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Effectiveness of Processing Techniques on the Retention and Bioavailability of Nutrients in Sorghum, *Sorghum bicolor* (L.) Moench

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***Abstract*:** The effect of various processing techniques namely soaking, blanching germination, roasting, puffing, decortication and milling on nutritional composition retention and bioavailability of nutrients of sorghum (PSC 4) was assessed. Puffing, soaking and germination resulted in a significant increase in the protein (6.8, 7.4 & 9.4% respectively) and dietary fiber (4.4%) while roasting and puffing significantly enhanced *in vitro* starch digestibility of starch (27.8-33.5%). Bioactive compounds like phenols (11.1-26.0%) and flavonoids (14.5-28.0%) were significantly reduced by processing while germination increased its antioxidant activity (16.7%). However, iron content was significantly increased by roasting and puffing (14.4-17.9%) while calcium and zinc content was reduced with processing applications. Since, germination and puffing showed affirmative relationship with retention of nutrients with enhanced starch, protein and mineral absorption, therefore, these techniques can be regarded as the most viable applications for household processing and are rather instrumental in popularizing sorghum as a sustainable substitute of staple cereals with enhanced nutrition to combat food and nutritional security.

***Keywords*:** Germination, Puffing, Parling, Dietary fiber, Iron, Zinc, Bioavailability

As the world is currently experiencing climate change and ever-increasing burden of population, the coming decades might see a decline in the crop production. The proportion of less fertile soils is predicted to increase by 50 to 56 per cent with 78 per cent of it affecting developing countries. Besides, an increase in the cultivation of crops like rice, maize, sugarcane etc. requiring extra water is responsible for a loss of approximately 7191 litres of ground water per hectare (Kumar et al., 2018). Research showed that cultivation of millets also plays a distinct role in decreasing atmospheric carbon dioxide, thus contributing constructively to climate change (Saxena et al., 2018). Among these, Sorghum, *Sorghum bicolor L. moench* requires soil salinity of 4-6 dS/m and rainfall required for optimum maturity (90-120 days) is 40-100 cm (Fageria et al., 2010). However, other research studies suggest that seedlings of some of the genotypes of sorghum are capable of surviving high soil surface temperature up to 40^{o}C (Nguyen et al., 2013). These grains score better over rice and wheat in terms of amino acid profile, dietary fiber and a great virtue of nutrients including iron, folate, calcium, zinc, magnesium, phosphorus, copper, vitamins, antioxidants and bioactive compounds.

Sorghum grains are loaded with starch, cellulosic and non-cellulosic polysaccharides (mainly glucuronoarabinoxylans [GAX]). Thus, they have somewhat high gelatinization temperature leading to lower starch digestibility. Addition of sorghum bran to the diet may help protect against development of metabolic disease states such as obesity, type II diabetes, and inflammation by improving colonic microbiota (Lloyd et al., 2016). Being a gluten-free cereal and a chief source of a bundle of nutrients, sorghum is a good dietary substitutes for celiac disease patients. Since sorghum is not available in convenient food forms besides their coarse nature, low digestibility and presence of anti-nutritional factors such as phenolic compounds, these nutri-grains lost their popularity with the transforming world. Sorghum has low protein bioavailability due to presence of anti-nutritional factors like trypsin inhibitors, tannin, and phytic acid and it lacks essential amino acids like methionine, lysine, and isoleucine.

Some conventional processing techniques are applied prior to preparation and consumption, such as soaking, decorticating, germination, malting and fermentation which tend to improve nutritive, and sensory characteristics of the millets (Jaybhaye and Srivastav 2015). In addition, improved bioavailability of nutrients and reduced anti-nutritional factors are the benefits of processing. Malting tends to improve bioavailability of iron by increasing its absorption up to 300 per cent while manganese absorption is increased by 17 per cent (Platel et al., 2010). Germination causes hydrolysis of phytate phosphorus to form inositol monophosphate causing decrease in phytic acid, thus reducing its phytate content (Handa et al., 2017). Soaking followed by germination helps in leaching tannins out of millet grains (Hussain et al., 2011).

Fermentation improves protein digestibility by reducing anti-nutrient load. Germination and fermentation increase the antioxidants characteristics and reduces the phytate content of sorghum and pearl millet (Kayode et al., 2013). Keeping in view the benefits of these nutri-cereals in health and disease, the present study attempts to assess the nutritional aptitude such as retention and bioavailability of nutrients by application of various processing techniques.

