Physical properties and estimated glycemic index of protein-enriched sorghum based chips

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Abstract Sorghum is a gluten-free grain and more attention has been given to the nutritional properties and recently its usage as a wheat replacement in food products. In the present work, protein-enriched sorghum based snack chips, prepared from sorghum meal with soy protein isolates and soy flour to meet the final protein content of 35.7%, were produced. The effect of varying baking powder (1.5–2.5%), dough sheet thickness (0.7–1.7 mm), and baking time (6–12 min) on the physical properties of the snack chips was investigated using a central composite design of response surface methodology. Under baking temperature of 160 °C, with baking powder added, the water activity and puffiness of chips significantly increased. Baking time was the most significant factor for all the parameters detected except for puffiness. The optimized conditions of preparing protein-enriched sorghum chips were baking powder 2.5%, dough sheet thickness 0.7 mm, and baking time 7.66 min. The estimated glycemic index (eGI) of the protein-enriched sorghum chips (eGI = 59.8) was significantly lower than soybean-free sorghum chips. The gluten-free protein-enriched sorghum chips developed could be considered as protein rich with lower intermediate-glycemic index classified healthy snacks and potential commercialization.

Keywords Sorghum · Chips · Protein enrichment · Physical properties · Glycemic index

Introduction

Globally, the United States is the largest producer of sorghum, the fifth most important cereal in the world (USDA-FAS 2017). Although the majority portion of sorghum is used as animal feed and in alcohol products (Wang et al. 2005), there has been a growing awareness of developing sorghum products due to its human health promoting benefits, such as antioxidant, reducing the risk of cancer (Gómez-Cordovés et al. 2001), anti-cardiovascular disease (Awika and Rooney 2004), and combating obesity (Muriu et al. 2002). Gluten-free is another benefit of sorghum as human food source to replace wheat, which may cause celiac disease primarily in the US and other western countries (Mirhosseini et al. 2015).

During the last decades, sorghum has been increasingly studied as an ingredient being incorporated into snack foods and bakery products, including breads and cake (Marston et al. 2016; Schober et al. 2007), tortilla (Quintero-Fuentes et al. 1999), and extruded snacks (Jafari et al. 2017). However, due to the lack of gluten network in gluten-free dough, developing products fully or partially made from sorghum flour is difficult and challenging (Taylor et al. 2006). Extrusion is a major processing method for preparing puffy and porous sorghum snacks (Jafari et al. 2017). Although baking was another method when tortilla chips were made from sorghum (Quintero-Fuentes et al. 1999; Winger et al. 2014), this method was used more extensively for preparing sorghum breads (Carson et al. 2000; Marston et al. 2016).

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It is claimed that high protein food products should provide more than 20% of daily reference value protein (50 g) for adults and children over 4-year old (CFR 2016). With an aim of increasing protein content, soybean is one of the protein-rich sources and has been applied to prepare snack foods or to fortify cereal-based foods to improve their protein content or nutritional qualities (Maetens et al. 2017; Nath and Chattopadhyay 2007). The protein content of soybean is about 40–53% in dry soybean, while in the form of isolate the protein content can reach up to 90% for various food application due to its high nutritional value (Rayaprolu et al. 2015). In contrast, sorghum flour contains only approximately 10–12% of protein (Afify et al. 2012). So, there is a potential to use soybean to enhance the protein content of food products when sorghum is used as the main ingredient. However, there is no study reported the use of soy flour or soy protein added into sorghum based food production to enhance protein content.

In the present study, protein-enriched sorghum snack chips (35.7% protein content) were prepared from sorghum flour added with soy flour and soy protein isolate (SPI). Physical properties including moisture content, water activity, texture, and color, and estimated glycemic index (eGI) of the chips were investigated to optimize the procedure of preparing the protein-enriched sorghum chips.

Materials and methods

Materials

White whole grain sorghum flour (protein 10.0%, carbohydrates 76.6%, fat 3.3%, and crude fiber 6.6%) was purchased from D'allesandro Corporation (Avon, MA, U.S.A.). Baking powder (Clabber Girl Corp., Terre Haute, IN, U.S.A.) was purchased from a local store, while cellulose gum BAK130 was provided by Danisco, Inc. (New Century, KS, U.S.A.). Soybean provided by The Natural Soybean and Grain Alliance (Fayetteville, AR, U.S.A.) was milled and passed through 60 mesh sieve to obtain soy flour (protein 46.0%, carbohydrates 4.3%, fat 20.9%, and fiber 2.2%). Soy protein isolate (SPI, 90% protein) was obtained from Archer Daniels Midland Co. (Decatur, IL, U.S.A.).

