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Original research paper

SNACK PRODUCTS FROM WHOLE-GRAIN RED SORGHUM FLOUR WITH PAPRIKA AND COCOA POWDERS

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Abstract: Among the cereals, sorghum (*Sorghum bicolor* L. Moench) is a member of the gluten-free cereal family. This crop is widely cultivated in a wide range of geographic locations due to its strong heat and drought resistance and high photosynthetic efficiency. Rich in macronutrients (proteins, fats, and carbohydrates) and micronutrients (minerals, vitamins), sorghum also contains phenolic compounds (tannins, phenolic acids, and flavonoids), which have antioxidant properties. Given its many health benefits, including its ability to suppress the formation of cancer cells and reduce obesity, heart disease, and diabetes, sorghum is used for both human and animal consumption. It can be used for baking, extrusion, and different cereal-based products such as bread, cookies, pasta, expanded snacks, and breakfast cereals. This study aimed to develop four types of snack products based on red sorghum flour (95, 92, 90, and 89%) with the addition of *i)* a mixture of sweet and hot ground red pepper (5, 8 and 10%); *ii)* cocoa powder (5, 8 and 10%); and *iii)* a mixture of cocoa powder (10%) and cinnamon (1%), while a 100% red sorghum snack product served as a control sample. The following extrusion processing parameters were used: feeding rate of 50 kg/h, screw speed of 800, 850, and 900 RPM, and the material moisture content in the extruder barrel ranged from 13 to 14%. The following quality attributes of snacks obtained were determined: expansion ratio, bulk density, water absorption index, water solubility index, colour and texture (hardness, number of fractures, crispiness work, crispiness index). Based on the selected quality indicators, all types of snack products obtained in this study have the potential for commercialization. However, before commercialization, consumer acceptance tests and preference tests need to be conducted.

Key words: *snacks, whole-grain red sorghum, twin-screw extruder, quality properties*

INTRODUCTION

Sorghum (*Sorghum bicolor* L. Moench) is a cereal belonging to the gluten-free family and ranks sixth in the world in harvested area, covering 40.8 million ha in 2022 (FAO, 2024). This crop is commonly grown in various geographical regions due to its high photosynthetic efficiency, and robust resilience to heat, and drought (Astoreca, Emateguy & Alconada, 2019).

In the period 2013 - 2022, the production share of sorghum grain by region was the following: Africa (45.8%), USA (35.8%), Asia (13.9%),

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Oceania (2.6%), and Europa (1.9%). In the same period, the largest cultivating countries of sorghum grain were: the USA (≤101,065,920 t in total), Nigeria (≤67,271,135 t in total), Mexico (≤52,468,516 t in total), India (≤47,091,120 t in total), Ethiopia (≤46,852,964 t in total), Sudan (≤45,062,632 t in total), China, mainland (≤28,518,243 t in total), Argentina (≤26,954,092 t in total), Brazil (≤23,065,372 t in total) and Niger (≤17,855,018 t in total) (FAO, 2024). The sorghum production in the countries as mentioned earlier accounts for more than 75% of the global total. It is important to emphasize that sorghum is a rich source of micronutrients like minerals and vitamins and macronutrients like proteins, lipids, and carbohydrates. Additionally, phenolic substances (flavonoids, phenolic acids, and tannins) found in sorghum have antioxidant properties (Khoddami et al., 2023). Sorghum is utilized for human and animal consumption due to its many health benefits, which include the potential to inhibit the development of cancer cells and reduce obesity, heart disease, and diabetes. It can be used to extrude, bake, and make various cereal-based goods, including bread, cookies, pasta, extruded snacks (salty and sweet snacks), and breakfast cereals (Astoreca et al., 2019; Khoddami et al., 2023; Pontieri et al., 2022; Stefoska-Needham, Beck, Johnson & Tapsell, 2015). However, in most countries, particularly in south-eastern Europe it is mainly used as animal feed. On the other hand, the chemical composition of sorghum grain is similar to that of maize (except for the lysine content), sorghum can be processed using the same processes as maize or other cereals to produce food and industrial products (Llopart, Drago, De Greef, Torres, and González, 2014). This could maximize its potential as a food source in developing various products, with the extrusion process being highly recommended to accomplish this (Llopart et al., 2014). Compared to other cereals, sorghum proteins contain more cross-linked prolamines, which lower the digestion and functionality of sorghum flour. Extrusion processing has been shown to improve the solubility and functionality of sorghum proteins, making it a promising process for obtaining easily digestible foods made from high-protein sorghum (Devi et al. 2013). Extrusion is a short-lived mechanical process that treats materials at high temperatures and pressures. This process is flexible and can handle a range of cereal products and animal feeds (Riaz, 2000). The extrusion process inactivates enzymes, microbes, and several antinutritional agents in addition to gelatinizing starch, denaturing proteins, and changing lipids. Extrusion cooking at high temperatures for a short time has the potential to yield sorghum-based snack products that are both highly nutritious and readily consumable (Devi et al., 2013). Thus, this study aimed to develop four types of snack products based on high protein whole-grain red sorghum flour with the addition of *i)* a mixture of sweet and hot ground red pepper; *ii)* cocoa powder; and *iii)* a mixture of cocoa powder and cinnamon, while a 100% red sorghum snack product served as a control sample.