MATERIAL AND METHODS

Sample preparation: Sorghum cultivar (PSC 4) sourced from the Seed Production Farm of Punjab Agricultural University, Ludhiana, (sown in May 2017) was cleaned and subjected to following treatments (Table 1).

Control (unprocessed grains) and processed sorghum grains were dried in a hot air oven (Model MSW 211, Macro Scientific Works Pvt. Ltd., India) to achieve 5 % moisture content and finely ground using mortar and pestle. Samples were stored in labelled, airtight containers. All chemical reagents used were of analytical grade and reagent kits were purchased from Sigma-Aldrich, Inc. Sigma Chemical Co. (USA).

Determination of proximate composition: Moisture (method 44–10.01, AACC 2010) and ash (gravimetrically by charring then igniting at 550 °C in a muffle furnace using method 08-01.01, AACC 2010) was measured. Crude fat was analysed (920.39, AOAC 1997) using SOCS plus Solvent Extraction system (Pelican, India) while crude protein using Kjeldahl method (46-13.01, AACC 2010) in KEL PLUS Automatic Nitrogen System (Pelican Equipment, Chennai, India) with a factor of 6.25 applied to convert the amount of nitrogen to crude protein. The carbohydrate content was calculated by subtracting sum of all proximate parameters (moisture content, crude protein, crude fat, crude fiber, and total ash) from 100. Total dietary fiber was quantified using a modified enzymatic gravimetric method (991.42, AOAC 2005).

Dietary fiber: The soluble, insoluble and total dietary fiber contents of the samples were analyzed in triplicates using Megazyme-K-TDFR- 200A. The soluble and insoluble dietary fiber contents were analyzed using the standard protocol given by AOAC (1997).

Bioactive Compounds and Antioxidant Activity

Bioactive compounds: Total phenolic content was determined by method described by (Singleton et al., 1999) whereas tannins was estimated by modified method of Owheruo et al. (2018). The determination of flavonoid content was performed using a method followed by Zhischen et al (1999) as elucidated by Owheruo et al. (2018) and measured as mg rutin equivalent per 100g dry weight.

Antioxidant activity was estimated by following two methods: Total antioxidant activity by DPPH was measured following the methodology stated by Brand-Williams et al. (1995) and total antioxidant activity by FRAP was measured according to method by Benzie and Strain (1999).

***In vitro* digestibility:** *In vitro* starch digestibility was analysed using methodology by Sharma et al. (2018) and protein digestibility as per the methodology of Sharma et al. (2018).

Minerals analysis: Iron, calcium and zinc were estimated using atomicabsorption spectrophotometer (Analyst 2000, Perkin Elmer, USA) post wet digestion (Merwe et al., 2019).

***In vitro* mineral bioavailability:** For iron the methodology stated by Rao and Prabhavati (1978) was used. For calcium and zinc bioavailability methdology specified by Rebellato et al. (2020) was used.

Statistical analysis: Data so obtained was expressed as mean with standard deviations, analysed for one-way analysis of variance and post hoc test (Tukey's) and the means separated using Least Significant Difference at $p = 0.05$, performed using IBM SPSS Inc. (version 23, Chicago, USA).

RESULTS AND DISCUSSION

Proximate composition: As represented in Table 2, the crude protein content was significantly ($p \leq 0.05$) varied among control and processed flour of sorghum PSC-4 (SOR). The highest and lowest crude protein content of control and processed SOR was detected in puffed and parled grains' flour, respectively with a range varying between 8.09 to 9.86 percent with comparable increase by soaking (9.68 g/100g) and germination (9.62 g/100g). Similar increase in protein content of fermented cereals was also reported by Tian et al. (2010) in their study attributing to microbial synthesis of protein during the process of germination (Adebiyiet al., 2017). It was also observed in the literature that increase in germ size of grains by processing is responsible for the increase in its protein content (Singh and Raghuvansi 2012). However, the fat content of milled and parled SOR flour was observed to be significantly different from all other processed SOR flours. The fat content of control and processed sorghum flour varied between 1.90 to 4.00 per cent with highest content in parled flour and lowest in germinated flour. Our results were in agreement with the findings reported by Mohapatra et al. (2018) who revealed reduction in fat content post fermentation of sorghum grains from 4.7 per cent to 3.6 per cent. The low-fat content of processed flours can contribute to increased shelf-life due to decreased probability of rancidity but at the stake of reduced energy value. Nevertheless, the crude fiber content of

germinated SOR grain flour was found to be significantly ($p \leq 0.05$) higher (1.91 g/100g) as compared to control and other processed SOR grain flours while parled SOR flour had lowest (0.81 g/100g) content. This observation was accredited to the removal of bran layer during decortication process, thus reducing the fiber content of the grain. Our finding corroborated the findings of Fasasi (2009) who reported the crude fiber content of germinated pearl millet flour to be 1.80 per cent attributing to the utilization of sugar for energy to perform metabolic activities like sprouting while leaving the fibrous content in the grain.