Optimization of sorghum chip preparation

For the preparation of protein-enriched sorghum based dough, 55.6 g sorghum flour was blended with 22.2 g soybean flour and 22.2 g SPI to obtain a total of 100 g flour-mix to meet a final protein content of 15 g per serving size (approx. 42 g). Then, 2.0 g salt, 1.5–2.5 g baking powder (0.15–0.25% w/w), 1.0 g cellulose gum and 45.0 g

water were mixed into the flour-mix, sequentially. The mix was kneaded manually to form dough. After resting for 30 min in ambient temperature, the dough was flattened using a stainless pasta maker with a thickness of 0.7–1.7 mm and cut into 2×2 cm dough sheets. The square-shaped dough pieces were placed on a baking pan and baked in an air-impingement oven at 160 °C for 6–12 min. After baking, the chips were cooled to ambient temp and placed in Ziploc bags.

A central composite rotatable design (CCD) of three-factor three levels pattern with 17 design points (8 axial, 6 factorial, and 3 central points) was selected to optimize the processing procedure of the sorghum chip preparation. According to preliminary trials, baking powder (0.15, 0.20, or 0.25%), thickness of the dough sheets (0.7, 1.2, or 1.7 mm), and baking time (6, 9, or 12 min) were set as independent variables. The experiment runs, coded values for all factors are shown in Table 1. The physical properties of the chips including color, moisture, water activity, puffiness (shrinkage expansion), and texture were investigated as dependent variables. The experiments were performed in quadruplicate.

Moisture content and water activity

The moisture content of the samples was determined by a hot air-oven method according to AACC (1999). Water activity (A_w) of samples was analyzed by a dew point water activity meter (model 4TE, AquaLab, Pullman, WA, U.S.A.).

Color analysis

The color of the sorghum chips was analyzed by CR-300 Chroma meter (Konica Minolta Inc., Tokyo, Japan); the color parameters of lightness/darkness (L^*), greenness/redness (a^*) and blueness/yellowness (b^*) were determined in duplicate. The data were then expressed as brownness index (BI), which was calculated according to Shittu et al. (2007), using following equations:

$$BI = 100 \times (x - 0.31) / 0.17 \quad (1)$$

$$x = (a^* + 1.75 \times L^*) / (5.645 \times L^* + a^* - 3.012 \times b^*) \quad (2)$$

Textural analysis

The textural characteristics of the sorghum snack chips in terms of hardness and fracturability were measured using TA-XT2i texture analyzer (Scarsdale, NY, U.S.A.) fitted with a P/0.25S ball probe and a middle-hole base. The studies were conducted at a pre-test speed of 1.0 mm/s, test speed of 1.0 mm/s, distance of 10.0 mm, and trigger force

Table 1 Physical properties of protein-enriched sorghum chips ($n = 4$) prepared by central composite rotatable design with different levels of baking powder, thickness of chip dough sheet, and baking time