MATERIALS AND METHODS

Material grinding and mixing

A hammer mill (ABC Inženjering, Pančevo, Serbia) fitted with a 1 mm diameter sieve was used to finely grind about 100 kg of commercially purchased red sorghum grain (*Sorghum bicolor* (L.) Moench). The paprika, cocoa and cinnamon powders were purchased from the market. The chemical composition of sweet paprika was the following: 9.1 g/100 g fat content; carbohydrates 24 g/100 g, of which sugar 17.5 g/100 g; fibers 38.4 g/100 g; salt 16.2 g/100 g, and beta-glucan 0.05 mg/100 g, while for hot paprika powder was: 11.1 g/100 g fat content; carbohydrates 20.7 g/100 g, of which sugar 14.1 g/100 g; fibers 41.1 g/100 g; salt 16.5 g/100 g and beta-glucan 0.04 mg/100 g. The mixture of sweet and hot paprika powder 3:1 w/w was added to the whole grain sorghum flour (5, 8, and 10%). The nutritional composition of the cocoa powder was: fat content 11 g/100g, of which saturated fatty acids 7 g/100 g; carbohydrates 10 g/100 g of which sugar content was 2 g/100 g; proteins 20 g/100g and salt 0.04 g/100 g. The Ceylon cinnamon powder used in this study had the following nutritional composition: carbohydrates 50.6 g/100 g; proteins 4 g/100 g; fat content 1.24 g/100 g and fibers 53.1 g/100 g. Milled sorghum with mixtures of paprika, cocoa and cinnamon powders in the ratio shown in Table 1 were blended for 90 seconds in a Muyang SLHSJ0.2A twin-shaft mixer (Muyang, Yangzhou, China) to obtain the proper degree of homogeneity before samples were taken for extrusion.

Table 1.
Raw material composition and technological parameters of extrusion

Code	Raw material composition				Process inputs		
	Whole-grain sorghum flour (%)	**Cacao powder (%)**	**Cinnamon powder (%)**	**Red paprika powder (%)**	***MC* (%)**	***FR* (kg/h)**	***SS* (RPM)**
0	100	-	-	-	14	50	900
1	95	5	-	-	14	50	800
2	92	8	-	-	14	50	800
3	90	10	-	-	14	50	800
4	90	10	-	-	14	50	850
5	89	10	1	-	14	50	850
6	95	-	-	5	14	50	900
7	92	-	-	8	14	50	900
8	90	-	-	10	14	50	900

MC—moisture of the material in the extruder barrel; FR—feed rate; SS—screw speed

Extrusion conditions

For the extrusion of whole-grain red sorghum flour and its mixtures with cacao and paprika powder, a co-rotating twin-screw extruder (Bühler BTSK-30, Bühler, Uzwil, Switzerland) with seven sections and a total barrel length of 880 mm and a length-to-diameter ratio of 28:1 was used. This extruder was equipped with two tempering tools, allowing for the adjustment of water temperature to either heat or cool the barrel sections. Sections 2, 3, and 4 were kept at 80 °C by the first tempering tool, while sections 6 and 7 were maintained at 120 °C by the second. A die plate with a cone inlet and a single 4 mm diameter aperture was used, providing a total die area of 12.56 mm^2. Furthermore, this procedure made use of a screw configuration that was specifically designed for directly expanded products (Kojić et al., 2019). The feed rate of dry materials and the moisture content of the materials in the extruder barrel were set at 50 kg/h and 14%, respectively, while the screw speed in the extruder barrel was adjusted (Table 1). To guarantee that the material in section 2 of the extruder barrel had the appropriate moisture content, water was directly injected into it using a cavity pump. Sensors installed at the die head measured the temperature and pressure at the material output. The control screen of the extruder provided immediate access to all extrusion parameters, including die temperature (*T*), die pressure (*P*), motor load (*Torque*), and specific mechanical energy (*SME*). Six knives on the extruder die's output cutter rotated at 700 RPM to produce the required product length. After extrusion, the products were allowed to cool at room temperature, and packed in plastic bags before being subjected to further analysis. The composition of mixtures used and the technological parameters of extrusion are listed in Table 1.

Moisture content

The established ISO 712/2009 standard method (ISO, 2009) was used to determine the moisture content of the sorghum flour and the extruded products.

Expansion ratio

Using a sliding caliper fitted with a Vernier scale, the cross-sectional diameter of the extrudates was measured. By dividing the extrudate's cross-sectional diameter by the die opening's diameter, the expansion ratio (*ER*) was calculated (Ding, Ainsworth, Tucker & Marson, 2005; Onwulata, Smith, Konstance & Holsinger, 2001). To obtain the *ER* values ten random samples from each trial were used.

Bulk density of extrudates

Using a bulk density tester (Tonindustrie, West und Goslar, Germany), the bulk density (*BD*) of each snack trial was determined in triplicate.

Color analysis

Sorghum snack color (L*, a*, b*) was determined using a Chroma Meter Konica Minolta CR-400 (Minolta, Japan) with a CR-A33 attachment calibrated with a white standard plate CR-A43 D65 illumination and 10° standard observer angle. From each trial, six measurements were taken on the surface of milled (KnifetecTM 1095 mill, Foss, Hoganas, Sweden) and homogenized sorghum extrudate. L* value (0–100) measures lightness ranging from black to white; a* (+/-) value measures red/green; b* (+/-) value measures yellow/blue; C* value measures color intensity and saturation.

