SPDFC-HD ($p < 0.05$), maybe by a chemical change of the phenolic acid structure such as decarboxylation and polymerization caused by the heat treatment (Nayak et al., 2015) during the production of PDFC powder (hot water with mechanical agitation and subsequent hot air-drying). Contrarily, the concentration of cinnamic acid increased after the production of SPDFC-HD (Table 4) although its content significantly decreased after pressure steaming (SPP) of FPP. This could be due to a chemical damage in the structure of free cinnamic acids by the heat of steaming under pressure with the subsequent release of this polyphenol from the cellulose, lignin and cell wall proteins (where it is bonded through ester bonds) (Haminiuk et al., 2012; Nayak et al., 2015) caused by disruption of cell wall matrix because of the mechanical agitation and heat treatments applied during the production of SPDFC-HD.

This is the first work that phenolic acid profile is determined in PP and PDFCs and showed that SPDFC-HD was the sample with the highest content of both types of polyphenols.


**Table 3.** The results of WHC, SWC and OHC as technological properties of FPP, SPP and selected PDFCs are presented in Table 3. There was no significant difference (p > 0.05) in WHC between all samples except SPDFC-HD, which showed the highest value (p < 0.05). This could be due to the higher TDF and SDF contents of this sample (Table 3) and its broken cell wall microstructure (Figure 3), which may release hydrophilic polysaccharides whose water is held on the strongly hydrophilic sites or within void spaces in the molecular structure (Sharma et al., 2016). The SPDFC-HD had higher WHC than those reported for DFCs from pineapple, passion fruit, guava and mango co-products (14.6, 13.5, 10.2 and 6.4 g/g, respectively) (Martínez et al., 2012), passion fruit co-products such as pulp-seeds and albedo (1.80 and 13.0 g/g, respectively) (López-Vargas et al., 2013), carambola pomace (11.1 g/g) (Pantaleón-Velasco et al., 2014) and artichoke stems (8.17 g/g) (Boubaker et al., 2016).

As shown in Table 3, PDFCs showed higher SWC values than FPP and SPP, maybe by the higher content of TDF, IDF and SDF than their raw materials (Table 3), and because of their modified cell matrix structure (Figure 2). SPDFC-HD was the sample with the highest value followed by FPDFC-HD, which can be related to its higher TDF, IDF and SDF contents (p < 0.05) (Table 3) and the modified cell wall structure (Figure 3). This indicates the positive impact of hot-air drying on SWC. The SWC of SPDFC-HD (16.49 mL/g) was higher than those reported by DFC powders prepared from guava, mango, pineapple and passion fruit by-products (1.4, 4.6, 6.6 and 7.2 mL/g, respectively) (Martínez et al., 2012) and persimmon peels (5.76–6.18 mL/g) concentrated by different washing treatments (Akter et al., 2010a).

Regarding OHC, all samples showed very low values and significant differences between them (Table 3). FPP was the sample with the highest OHC value followed by SPP. They had higher OHC than PDFCs, which could be due to the lower TDF content of the PP samples than PDFCs (Table 3). These results were lower than the range reported for DFCs from pineapple, guava and passion fruit by-products (0.7–0.9 g oil/g) (Martínez et al., 2012).

The low OHC values of PDFCs could be useful in low fat foods, while high WHC and SWC values specifically indicate that SPDFC-HD has potential application in products requiring hydration, viscosity and gelling, and freshness preservation such as baked foods or cooked meat products. Therefore, SPDFC-HD was selected and produced to be used as ingredient in the formulations of Vienna-type sausages.

**Effect of the mixture of PDFC powder, pork and turkey meats on chemical and physical characteristics of Vienna-type sausages**

The Table 5 shows the cubic model equations that model the experimental and predicted values for the responses. With regard to chemical responses, the residual nitrites, carotenoids and polyphenols had very high determination
coefficients, while moisture and AOX had high determination coefficients ($p < 0.05$). The ANOVA of the lineal regression model showed that there was a decrease in residual nitrates as the proportion of SPDFC-HD increased in the formulation of Vienna-type sausages ($p < 0.05$), while there was a slight tendency to increase this value when the SPDFC-HD is mixture with pork and turkey. Contrarily, the lineal regression model showed that polyphenol and its antioxidant capacity significantly increased when SPDFC-HD was in mixture with pork and turkey meats ($p < 0.05$).

In addition, the ANOVA of the lineal regression model demonstrated that carotenoid content showed a tendency to increase its content as the concentration of SPDFC-HD increases in the formulations ($p < 0.05$). These results demonstrated that reduction of residual nitrite content was related with the increase in carotenoids and polyphenols with AOX, which in turn depends on the increase in the SPDFC-HD proportion in the mixture up to the highest proportion (10%). This behavior could be explained by reactions between nitrates with bioactive compounds present in the DF. Thus, nitrite maybe transformed into nitrous acid, which in turn reacts with the exogenous reducing substances such as ascorbic acid and polyphenols, with a final transformation into nitric oxide (Li et al., 2013). The reduced residual nitrite content in the sausage products has potential health effects because it reduces the possibility of toxic nitrosamines formation (Honikel, 2008).