Run	Variable codes	Moisture (g/100 g)	Water activity	Fracturability (g)	Hardness (g)	Puffiness (%)	Brownness index
1	− 1, − 1, − 1	7.4 ± 1.7	0.38 ± 0.04	351 ± 73	532 ± 115	690 ± 61	36.6 ± 0.4
2	1, − 1, − 1	7.3 ± 0.5	0.44 ± 0.02	412 ± 107	766 ± 86	775 ± 51	34.9 ± 0.3
3	− 1, 1, − 1	22.7 ± 0.0	0.71 ± 0.04	664 ± 128	667 ± 148	331 ± 33	33.6 ± 0.8
4	1, 1, − 1	14.6 ± 1.9	0.75 ± 0.03	911 ± 109	916 ± 121	321 ± 21	34.8 ± 0.3
5	− 1, − 1, 1	2.1 ± 0.7	0.33 ± 0.01	762 ± 140	762 ± 162	643 ± 88	57.2 ± 1.4
6	1, − 1, 1	5.2 ± 1.3	0.35 ± 0.03	758 ± 122	894 ± 160	749 ± 90	56.7 ± 3.3
7	− 1, 1, 1	4.5 ± 1.4	0.33 ± 0.01	2687 ± 140	2736 ± 114	359 ± 16	41.9 ± 1.3
8	1, 1, 1	4.5 ± 1.8	0.42 ± 0.02	2775 ± 193	2816 ± 169	409 ± 34	38.3 ± 1.3
9	− 1, 0, 0	4.5 ± 0.7	0.26 ± 0.01	968 ± 76	1024 ± 86	432 ± 18	36.7 ± 1.0
10	1, 0, 0	2.2 ± 0.4	0.41 ± 0.03	1022 ± 77	1049 ± 126	474 ± 20	35.8 ± 1.3
11	0, − 1, 0	2.7 ± 0.9	0.34 ± 0.00	605 ± 131	919 ± 136	809 ± 79	51.0 ± 1.1
12	0, 1, 0	14.1 ± 0.3	0.58 ± 0.01	1858 ± 372	1919 ± 190	392 ± 35	35.7 ± 0.7
13	0, 0, − 1	15.8 ± 0.5	0.56 ± 0.02	760 ± 209	814 ± 179	487 ± 33	35.2 ± 0.8
14	0, 0, 1	2.4 ± 0.5	0.33 ± 0.01	1514 ± 166	1536 ± 189	446 ± 40	53.1 ± 2.5
15	0, 0, 0	6.9 ± 0.2	0.42 ± 0.01	1288 ± 227	1392 ± 174	544 ± 34	36.4 ± 0.7
16	0, 0, 0	5.7 ± 0.0	0.39 ± 0.01	1103 ± 125	1103 ± 125	476 ± 15	39.8 ± 1.3
17	0, 0, 0	5.3 ± 0.2	0.39 ± 0.02	1046 ± 164	1089 ± 56	544 ± 70	37.5 ± 1.0

Variable codes (− 1, 0, 1) of baking powder level (1.5, 2.0, 2.5%, respectively), dough sheet thickness (0.7, 1.2, 1.7 mm, respectively), and baking time (6, 9, 12 min, respectively) represent for X_1 , X_2 , and X_3 , respectively. The initial moisture content and water activity of the dough were approximately $31.0 \pm 0.4\%$ and 0.92 ± 0.02 respectively

of 0.49 N. Hardness was determined from the highest peak force value (in gram), while fracturability was recorded as the first peak force value obtained during compression. The average values of four readings were used for each replication.

Degree of puffiness

The degree of puffiness of the chips was calculated according to the method described by Kawas and Moreira (2001). Briefly, the thickness was measured using an electronic caliper (MSC Industrial supply, NY, U.S.A.). The degree of puffiness (P_i) was calculated by Eq. (3).

$$P_i = (h_t - h_0)/h_0 \times 100 \quad (3)$$

where h_0 and h_t represent the thickness of chips before and after baking, respectively.

Determination of estimated glycemic index in vitro

The estimated glycemic index of the protein-enriched sorghum chips developed was investigated in the present study. Meanwhile, full sorghum chips and soybean flour-sorghum chips were also made for comparisons. The flour-mix of full sorghum chips was made of sorghum flour only, while a mix of 55.6 g sorghum flour blended with 44.4 g soybean flour was used for preparing soybean flour-

sorghum chips. The protein-enriched sorghum chips were prepared using the obtained optimum processing condition. The eGI values of sorghum chips were determined according to the method of Goñi et al. (1997). Briefly, the samples were ground through 60 mesh and hydrolyzed by pepsin, α -amylase and amyloglucosidase, successively. The glucose concentration was measured with glucose assay kit (GAGO-20, Sigma, U.S.A.). The hydrolysis index (HI) of the sample was calculated from the ratio of the area under hydrolysis curve of samples (0–180 min hydrolysis in 30 min increment) and that of white bread as a reference (Goñi et al. 1997). The eGI was calculated by Eq. (4).

$$eGI = 39.71 + 0.549HI \quad (4)$$

Statistical analysis

The optimization of protein-enriched sorghum chip was determined by using Minitab-17 and IBM SPSS Software following central composite rotatable model (Table 1). For the description of the response, a second order polynomial equation (Eq. 5) was used to fit the experiment data.

$$Y = \beta_0 + \sum_{i=1}^3 \beta_i X_i + \sum_{i=1}^3 \beta_{ii} X_i^2 + \sum_{i=1}^3 \sum_{j=1}^3 \beta_{ij} X_i X_j \quad (5)$$

where, Y is the predicted response, β_0 , β_i , β_{ii} and β_{ij} are regression coefficients for the intercept, linear, quadratic and interaction effects respectively, and X_i and X_j are independent variables. The regression equations were summated to the F test to determine the coefficient of determination (R^2) and a test of significance was performed for each parameter estimator according to analysis of variance (ANOVA). Parameters with significance $< 95\%$ were excluded. The combination of different optimized parameters was tested experimentally to confirm the suitability of the model.