Texture analysis

A Texture Analyzer (model TA.XTplus, Stable Micro Systems Ltd., Godalming, Surrey, UK) fitted with a 50 kg load cell, was used to evaluate the textural properties of the sorghum snacks. Samples, arranged on a single-layer bed, underwent compression using an Ottawa cell with a 17-bladed extrusion plate. The test settings were as follows: probe distance: 57 mm; pre-test speed: 5 mm/s; post-test speed: 10 mm/s. Twenty replicates were used for each measurement. The maximum peak force from the force-time graph was considered an indication of hardness (*H*). A multi-peak force-time curve was used as an indicator of sample crispness and hardness. Indicators for crispness included three parameters: the count of fractures, crispiness work and crispiness index. The number of fractures *(CPNo)* corresponds to the count of force peaks recorded during sample compression. The crispiness work *(CPW)* can be associated with the sensory perception of fracturability and describes the energy required to fracture a pore or a group of pores in an extrudate. A greater crispiness index and a higher number of force peaks both indicate increased sample crispness whereas higher crispiness work usually corresponds to decreased crispiness.

The crispiness work was calculated according to Van Hecke, Allaf and Bouvier, (1998):

$CPW(N\ mm) = A/N$ where

A is the area under the compression curve and *N* is the number of force peaks.

The crispiness index was calculated following an equation by Heidenreich, Jaros, Rohm and Ziems (2004):

$$CPI = \frac{L_N}{A \times F_{mean}} \text{ where}$$

CPI is the crispiness index; L_N is the normalized curve length (length of the actual curve /maximum force); A is the area under the compression curve (N mm) and F_{mean} is the sum of the actual force values divided by the number of peaks.

Water absorption index and water solubility index

With slight alterations, as described by Janić Hajnal et al. (2022), the water absorption index (*WAI*) and water solubility index (*WSI*) were determined using the method described by Anderson, Conway, and Peplinski, (1970). The results for *WAI* and *WSI* were presented as the average values obtained across 4 replicants of snack products from each trial.

Statistical analysis

Principal Components and Classification (PCA) module of multivariate exploratory analysis was employed to elucidate and identify patterns within the collected data via TIBCO® Data Science/STATISTICA™14.0.0.15 software (StatSoft, Hamburg, Germany). Data were standardized before multivariate analysis to avoid bias that may occur when comparing variables measured at different scales. Standard scores (*Score*) were assessed across sorghum snacks' most important quality indicators (*ER*, *CPNo*, and *CPI*). The ratio between the raw data and the extreme values for selected responses was the basis for the ranking algorithm (Janić Hajnal et al., 2022).

Sample means were compared by One-way ANOVA using Fisher's LSD post-hoc test. Differences were considered significant at probability level $p<0.05$.

RESULTS AND DISCUSSION

The input parameters of the extrusion process were determined by the preliminary trial. The determined responses of the extrusion process and extruded products (*T, P, SME, Torque, ER, BD, H, CPNo, CPW, CPI, L*, a*, b*, C*, WAI*, and *WSI*) as consequences of the applied extrusion process parameters and mixture composition (Table 1) are shown in Tables 2 and 3. The co-rotating twin-screw extruder responded differently in each of the following ranges: die temperature (*T*) ranged from 156 to 183 °C, pressure (*P*) from 0.02 to 0.19 MPa, specific mechanical energy (*SME*) from 124.2 to 146 kWh/t, and the torque from 99.0 to 121 Nm. In response to the applied process parameters and mixture composition, the physicochemical and sensory quality indicators of sorghum snacks were: an *ER* from 2.96 to 3.53, *BD* from 0.0383 to 0.0772 g/mL, *H* from 64.7to 80.5 N, *CPNo* from 61.2 to 107.8, *CPW* from 4.52 to 7.47 Nmm, *CPI* from 0.20 to 0.27 $\times10^{-3}$, *L** from 46.7 to 66.0, *a** from 8.91 to 22.0, *b** from 16.4 to 48.0, *C** from 18.6 to 52.8, *WAI* from 4.95 to 6.11 g/g, and *WSI* from 17.7 to 27.9 g/100 g.

When assessing the quality of extruded sorghum snacks, the expansion ratio (*ER*) is one of the most important characteristics to consider when evaluating the quality of extruded snacks. Expansion takes place at the die exit in a matter of seconds and involves multiple stages, including the production of bubbles, growth, merging, shrinkage, and solidification when the starchy matrix becomes glassy. During extrusion, after mixing and hydration, the starch is melted both by external heating and by viscous dissipation and comes out of the die. On that occasion, water evaporates, and expansion occurs instantaneously, bubbles stop growing, expansion ceases before the wall material becomes glassy, and cellular structure sets at a setting temperature. In case the setting temperature is above 100 °C, at a low moisture content of the raw material in the extruder barrel, the vapor bubbles swell up to a melt temperature above 100 °C and the structure is set before the bubble may collapse, which results in a higher expansion (Kristiawan, Chaunier, Sandoval & Della Valle, 2020). In the current study, the setting temperature of sections 6 and 7 of the extruder barrel was set at 120 °C. The highest *ER* was observed for sample 4 - 90% sorghum flour with 10% cocoa powder at *SS*=850 RPM (Table 3, Fig. 1), while the lowest *ER* matches with sample 8 - 90% sorghum flour with 10% paprika powder at *SS*=900 RPM (Table 3, Fig.1).