With reference to the physical responses (Table 5), the cubic model equations showed a very close relationship between the experimental and predicted values of shear force, while shrinkage showed a high correlation between them. The model equations for shear force showed that there was a trend to increase the shear force value with the increase of SPDFC-HD proportion in the mixture with either pork meat or turkey meat ($p < 0.05$). However, there were significant binary and ternary effects, which demonstrated a decrease of shear force with the decrease in SPDFC-HD proportion in the mixture with pork and turkey meats ($p < 0.05$). On the other hand, the model equations for shrinkage showed an effect of pure component, with a significant increase in this value as the proportion of pork meat or turkey meat increased as unique component in the formulation ($p < 0.05$). However, there was a ternary effect, which showed a decrease of shrinkage as the proportion of SPDFC-HD increases in the mixture with pork and turkey meats ($p < 0.05$). The lower values of shear force and shrinkage as the proportion of SPDFC-HD increased in the mixture with pork and turkey meats is a desirable physical quality in the Vienna-type sausages, and could be due to a structuration of the emulsion matrix of the sausage caused by DF, which avoid their shrinkage during the oven heating, making it harder. This could be also related to the hydration functional properties of DF (Sánchez-Zapata et al., 2011).

The mathematical equations obtained for the color responses (Table 5) showed that $L^*$ and $b^*$ parameters had high determination coefficients. The ANOVA of the regression analysis demonstrated that as the concentration of SPDFC-HD increased in the Vienna sausage formulation, the lightness ($L^*$) and yellowness ($b^*$) values increased in the Vienna sausage formulation, which was related to yellow carotenoid pigments presence in the SPDFC-HD (Table 2). Similar findings has been reported by Kim et al. (2011) in low-fat pork sausages and cooked beef Frankfurter sausages added with tomato powder and was also attributed to the carotenoid pigments.

Conclusions

The pretreatment of steaming under pressure increased the values of DF, protein, fat, carotenoids, polyphenols and antioxidant capacity of FPP. In addition, drying applied to fresh PDFCs also impacted on their chemical composition and technological properties. Chemical composition allowed to select one of the PDFCs from the four PDFCs produced by the technological process proposed in this work. The selected PDFC (SPDFC-HD) was a powder produced from SPP, concentrated by hot water/mechanical agitation and dried by hot air, with high content of TDF and insoluble and soluble fractions, carotenoids and polyphenols with AOX, which was related with its high content of gallic, cinnamic and p-coumaric acids. A cell wall disruption of the matrix of SPP and even more severe in SPDFC-HD was evidenced by the microstructural analysis. The high values in hydration properties of SPDFC-HD indicated the potential application of SPDFC-HD as sausage ingredient. The cubic model equations demonstrated that with the increase in SPDFC-HD proportion in the mixture, a reducing effect on nitrates, moisture, shear force and shrinkage was obtained in Vienna-type sausages, while carotenoids and antioxidant polyphenols increased. This study demonstrated that SPDFC-HD was produced with characteristics to be used as ingredient in mixture with pork/turkey meats in potential functional Vienna-type sausages with good physical properties.

Table 5. Regression coefficients of special cubic model equations.

| Parameters | $b_1$  | $b_2$  | $b_3$  | $b_{12}$ | $b_{13}$ | $b_{23}$ | $b_{123}$ | $R^2$ |
|------------|--------|--------|--------|----------|----------|----------|-----------|-------|
| Moisture   | 67.87  | 70.70  | −313.53| −7.34    | −347.98  | 352.98   | 17.89     | 0.8967|
| Residual nitrates | 69.74  | 71.20  | −615.69| −6.12    | 458.02   | 457.20   | 93.99     | 0.9847|
| Carotenoids | 0.10   | 0.11   | 6.29   | 0.015    | −2.275   | −3.124   | −0.987    | 0.9777|
| Polyphenols x $10^2$ | 159.88 | 254.08 | −7545.59| −106.55  | 11.150.07| 9424.76  | −145.02   | 0.9139|
| Antioxidant capacity (FRAP) | 9.57   | 11.55  | −937.29| 8.42     | 1196.83  | 1166.44  | −46.17    | 0.8259|
| Shear force | 7.68   | 7.96   | 506.62 | 2.05     | −430.73  | −480.47  | −41.52    | 0.9031|
| Shrinkage  | 9.24   | 11.14  | 24.07  | −3.02    | −52.72   | −62.20   | −119.24   | 0.7731|
| $L^*$      | 60.02  | 64.11  | 315.21 | 11.66    | −301.45  | −333.90  | −69.39    | 0.8216|
| $a^*$     | 8.85   | 8.18   | 11.09  | 1.27     | −27.51   | −33.23   | −0.83     | 0.7667|
| $b^*$     | 10.65  | 13.02  | 312.39 | 4.05     | −253.28  | −259.38  | 9.35      | 0.8895|

Bold numbers indicate significant parameter estimates ($p < 0.05$).

Números en negritas indican parámetros estimados significativamente ($p < 0.05$).

Tabla 5. Coeficientes de regresión de las ecuaciones del modelo cúbico especial.
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No potential conflict of interest was reported by the authors.

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