Results and discussion

Effect of varying baking powder, dough sheet thickness, and baking time on moisture and water activity

Moisture and A_w are both very important for the texture property of snack foods due to the heat and mass transfer properties of water (Katz and Labuza 1981), and they are also significant factors of shelf stability in relation to bacterial growth in food. The initial moisture content and A_w of the dough were approximately 31% and 0.92 respectively. In the present study, moisture content and A_w of the protein-enriched sorghum chips were affected significantly by baking powder content (X_1), dough sheet thickness (X_2) and baking time (X_3) estimated according to CCD design (Tables 1, 2). The regression equation describing the effect of the process variables on moisture

and A_w of protein-enriched sorghum snack chip in terms of actual level are given as:

$$\text{Moisture}(\%) = -4.07 + 12.04X_2 - 7.39X_3 - 1.74X_2X_3 - 11.03X_1^2 + 0.33X_3^2 \quad (6)$$

$$A_w = -0.07 + 0.92X_1 - 0.09X_2 - 0.09X_3 - 0.05X_2X_3 - 0.22X_1^2 + 0.27X_2^2 + 6.21X_3^2 \quad (7)$$

Upon baking, water evaporation and diffusion within the product resulted in a significant moisture loss and A_w change (Feyissa et al. 2011). It can be observed that thickness of the dough sheets and baking time was the most significant parameters for the moisture content and A_w at the linear level ($P < 0.05$), but only for A_w at the interactive level ($P < 0.001$). Baking powder showed linear significant effects on the A_w ($P < 0.05$) and quadratic significant effects on both moisture and A_w ($P < 0.05$). The range of moisture content of the chips was 2.1–22.7%, and 0.26–0.75 for A_w , much lower than the initial moisture content and A_w (Table 1). Although higher baking powder contents generated a significant decrease of chip's moisture and A_w under the same dough sheet thickness (Fig. 1a, b), there was no relationship between the moisture and A_w of the chips prepared with same thickness of dough sheet and baking powder content. This could be due to that baking is a very complex heating process, leading to the products undergoing water transition and water evaporation (Feyissa et al. 2011), while baking powder might change the water distribution and water binding ability between aqueous

Table 2 Estimated regression coefficients and significant for second-order polynomial model responses on physical properties of protein-enriched sorghum chips

Parameters	Moisture (g/100 g)	Water activity	Fracturability (g)	Hardness (g)	Puffiness (%)	Brownness index
Constant	6.07	0.40	1124.77	1171.33	508.80	39.32
X_1	− 0.74	0.034 ^a	44.36	71.86	27.31 ^a	− 0.56
X_2	3.57 ^c	0.094 ^c	600.72 ^c	518.04 ^c	− 185.39 ^c	− 5.20 ^c
X_3	− 4.92 ^c	− 0.11 ^c	540.02 ^c	505.06 ^c	0.25	7.21 ^c
X_1X_2	− 1.37	0.32	34.77	− 4.67	− 18.92	− .037
X_1X_3	1.42	0.091	− 28.13	− 33.89	10.22	− 0.47
X_2X_3	− 2.60 ^b	− 0.071 ^c	391.64 ^c	451.58 ^c	23.75	− 3.84 ^b
X_1^2	− 2.76 ^a	− 0.055 ^a	− 113.72	− 142.72	− 45.77 ^a	− 4.07 ^a
X_2^2	2.26	0.068 ^a	122.37	239.46 ^a	101.91 ^b	3.00
X_3^2	2.98 ^a	0.056 ^a	27.90	− 4.60	− 32.65	3.78 ^a
R^2	0.9543	0.9755	0.9868	0.9796	0.9825	0.9565
Model	0.0007	< 0.0001	< 0.0001	< 0.0001	< 0.0001	0.0006
Lack of fit	0.1243	0.1511	0.5979	0.8836	0.7842	0.2851

X_1 , baking powder content; X_2 , dough sheet thickness; X_3 , baking time

Values with lower letters are affected significantly; a, b, and c mean $P < 0.05$, $P < 0.01$, and $P < 0.001$, respectively

Fig. 1 Effect of baking powder content (%), dough sheet thickness (mm), and baking time (min) on moisture (a), water activity (b), puffiness (c), and browning index (d) of protein-enriched sorghum chips

phase and non-aqueous phase through the production of carbon dioxide and vapor heating (Singh et al. 2000).