It has been demonstrated that there is a negative correlation between bulk density and expansion ratio (Ding, Ainsworth, Plunkett, Tucker & Marson 2006; Singha, Singh, Muthukumarappan & Krishnan, 2018). This is because extrudates' bulk density decreases as a result of expansion, which raises volume as a result of bubble growth (Boakye et al., 2022). The results in this study are in agreement with these findings since the sorghum snack with 90% sorghum flour with 10% paprika powder (sample 8) had the lowest *ER* (2.96) and the highest *BD* (77.3 g/mL). The lowest *BD* (38.3 g/mL) and the second highest *ER* (3.51) were observed for sorghum snacks obtained from 89% sorghum flour with 10% cocoa powder and 1% cinnamon powder (sample 5).

The texture of an extruded product, which depends on its structural properties, plays a significant role in determining its quality and acceptability. Additionally, textural attributes substantially correlate with the extruded products' sensory qualities (Dalbhagat, Mahato & Mishra, 2019; Saeleaw, Dürrschmid & Schleining, 2012). Hardness is the maximum force required to break the extrudate, and it is associated with the expansion and cell structure of extrudates (Charunuch, Limsangouan, Prasert & Wongkrajang 2014). The high feed moisture results in a higher density of the extrudate, leading to increased hardness, while high screw speed and high temperature can lower melt viscosity reducing the density and hardness of the extrudates (Boakye et al., 2022).

It has been reported that there is a negative correlation between expansion ratio and hardness and a positive correlation with density (Chou & Hsu, 2021; Ding et al., 2006). In the present investigation for sorghum snacks obtained from 89% sorghum flour with 10% cocoa powder and 1% cinnamon powder (sample 5), the lowest hardness (*H* = 64.7 N), the lowest density (*BD* = 38.3 g/mL) and high expansion ratio (*ER* = 3.51) were recorded. Significantly the highest *H* and *BD* and lowest *ER* were achieved for sample 8, which aligns with the findings mentioned above. The cellular structure of the extrudate has an impact on its crispness.

Ding et al. (2006) found that the crispness of wheat extrudates was positively impacted by the extrusion temperature. For barley extrudate, a comparable temperature effect was documented (Altan, McCarthy, and Maskan, 2008). In the present study, the highest temperature at the die (183 °C) produced an extrudate with the lowest crispiness work (*CPW* = 4.52 Nmm) but a high number of fractures (*CPNo* = 107.4) and crispiness index (*CPI* = 0.26) indicating the formation of a crispy structure. This was not statistically different from the performance of samples elaborated at a temperature of 180° C. The highest crispiness work (*CPW* = 7.47) was achieved at 175 °C and 177 °C at the extruder die, and was associated with a crispiness index on the lower side (*CPI* = 0.21-0.22) due to the lowest number of fractures (*CLNo* = 68.5 i.e. 61.2). The lowest *CPI* values were achieved for samples 0 and 6, while the highest for sample 3, followed by sample 5. However, it should be noted that the difference in *CPI* values did not reach statistical significance (p>0.05).

Extrusion typically results in the amorphization of starch, which raises the capabilities for swelling, water absorption capacity, water retention capacity, and oil absorption (Guldiken et al., 2020). Namely, the *WAI* measures the volume of water mostly absorbed by starch, acting as a marker for gelatinization, and it depends on the presence of hydrophilic groups that regulate the binding of water molecules. The *WSI* quantifies the soluble components released from starch (soluble polysaccharide) post-extrusion and serves as an indicator of molecular component degradation, reflecting the extent of starch conversion during extrusion, attributed to gelatinization and dextrinization (Ding et al., 2005). Briefly, the *WAI* specifically reflects the ability of food components (starch or fiber) to bind with water, while the *WSI* indicates the extent to which soluble compounds are released from macronutrients (Rathod & Annapure, 2017). Additionally, the *WAI* and *WSI* assess how an extruded product interacts with water, which can forecast its behavior after processing (Alam et al., 2016). The *WAI* and *WSI* of whole-grain red sorghum flour were 2.54 ± 0.01 (g/g) and 3.97 ± 0.22 (g/100 g), respectively. The *WAI* of extrudates ranged from 4.95 to 6.11 g/g, while *WSI* from 17.7 to 27.9 g/100 g. The *WAI* and *WSI* of extrudates were significantly higher than those of unprocessed sorghum flour. Sample 8 was signifycantly the highest in *WAI* (p<0.05) while sample 5 was the highest in *WSI* (p<0.05) (Table 3). The lowest *WAI* and *WSI* were noted in samples 3 and 8 (p<0.05), respectively (Table 3).

The obtained results for color attributes (L*, a*, b*, C*) of the sorghum snacks are in line with expectations and depend to the greatest extent on the composition and color of the starting mixture.

Standard score analysis (*Scores*) was introduced to allow a more thorough comparison of the investigated samples. In the optimization study of quality indicators of sorghum snacks using standard *Scores*, the optimal *Score* was computed by averaging scores across selected quality indicator variables. The maximal score function revealed the optimal factor variables and the ideal levels for chosen quality indicator variables.

These results are illustrated in Table 3 (column *Score*). The optimal *Score* of 0.938 is achieved in sample 5 (89% sorghum flour with 10% cocoa powder and 1% cinnamon powder) by applying *MC* = 14 %, *FR* = 50 kg/h, and *SS* = 850 RPM (Table 2). The optimized quality indicators were as follows: *ER* = 3.51, *BD* = 0.0383 g/mL, *H* = 64.7 N, *CPNo* = 107.4, *CPW*= 4.52 Nmm, *CPI* = 0.26 x10^{-3}, L*= 47.3, a*=12.3, b*= 17.6, C* = 21.5, *WAI* = 5.09 g/g, and *WSI* = 27.9 g/100 g (refer to Table 3).