Total dietary fiber: The dietary fiber content of control, blanched, puffed and milled SOR flours were found to be significantly ($p \leq 0.05$) different from their other processed contemporaries (Table 2). It ranged between 7.33 to 8.57 per cent with highest content pertaining to germinated flour and lowest in parled flour. Germinated (8.57%) and soaked (8.53%) SOR flour was found to have significantly ($p \leq 0.05$) higher dietary fiber. The observed reduction may be attributed to the removal of germ and pericarp during parling process. Our findings were in accordance with the results reported by Pushparaj and Urooj (2011) who revealed a reduction in dietary fiber content (9.2%) post partial removal of bran layer as compared to whole flour (13.3%) while the dietary fiber content of germinated flour was reported to be higher (13.4%) than whole flour. Spike during germination could be due to structural disruption of polysaccharides in grain's cell wall possibly affecting the anatomical intactness of tissue and hampering the carbohydrate-protein interaction leading to extensive biosynthesis of new cell wall and producing new dietary-fiber (Sharma et al., 2015). Increase in puffed variant could be due to increase in *β*-glucan

Table 1. Processing of sample

Treatment	Method
Germination	Grains were soaked in water (1:2) overnight (30℃) and treated with formaldehyde (0.2 %) tailed by washing and incubating in muslin cloth at 30°C. Germination was done for 48 h (90–95% RH) and dried to a constant weight at 50℃ in a hot air oven.
Soaking	The cleaned grains of pearl millet were soaked overnight at room temperature (25℃) in excess distilled water in a dish, covered with a muslin cloth for 6 h.
Blanching	Blanching was done as per procedure described by Chavan and Kachare (1994). According to this method, distilled water was brought to boiling temperature of 98℃. The sorghum grains were subjected to blanching in boiling water (1:5 ratio of seeds to boiling water) for 30 seconds and then dried at 50℃ for 60 minutes.
Roasting	Application of dry heat at 190℃ and removed from the flame immediately after the roasted nutty flavour begin to arise from the pan of grains (after 3 min).
Puffing	By the method of Malleshi and Desikachar (1981), moisture content was raised to 19 % and puffed in an iron frying-pan using fine sand as a heat exchange medium (270°C). Puffed sample was separated by sieving through 40 mesh sieve.
Milling	Procured sorghum grains were milled by mechanical method using a laboratory hammer mill (Relitech Industries, Gujarat, India) using no. 0 stainless steel sieve (particle size < 70µm).
Parling	Grains were parled for one minute by mechanical method using 'Barley Parler Control Unit' with approximately 8-9 % removal of bran (decortication).

Table 2. Effect of various treatments on nutritional composition (%) of sorghum (dry matter basis)

Crop	Treatment	Moisture	Ash	Crude protein	Crude fat	Crude fiber	Carbohydrates	Total dietary fiber (%)	Energy (KCal)
SOR	C	$5.09^{a}\pm0.27$	$3.08^{a}\pm0.06$	$9.01^{ab}\pm0.53$	$2.46^{a}\pm0.58$	$1.37^{a}\pm0.16$	$78.36^{ab}\pm0.33$	$8.17^{ab}\pm0.32$	$374.14^{ab}\pm3.80$
	T1	$9.01^{b}\pm1.21$	$1.22^{b}\pm0.67$	$9.62^{a}\pm0.30$	$1.90^{a}\pm0.05$	$1.91^{ab}\pm0.03$	$77.02^{a}\pm1.61$	$8.57^{b}\pm0.32$	$363.63^{a}\pm7.68$
	T2	$6.08^{ac}\pm2.39$	$1.41^{b}\pm0.12$	$9.68^{a}\pm0.36$	$2.47^{a}\pm0.08$	$1.21^{a}\pm0.08$	$79.15^{ab}\pm2.68$	$8.53^{b}\pm0.39$	$377.54^{b}\pm10.24$
	T3	$5.78^{a}\pm0.53$	$1.29^{b}\pm0.03$	$8.68^{ab}\pm0.25$	$2.42^{a}\pm0.17$	$1.30^{a}\pm0.05$	$83.86^{c}\pm0.30$	$7.97^{ab}\pm0.25$	$391.91^{c}\pm1.30$
	T4	$2.58^{d}\pm0.04$	$1.28^{b}\pm0.03$	$8.65^{ab}\pm0.26$	$2.49^{a}\pm0.11$	$1.22^{a}\pm0.39$	$83.78^{c}\pm0.28$	$8.37^{b}\pm0.45$	$392.15^{c}\pm1.06$
	T5	$4.28^{ad}\pm0.03$	$1.57^{bc}\pm0.06$	$9.86^{a}\pm0.27$	$2.35^{a}\pm0.19$	$1.31^{a}\pm0.10$	$80.63^{bc}\pm0.40$	$7.87^{ab}\pm0.31$	$383.07^{bc}\pm1.09$
	T6	$5.20^{a}\pm0.06$	$2.34^{d}\pm0.05$	$9.05^{ab}\pm0.82$	$2.97^{ab}\pm0.92$	$1.26^{a}\pm0.08$	$79.19^{ab}\pm0.88$	$7.87^{ab}\pm0.42$	$379.64^{bc}\pm4.62$
	T7	$8.29^{c}\pm0.03$	$2.21^{cd}\pm0.52$	$8.09^{b}\pm0.58$	$4.00^{b}\pm0.96$	$0.81^{c}\pm0.06$	$76.60^{a}\pm1.86$	$7.33^{a}\pm0.40$	$374.75^{ab}\pm3.67$