Effect of baking powder content, dough sheet thickness, and baking time on fracturability and hardness

In this study, minimum fracturability (351 g) and hardness (532 g) were observed from the baking condition that included baking powder at 1.5%, with 0.7 mm of dough sheet thickness and baking time for 6 min (Table 1). The maximum fracturability (2775 g) and hardness (2816 g) were observed when the chips were prepared using 2.5% baking powder, with 1.7 mm of dough sheet thickness and baking time of 12 min. The fracturability and hardness of the chips were not significantly dependent on baking powder addition ($P > 0.05$). However, the thickness of the dough sheets and baking time are the most significant parameter affecting both fracturability and hardness ($P < 0.001$) at linear and interact levels ($P < 0.001$) (Table 2).

The coefficients of the first order terms (Table 2) indicated that baking powder, dough sheet thickness and baking time showed a positive relation to both the fracturability and hardness of the chip samples. This agrees with a study reported by Nath and Chattopadhyay (2007) who observed that temperature and time were the most significant parameters positively affecting the fracturability of air puffed potato–soy snack. Both the fracturability and hardness values of the chips from this study are higher than those of soybean composed snacks reported by others (Nath and Chattopadhyay 2007; Ostermann-Porcel et al. 2017). This might be due to the higher fiber content present in sorghum flour (6.6 vs 2.2% in soybean) that could increase the textural hardness.

Effect of baking powder content, dough sheet thickness, and baking time on puffiness

The puffiness values of protein-enriched sorghum chips under different process conditions are shown in Table 1. The puffiness values ranged widely from 321 to 809%,

which means the thickness of the obtained chips expanded about three to eight times after baking. The baking powder and thickness of the dough sheets significantly contributed to puffiness of the obtained chips at both linear and quadratic levels ($P < 0.05$). As shown in Fig. 1c, increasing baking powder content resulted in a gradual increase of the puffiness to reach the maximum and then decreased. This means that more baking powder in the formula is not necessary for better puffiness. Although the superheated steam and Carbon dioxide released by baking powder during baking would increase the expansion of chips, and the gelatinized starch of sorghum flour would also trap steam during expansion to form puffy chips (Quintero-Fuentes et al. 1999), the high protein content in the dough limited the starch gelatinization and caused the texture more firmness (Akin and Miller 2017). The high protein concentration (35.7%) of the chips made in the present study might be related to the limit the expansion capacity of baking powder and starch gelatinization. Other studies on the addition of baking powder into wheat starch (Singh et al. 2000) and corn starch (Chinnaswamy and Hanna 1988) also showed a similar consequence. In addition, with large interior air cells of the expanded thickness, the sorghum chips might be broken easily on the first bite, therefore, the suitable thickness of dough sheet and baking powder content to produce maximum puffiness of chips will be considered.

Effect of baking time on color

The surface color of a baked product is one of the important elements for the initial acceptability of baked foods by consumers. In the present study, the thickness and baking time significantly affected the color of the chip samples ($P < 0.001$) (Table 2). It can be observed that an increase in the dough sheet thickness caused a significant decrease in BI values ($P < 0.001$), while extended baking time increased BI values significantly ($P < 0.001$) (Fig. 1d). The regression equation describing the effect of the process variables for baking powder content (X_1), dough sheet thickness (X_2), and baking time (X_3) on BI values of the protein-enriched sorghum chips in terms of actual level are given as:

$$BI = -14.88 - 1.47X_2 - 0.15X_3 - 2.56X_2X_3 - 16.27X_1^2 + 0.42X_3^2 \quad (8)$$

The changes in brown color profiles in different thickness of the chip dough sheets at different baking time were also observed (Fig. 2). During baking from 0 min to 6 min, the lightness of chips changed very slightly and the difference could not be distinguished by naked eye. After

Fig. 2 Images of protein-enriched sorghum chips prepared under different baking time (6, 8, 10, or 12 min) at dough sheet thickness of 0.7 mm (a), 1.2 mm (b), and 1.7 mm (c) and a baking temperature of 160 °C