Under these setting conditions, the extrusion process resulted in T = 183 °C, P = 0.02 MPa, *SME* = 144.1 Wh/kg, and *Torque* = 116.6 Nm (Table 2, Fig. 1).

Sample 3, i.e. sorghum snack from 90% sorghum flour with 10% cocoa powder (Fig. 1) closely followed the optimal *Score*, achieving a *Score* of 0.915 (Table 3). Sample 3 was produced with extruder parameters set at M = 14% FR = 50 kg/h and *SS* = 800 RPM, resulting in T = 180 °C, P = 0.03 MPa, *SME* = 143.1 Wh/kg, and *Torque* = 116.6 Nm (Table 2). The physicochemical and sensory properties of this optimal sample were determined: *ER* = 3.47, *BD* = 0.0744 g/mL, *H* = 68.28.85 N, *CP*No = 100.5, *CPW* = 4.82 N, *CPI* = 0.27, L* =47.2, a*=12.7, b*=17.1, C*=21.3, *WAI* = 4.95 g/g, and *WSI* = 23.8 g/100 g (refer to Table 3). The third snack sample with a high standard *Score* (0.842) refers to sample 2 (Table 3, Fig. 1).

In general, sorghum snacks obtained with cacao powder addition give distinctly higher standard *Score* (0.565 – 0.9381), related to the snack products with the addition of paprika powder (*Score* = 0.095 -0.160), and to the control sample (sample 0) obtained from 100% whole-grain red sorghum flour (*Score*=0.391).

Although sorghum-based paprika-enriched snacks have low standard *Score* values due to reduced *ER* and *CPNo*, the crispiness index was not diminished. A gradual increase in *CPI* is observed (Table 3) with an increase in the proportion of paprika compared to the control sample. Curiously, here increased *CPI* was associated with a decreased number of fracture events and increased crispiness work which may be an indication of the crunchiness of the snack products.

Principal component analysis (PCA)

PCA was performed on the experimental data to describe and distinguish between the observed samples. PCA is a multivariate statistical tool that allows the reduction of variables and identifies latent structures of a set of variables to simplify the data and effectively display the similarities and groupings of the observed samples and variables (Watkins, 2018; Suhr, n.d.).

Table 2.
Extrusion process responses

Sample	Process responses			
	T	***P***	***SME***	***Torque***
0	156	0.08	143.2	116.6
1	167	0.04	140.4	116.6
2	176	0.03	142.1	116.6
3	180	0.03	143.1	116.6
4	180	0.03	146.0	121.0
5	183	0.02	144.1	116.6
6	172	0.11	127.3	105.6
7	175	0.16	124.6	99.0
8	177	0.19	124.2	101.2

0—100% sorghum snack;1—95% sorghum flour with 5% cocoa powder (SS=800 RPM);2—92% sorghum flour with 8% cocoa powder (SS=800 RPM);3—90% sorghum flour with 10% cocoa powder (SS=800 RPM);4—90% sorghum flour with 10% cocoa powder (SS=850 RPM); 5—89% sorghum flour with 10% cocoa powder and 1% cinnamon powder (SS=850 RPM);6—95% sorghum flour with 5% paprika powder (SS=900 RPM);7—92% sorghum flour with 8% paprika powder (SS=900 RPM);8—90% sorghum flour with 10% paprika powder (SS=900 RPM); T—die temperature (°C); P—pressure at the die (MPa); SME—specific mechanical energy (Wh/kg); Torque (Nm)

Table 3.
Quality indicators of sorghum snack products (means±SD)

Sample	Product responses												
	ER	***BD***	***H***	***CPNo***	***CPW***	***CPI***	***L****	***a****	***b****	***C****	***WAI***	***WSI***	***Score***
0	3.32±0.12^{b-d}	0.0560±0.71^{d}	77.90±7.35^{b,c}	86.3±6.48^{b}	6.02±0.95^{a-c}	0.20±0.05^{a}	65.99±2.44^{f}	8.91±0.47^{a}	16.41±0.60^{a}	18.67±0.75^{a}	5.46±0.04^{b,c}	21.08±0.60^{c}	0.391
1	3.34±0.24^{b-d}	0.0424±0.49^{b,c}	70.54±5.76^{a-c}	102.2±8.35^{c}	5.09±0.62^{a}	0.21±0.04^{a}	52.13±1.30^{c}	12.29±0.58^{b}	17.89±0.64^{b}	21.71±0.85^{b}	5.10±0.39^{a,b}	25.30±0.80^{e}	0.565
2	3.42±0.21^{c,d}	0.0427±0.67^{b,c}	69.96±4.60^{a-c}	107.8±7.45^{c}	4.74±0.41^{a}	0.25±0.03^{a}	49.49±1.58^{b}	12.69±0.42^{b}	17.45±0.50^{a,b}	21.58±0.65^{b}	5.34±0.31^{a-c}	25.79±0.54^{e}	0.842
3	3.47±0.23^{d}	0.0437±0.70^{c}	68.28±7.20^{a,b}	100.5±7.12^{c}	4.82±0.85^{a}	0.27±0.09^{a}	47.21±1.89^{a,b}	12.66±0.38^{b}	17.07±0.28^{a,b}	21.25±0.43^{b}	4.95±0.04^{a}	23.79±0.65^{d}	0.915
4	3.53±0.19^{d}	0.0419±0.83^{b}	74.18±7.07^{a-c}	104.1±10.11^{c}	5.38±0.77^{a,b}	0.22±0.05^{a}	46.70±1.03^{a}	12.77±0.35^{b}	17.02±0.49^{a,b}	21.28±0.59^{b}	5.14±0.49^{a,b}	25.00±0.29^{e}	0.735
5	3.51±0.18^{d}	0.0383±0.67^{a}	64.71±6.31^{a}	107.4±10.04^{c}	4.52±0.55^{a}	0.26±0.06^{a}	47.29±1.13^{a,b}	12.28±0.4^{b}	17.61±0.46^{a,b}	21.47±0.61^{b}	5.09±0.04^{a,b}	27.93±0.27^{f}	0.938
6	3.10±0.16^{a-c}	0.0584±1.45^{e}	78.16±7.12^{b,c}	72.2±6.34^{a}	6.75±1.03^{b,c}	0.20±0.01^{a}	63.07±0.34^{e}	16.44±0.45^{c}	40.48±0.89^{c}	43.69±0.99^{c}	5.68±0.05^{c}	19.76±0.28^{b}	0.160
7	3.07±0.23^{a,b}	0.0703±0.95^{f}	79.25±7.32^{b,c}	68.5±6.79^{a}	7.22±0.95^{c}	0.21±0.04^{a}	60.13±1.11^{d}	19.82±0.61	45.85±1.09^{d}	49.95±1.23^{d}	5.66±0.11^{c}	19.37±0.64^{b}	0.166
8	2.96±0.15^{a}	0.0772±1.08^{g}	80.46±4.54^{c}	61.2±8.63^{a}	7.47±1.44^{c}	0.22±0.06^{a}	58.94±0.76^{d}	21.99±0.65	47.96±1.61^{e}	52.76±1.72^{e}	6.11±0.15^{d}	17.70±0.05^{a}	0.095

[a,b...]Means designated with different superscript letters are significantly different according to Fisher's LSD test at p<0.05; 0—100% sorghum snack;1—95% sorghum flour with 5% cocoa powder (SS=800 RPM);2—92% sorghum flour with 8% cocoa powder (SS=800 RPM);3—90% sorghum flour with 10% cocoa powder (SS=800 RPM);4—90% sorghum flour with 10% cocoa powder (SS=850 RPM); 5—89% sorghum flour with 10% cocoa powder and 1% cinnamon powder (SS=850 RPM);6—95% sorghum flour with 5% paprika powder (SS=900 RPM);7—92% sorghum flour with 8% paprika powder (SS=900 RPM);8—90% sorghum flour with 10% paprika powder (SS=900 RPM);BD—bulk density (g/mL); H—snack hardness (N); CPNo—crispiness by number of fractures; CPW—crispiness work (Nmm); CPI— crispiness index (x10^{-3}); L— lightness; a* —red/green color; b*— yellow/blue color; C*— color intensity and saturation; WAI—water absorption index (g/g); WSI—water solubility index (g/100 g);SD—standard deviation*

Figure 1. Photographs of experimental sorghum snacks

0—100% sorghum snack;1—95% sorghum flour with 5% cocoa powder (SS=800 RPM);2—92% sorghum flour with 8% cocoa powder (SS=800 RPM);3—90%sorghum flour with 10% cocoa powder (SS=800 RPM);4—90%sorghum flour with 10% cocoa powder (SS=850 RPM); 5—89%sorghum flour with 10% cocoa powder and 1% cinnamon powder (SS=850 RPM);6—95% sorghum flour with 5% paprika powder (SS=900 RPM);7—92% sorghum flour with 8% paprika powder (SS=900 RPM);8—90% sorghum flour with 10% paprika powder (SS=900 RPM)

PCA was computed using the whole data set to reveal how different formulations of extrudates are distributed and linked with the measured quality features and process parameters. The dataset was organized in a matrix with nine lines corresponding to the samples (differently formulated extrudates) and sixteen columns corresponding to measured process parameters and product attributes.The two principal components PC1 and PC2 explained 93.9%

variability in data. Factor loading values higher than 0.7000 are marked bold in Table 4 and indicate a significant correlation of a measured variable with the abstract principal components.

It is evident, that all observed variables except temperature are well explained by PC1 (loading values of most variables are >0.9 or -0.9). Negative values indicate an inverse correlation.

The process variables, *Torque*, *SME,* and the expandate attributes *WSI*, *ER*, number of fractures, and crispiness index are located on the opposite side compared to other variables showing an inverse relationship between the two groups (Fig. 2a).

Die temperature stands out as the only variable to well represent the second principal factor PC2 which explains almost 14.8% of the total variability in the dataset. 90.0% of the variance of die temperature was captured by PC2.

Along with the level of feed moisture, die temperature affects starch gelatinization during extrusion. Increasing die temperature was associated with a decrease in native sorghum starch granule structure (Jafari, Koocheki & Milani, 2017). The PCA score plot shows the similarities between the extrudates enriched with different ingredients (Fig. 2b). The enriched extrudates significantly differ from the control (100% sorghum extrudate) since the control is distant from the other samples. The location of the control sample is close to the PC2 axis, opposite to the temperature which loads highly to PC2.