6 min of baking, the BI values varied among the three different thicknesses. This might be caused by the evaporation of the water on the product surface during the early stage of baking (Shibukawa et al. 1989) and the temperature on the surface of chips at the beginning of baking was not enough to initiate browning reactions (Broyart et al. 1998). It can also be seen from Fig. 2, the phenomenon of browning was delayed with the increase of the dough sheet thickness, which means that thicker surface of the dough need more time to increase the surface temperature of the chips. This disagrees with another study that concluded that the development of surface color was only dependent on the product temperature (Shibukawa et al. 1989); this difference may be due to the difference in baking temperature. While this study used 160 °C, the baking temperature used by Shibukawa et al. (1989) was 200 °C. At lower baking temperature, heat transfer within the dough sheet during baking could be affected by the thickness of the chip dough sheet due to the effect of water evaporation (Sablan et al. 1998).

Optimized parameters for protein-enriched sorghum chip preparation

Baking is a complex process which results in a series of physical, chemical, and biochemical changes in baked products. The concept of desirable function was chosen to optimize the process conditions (baking powder content, baking time, and dough sheet thickness). As the puffiness was more significantly affected by the process conditions

Table 3 Quality properties of protein-enriched sorghum chips obtained according to experimental and predicted optimum process condition

Optimum process condition	Moisture (g/100 g)	Water activity	Fracturability (g)	Hardness (g)	Puffiness (%)	Brownness index
Experimental (n = 4)	4.0 ± 1.0	0.28	478 ± 64	789 ± 45	793 ± 38	39.82 ± 1.9
Predicted	3.63	0.37	501	817	796	39.95
Variation (%)	9.70	3.21	4.82	3.53	0.38	0.32

All the values obtained under the optimized condition as baking powder of 2.5%, dough sheet thickness of 0.7 mm, and baking time of 7.66 min. Variation is the difference between experimental and predicted values

than hardness and fracturability (Table 2), the optimization was conducted by specifying criteria as follow: minimal A_w value, minimal BI value, and maximum puffiness. The predicted optimized baking condition was a baking powder of 2.5%, dough sheet thickness of 0.7 mm, and baking time of 7.66 min at a baking temperature of 160 °C. The predicted as well as experimentally determined variants and quality parameters are given in Table 3. Variations between the experimental and predicted values of the quality parameters indicated the suitability of the corresponding models. Considering a long shelf life, A_w for snack chips should be kept below 0.7 (Schmidt and Fontana 2007). As shown in Table 3, the optimized baking condition could provide a low A_w (0.28), which means water molecules were strongly bound to other components in the chips after baking. As a consequence the chips could exhibit less microbial contaminated potential. There was no significant difference between the experimental and predicted values ($P > 0.05$) of the quality parameters indicating the suitability of the corresponding models (Table 3).

Estimated glycemic index of protein-enriched sorghum chips

The effect of the dough flour mix composition of the protein-enriched sorghum chips on eGI was compared with full sorghum chips (without SPI and soybean flour) and soybean flour-sorghum chips (without SPI). The protein-enriched sorghum chips, composed of sorghum flour, soybean flour and SPI and prepared using the optimum process, had significantly lower eGI (59.8 ± 0.0) than the chips made without SPI (70.6 ± 0.3) or without SPI and soybean flour (79.9 ± 0.2) ($P < 0.05$). It has been reported that protein-starch interaction might mitigate enzymatic access to starch, which could reduce the starch digestibility in cereals to lower down GI after food intake (López-Barón et al. 2017). The eGI of soybean flour-sorghum chips was significant higher than protein-enriched sorghum chips ($P < 0.05$), which means that SPI is a significant component to trap starch in chips to reduce the speed of starch digestion. Since the intermediate-glycemic index range is

55–70, the protein-enriched sorghum snack chips produced in the present study could be considered as a lower intermediate-GI food.

Conclusion

In the present study, the effect of process conditions on the physical properties was evaluated to obtain the optimized protein-enriched sorghum based chip preparation conditions. The optimum process of the chips was found to be the baking powder content of 2.5%, dough sheet thickness of 0.7 mm, and baking time at for 7.66 min under a baking temperature of 160 °C. The baking powder addition had an effect on puffiness, which also might change the water distribution and therefore affected A_w of the chips during baking. Increasing dough sheet thickness increased moisture and water activity, fracturability and hardness, but decreased puffiness. Baking time is the most significant factor affecting the sorghum chip properties except puffiness. Soy components of the dough flour mix play an important role on lowering the estimated glycemic index of the protein-enriched sorghum based chips. The developed chips could be considered as potential lower intermediate-glycemic index sorghum based chips.

References

- AACC International (1999) Approved methods of analysis. Method 44-15.02. Moisture—air-oven methods, 11th edn. AACC International, St. Paul. <https://doi.org/10.1094/AACCIntMethod-44-15.02>
- Afify AE-MMR, El-Beltagi HS, Abd El-Salam SM, Omran AA (2012) Protein solubility, digestibility and fractionation after germination of sorghum varieties. PLoS ONE 7(2):e31154. <https://doi.org/10.1371/journal.pone.0031154>
- Akin PA, Miller RA (2017) Starch-hydrocolloid interaction in chemically leavened gluten-free sorghum bread. J Cereal Chem 94:897–902
- Awika JM, Rooney LW (2004) Sorghum phytochemicals and their potential impact on human health. Phytochemistry 65:1199–1221. <https://doi.org/10.1016/j.phytochem.2004.04.001>

- Broyart B, Trystram G, Duquenoy A (1998) Predicting colour kinetics during cracker baking. *J Food Eng* 35:351–368. [https://doi.org/10.1016/S0260-8774\(98\)00021-1](https://doi.org/10.1016/S0260-8774(98)00021-1)
- Carson L, Setser C, Sun X (2000) Sensory characteristics of sorghum composite bread. *Int J Food Sci Technol* 35:465–471
- CFR [Code of Federal Regulations] (2016) Title 21-food and drugs. Sec. 101.54 Nutrient content claims for “good source,” “high,” “more,” and “high potency.” U.S. Food and Drug Administration
- Chinnaswamy R, Hanna MA (1988) Expansion, color and shear strength properties of com starches extrusion-cooked with urea and salts. *Starch-Stärke* 40:186–190. <https://doi.org/10.1002/star.19880400507>
- Feyissa AH, Gernaey KV, Ashokkumar S, Adler-Nissen J (2011) Modelling of coupled heat and mass transfer during a contact baking process. *J Food Eng* 106:228–235. <https://doi.org/10.1016/j.jfoodeng.2011.05.014>
- Gómez-Cordovés C, Bartolomé B, Vieira W, Virador VM (2001) Effects of wine phenolics and sorghum tannins on tyrosinase activity and growth of melanoma cells. *J Agric Food Chem* 49:1620–1624. <https://doi.org/10.1021/jf001116h>
- Goñi I, Garcia-Alonso A, Saura-Calixto F (1997) A starch hydrolysis procedure to estimate glycemic index. *Nutr Res* 17:427–437. [https://doi.org/10.1016/S0271-5317\(97\)00010-9](https://doi.org/10.1016/S0271-5317(97)00010-9)
- Jafari M, Koocheki A, Milani E (2017) Effect of extrusion cooking of sorghum flour on rheology, morphology and heating rate of sorghum–wheat composite dough. *J Cereal Sci* 77:49–57. <https://doi.org/10.1016/j.jcs.2017.07.011>
- Katz EE, Labuza TP (1981) Effect of water activity on the sensory crispness and mechanical deformation of snack food products. *J Food Sci* 46:403–409. <https://doi.org/10.1111/j.1365-2621.1981.tb04871.x>
- Kawas ML, Moreira RG (2001) Characterization of product quality attributes of tortilla chips during the frying process. *J Food Eng* 47:97–107. [https://doi.org/10.1016/S0260-8774\(00\)00104-7](https://doi.org/10.1016/S0260-8774(00)00104-7)
- López-Barón N, Gu Y, Vasanthan T, Hoover R (2017) Plant proteins mitigate in vitro wheat starch digestibility. *Food Hydrocoll* 69:19–27. <https://doi.org/10.1016/j.foodhyd.2017.01.015>
- Maetens E, Hettiarachchy N, Dewettinck K, Horax R, Meoens K, Moseley O (2017) Physicochemical and nutritional properties of a healthy snack chip developed from germinated soybeans. *LWT Food Sci Technol* 84:505–510. <https://doi.org/10.1016/j.lwt.2017.06.020>
- Marston K, Khouryieh H, Aramouni F (2016) Effect of heat treatment of sorghum flour on the functional properties of gluten-free bread and cake. *LWT Food Sci Technol* 65:637–644. <https://doi.org/10.1016/j.lwt.2015.08.063>