The isolated position of the control sample could be due to the lowest temperature, compared to the rest of the samples. Extrudates are distinctively separated into 3 groups: the isolated control, extrudates with paprika, and extrudates with cacao.

Paprika and cacao-enriched extrudates were similarly positioned in relation to PC2, but the paprika-enriched extrudates were grouped on the negative side of PC1 while those cacao-enriched were grouped on the positive side.

Variables with the highest loading on PC1 (loadings > 0.95) that caused this clustering pattern were *P* and *SME* as processing parameters, and *ER*, *BD*, indicators of crispiness (fracture count, crispiness work) and a yellow tone (*b**) intensity.

Within the extrudates with cacao, that enriched with 5% cacao was more distant from the subgroup of extrudates enriched with 8 and 10% cacao.

Table 4.
Factor loadings based on correlations

Variable	**PC 1**	**PC 2**
T (°C)	0.1916	**-0.9482**
P (Mpa)	**-0.9861**	-0.0574
SME (Wh/kg)	**0.9510**	0.2224
Torque(Nm)	**0.9365**	0.2578
ER	**0.9799**	0.0094
BD (g/mL)	**-0.9752**	-0.0108
Hardness (N)	**-0.8904**	0.3260
Number of fractures (*CPNo*)	**0.9879**	-0.0218
Crispiness work (Nmm) (*CPW*)	**-0.9855**	0.0692
Crispiness index (x 10^{-3}) (*CPI*)	0.6136	-0.6461
WAI (g/g)	**-0.9354**	0.0050
WSI (g/100g)	**0.9468**	-0.1473
L*	**-0.7681**	0.5790
a*	**-0.8311**	-0.5325
b*	**-0.9506**	-0.2846
C*	**-0.9393**	-0.3243
% variation explained	**79.10%**	**14.84%**

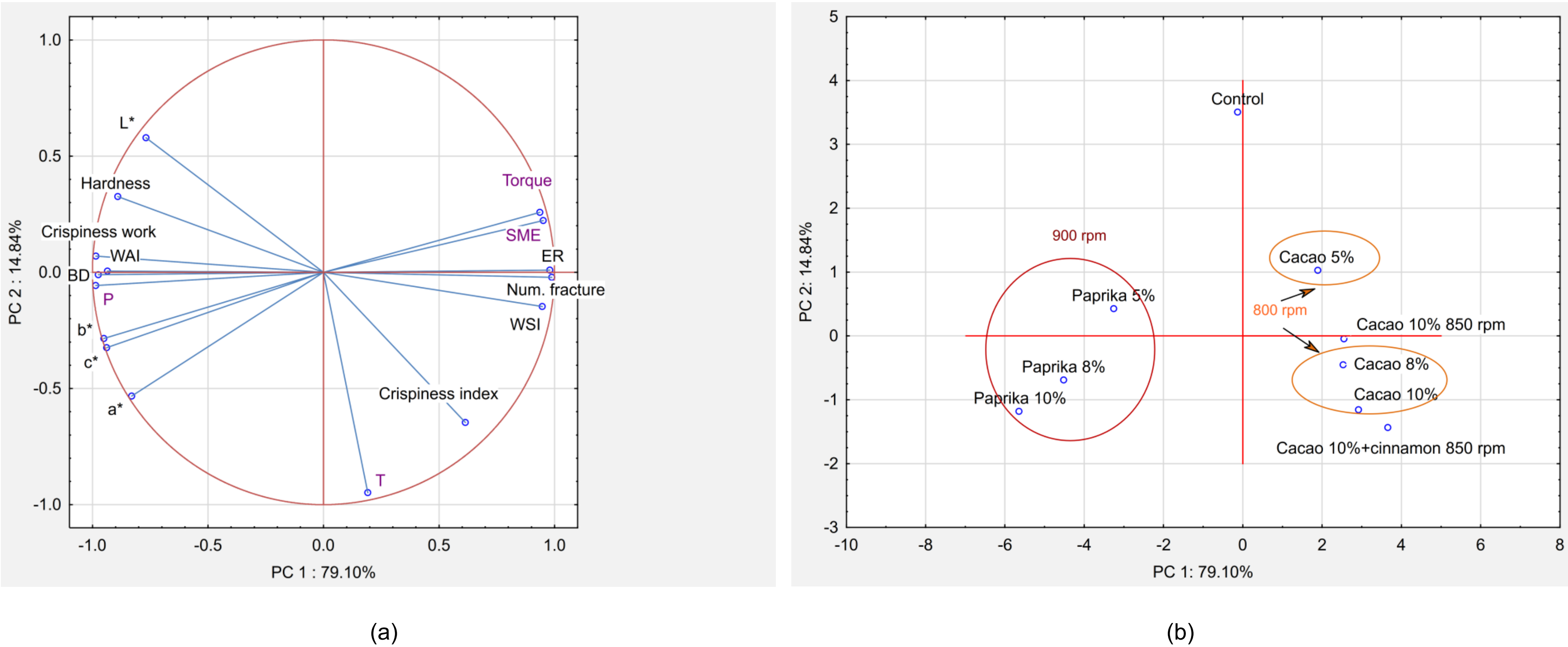

Figure 2. Principal components analysis (PCA) plots; (a) PCA loading plot for process and response variables; (b) score plot for extrudate samples

This may be due to lower expansion (*ER*), crispiness *(CPNo, CPI)*, and a lighter color. Cacao extrudate that contains 10% cacao produced at 850 rpm was separated from the same formulation with added cinnamon, but both extrudates were more similar to the cacao extrudates with 8 and 10% cacao at 800 rpm. Comparing the 10%-cacao extrudates produced at 850 RPM speed, the distance between the samples with and without cinnamon is probably due to lower torque, bulk density, and hardness, as well as higher crispiness and *WSI* caused by cinnamon addition.

Within the group of paprika-enriched extrudates, a similar grouping pattern could be observed as with the cacao-enriched extrudates: extrudates with 5% paprika were more distant from those with higher paprika levels (Fig. 2b). Extrudates with low paprika level had a low bulk density and were somewhat softer and crispier as indicated by the lower values of hardness, a higher number of fractures and lower crispness work. During compression, the 8% and 10%-level extrudate produced fewer fractures during compression (lower *CPNo*) with slightly higher hardness and work of crispiness (*CPW*) but somewhat higher crispiness index (*CPI*) which may be associated with the formation of a more crunchy structure rather than crispy. Crunchy products are associated with a less fragile structure in contrast to crispy products mostly due to the formation of thicker walls of pores.

CONCLUSIONS

According to the standard *Score* analysis, optimal characteristics were achieved in the products formulated with 10% cacao powder and 1% cinnamon addition sorghum extrudate (sample 5). Two principal components (PCs) explained nearly 94% variation of data. The die temperature was the only variable to significantly load on PC2, explaining 15% of total data variability. The samples were segregated into 3 groups: control, paprika-enriched and cocoa-enriched extrudates. In both enriched sorghum snacks, those at low enrichment levels (5%) were more distant from the corresponding extrudates at 8 and 10% enrichment levels. Although snacks with paprika addition showed the lowest standard *Score*, they still have the potential to be processed into a salty type of snack product due to their attractive color, taste, and crunchiness. The snack obtained from 100% whole-grain sorghum flour is an excellent basis for creating various salty and sweet sorghum-based snack products. All of the whole-grain red sorghum snack product varieties elaborated in this study have the potential to be commercialized, according to the quality indicators. However, consumer preference and acceptance testing must be carried out before upscaling.

AUTHOR CONTRIBUTIONS

Conceptualization, E.J.H. and B.F.; Methodology, V.B.. B.F. and E.J.H.; Investigation, formal analysis, validation, E.J.H., V.B., B.F., B.R., and J.K.; writing-original draft preparation, E.J.H., B.F., and V.B.; Writing-review and editing, E.J.H., V.B., B.F., B.R., J.K., O.Š. and B.C.; Supervision, E.J.H.

DATA AVAILABILITY STATEMENT

Data contained within the article.

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CONFLICT OF INTEREST

The authors declare no conflict of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript, or in the decision to publish the results.

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SNEK PROIZVODI OD INTEGRALNG BRAŠNA CRVENOG SIRKA SA PAPRIKOM I KAKAOM

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Sažetak: Sirak (*Sorghum bicolor* L. Moench) se ubraja u žita koja ne sadrže gluten. Usled izuzetne otpornosti na toplotu i sušu, može se uspešno uzgajati na različitim geografskim uslovima. Sirak je bogat makronutrijentima, uključujući proteine, masti i ugljene hidrate, kao i mikronutrijentima poput minerala i vitamina. Pored toga, sirak sadrži fenolna jedinjenja, kao što su tanini, fenolne kiseline i flavonoidi, koja su poznata po svojim antioksidativnim svojstvima. Zbog svojih brojnih zdravstvenih prednosti, uključujući potencijal da smanji rizik od raka, gojaznosti, srčanih oboljenja i dijabetesa, sirak se sve više koristi u ishrani ljudi i životinja. Ova nutritivno bogato žito može se koristiti za pečenje, ekstrudiranje i različite proizvode na bazi žita kao što su hleb, kolači, testenine, grickalice i žita za doručak. Ova studija je imala za cilj razvoj četiri vrste snek proizvoda na bazi brašna od crvenog sirka (95, 92, 90 i 89%) sa dodatkom *i*) mešavine slatke i ljute mlevene crvene paprike (5, 8 i 10%), *ii*) kakao praha (5, 8 i 10%) i *iii*) mešavine kakao praha (10%) i cimeta (1%), dok je kao kontrolni uzorak poslužio snek proizvod od 100% crvenog sirka. Korišćeni su sledeći parametri obrade ekstrudiranjem: brzina hranjenja ekstrudera od 50 kg/h, brzina obrtaja puža od 800, 850 i 900 o/min a vlaga materijala u buretu ekstrudera kretao se od 13 do 14%. Određeni su sledeći atributi kvaliteta dobijenih snek proizvoda: koeficijent ekspanzije, zapreminska gustina, indeks upijanja vode, indeks rastvorljivosti u vodi, boja i tekstura (tvrdoća, broj preloma, rad hrskavosti, indeks hrskavosti). Na osnovu pokazatelja kvaliteta, sve vrste snek proizvoda dobijene u ovoj studiji imaju potencijal za komercijalizaciju. Međutim, pre komercijalizacije, potrebno je sprovesti testove prihvatanja od strane potrošača i testove preferencije.

Ključne reči: *snek proizvodi, integralno brašno crvenog sirka, dvopužni ekstruder, pokazatelji kvaliteta*

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