- Mirhosseini H, Abdul Rashid NF, Tabatabaee Amid B, Cheong KW, Kazemi M, Zulkurnain M (2015) Effect of partial replacement of corn flour with durian seed flour and pumpkin flour on cooking yield, texture properties, and sensory attributes of gluten free pasta. *LWT Food Sci Technol* 63:184–190. <https://doi.org/10.1016/j.lwt.2015.03.078>
- Muriu JI, Njoka-Njiru EN, Tuitoe JK, Nanua JN (2002) Evaluation of sorghum (*Sorghum bicolor*) as replacent for maize in the diet of growing rabbits (*Oryctolagus cuniculus*). *Asian Australas J Anim Sci* 15:565–569. <https://doi.org/10.5713/ajas.2002.565>
- Nath A, Chattopadhyay PK (2007) Optimization of oven toasting for improving crispness and other quality attributes of ready to eat potato–soy snack using response surface methodology. *J Food Eng* 80:1282–1292. <https://doi.org/10.1016/j.jfoodeng.2006.09.023>
- Ostermann-Porcel MV, Quiroga-Panelo N, Rinaldoni AN, Campderrós ME (2017) Incorporation of okara into gluten-free cookies with high quality and nutritional value. *J Food Qual*. <https://doi.org/10.1155/2017/4071585>
- Quintero-Fuentes X, McDonough CM, Rooney LW, Almeida-Dominguez H (1999) Functionality of rice and sorghum flours in baked tortilla and corn chips. *Cereal Chem* 76:705–710. <https://doi.org/10.1094/cchem.1999.76.5.705>
- Rayaprolu S, Hettiarachchy N, Horax R, Satchithanandam E, Chen P, Mauromoustakos A (2015) Amino acid composition of 44 soybean lines and ACE-I inhibition activities of peptide fractions prepared from selected lines. *J Am Oil Chem Soc* 92(7):1023–1033. <https://doi.org/10.1007/s11746-015-2655-y>
- Sablani SS, Marcotte M, Castaigne F (1998) Modeling of simultaneous heat and water transport in the baking process. *LWT Food Sci Technol* 31:201–209. <https://doi.org/10.1006/ftl.1997.0360>
- Schmidt SJ, Fontana AJ (2007) Appendix E: Water activity values of select food ingredients and products. In: Barbosa-Cánovas GV, Fontana AJ, Schmidt SJ, Labuza TP (eds) *Water activity in foods: fundamentals and applications*. Blackwell Publishing Ltd., Oxford, pp 407–420
- Schober TJ, Bean SR, Boyle DL (2007) Gluten-free sorghum bread improved by sourdough fermentation: biochemical, rheological, and microstructural background. *J Agric Food Chem* 55:5137–5146. <https://doi.org/10.1021/jf0704155>
- Shibukawa S, Sugiyama K, Yano T (1989) Effects of heat transfer by radiation and convection on browning of cookies at baking. *J Food Sci* 54:621–624. <https://doi.org/10.1111/j.1365-2621.1989.tb04666.x>
- Shittu TA, Raji AO, Sanni LO (2007) Bread from composite cassava–wheat flour: I. Effect of baking time and temperature on some physical properties of bread loaf. *Food Res Int* 40:280–290. <https://doi.org/10.1016/j.foodres.2006.10.012>
- Singh N, Sharma S, Singh B (2000) Effect of sodium bicarbonate and glycerol monostearate addition on the extrusion behaviour of maize grits. *J Food Eng* 46:61–66. [https://doi.org/10.1016/S0308-8146\(00\)00140-0](https://doi.org/10.1016/S0308-8146(00)00140-0)
- Taylor JRN, Schober TJ, Bean SR (2006) Novel food and non-food uses for sorghum and millets. *J Cereal Sci* 44:252–271
- USDA-FAS (2017) Grain: world markets and trade. United States Department of Agriculture—Foreign Agricultural Service. <https://apps.fas.usda.gov/psdonline/circulars/grain.pdf>. Accessed 17 Aug 2017
- Wang L, Weller CL, Hwang KT (2005) Extraction of lipids from grain sorghum DDG. *Trans Am Soc Agric Eng* 48:1883–1888
- Winger M, Khouryieh H, Aramouni F, Herald T (2014) Sorghum flour characterization and evaluation in gluten-free flour tortilla. *J Food Qual* 37:95–106. <https://doi.org/10.1111/jfq.12080>