Mean values followed with different subscripts are significantly different ($p \leq 0.05$) using Tukey's test for different parameters (moisture, ash, crude protein, crude fiber, carbohydrates, total dietary fiber and energy).

PM-1: Pearl millet FBC 16; PM-2: Pearl millet PCB 165; SOR: Sorghum PSC 4

C- control sorghum/ pearl millet flour, T1-germinated sorghum/ pearl millet flour, T2- soaked sorghum/ pearl millet flour, T3- blanched sorghum/ pearl millet flour, T4- roasted sorghum/ pearl millet flour, T5-puffed sorghum/ pearl millet flour, T6-milled sorghum/ pearl millet flour, T7-parled sorghum/ pearl millet flour

availability accounting to release of bound *β*-glucan due to thermal effect (Kora 2019).

Bioactive Compounds and Antioxidant Activity

Total phenols: Total phenol content of control and processed flours were expressed as mg gallic acid equivalent per 100g sample (Table 3). A significant ($p \leq 0.05$) rise of 10 per cent in the total phenol content was found in milled SOR flour as compared to control. Total phenols of control and processed SOR flour ranged between 105.18 to 156.51mg GAE/100g with the highest content exhibited in milled SOR flour and lowest in its blanched counterpart. All processing treatments except milling resulted in a significant decrease in the total phenol content when compared to control. According to Taylor and Duodo (2015), phenolic compounds of sorghum grains are concentrated in the outer layers, therefore, removal of bran during decortication could be possible cause for their reduction in flour. As well as the reduced phenolic compounds due to germination can be accredited to the leaching of phenolic compounds in the steeping liquid owing to its enhanced solubilization. Also, the drifting of phenols from outer layers to endosperm during soaking hampers its extractability due to formation of complexes with protein and other major molecules, might be another reason for reduction in total phenol content during soaking and germination. Oxidation and thermal degradation of phenols during thermal processing like roasting and puffing could be the consequence of its reduced content than control. It was also reported that post-harvest treatment had a negative impact on retention of total phenols as conjugated polyphenolics degrades to simpler compounds (Kadiri 2017). Another study by Zhang et al., (2010) reported a significant decline in total phenols of buckwheat flour post thermal processing.

Tannins: The tannin content of control and processed sorghum flour had a range between 25.30 to 35.22 mg/100g with highest content in control flour and lowest in germinated and flour. Research evidence revealed migration of condensed tannins to the endosperm along with imbibed water during steeping and germination. Taylor and Duodo (2015) also stated that tannin extractability of sorghum flour could be reduced post germination owing to the formation of irreversible complexes with its kafirin prolamin protein. Although, prolonged germination may cause reverse migration of tannins towards the outer layers and enhance its extractable content as in case of malting (Kayodé et al., 2007). Additionally, production and catalytic effect of enzymes (esterases) due to sprouting tend to hydrolyse the tannins, thus causing its reduction in the produced flour (Chethan et al., 2008).

Total flavonoid content: The total flavonoid content of control and processed samples were expressed as 'mg rutin equivalents per 100g sample' (Table 3) and analysis pronounced that the processed SOR flours except puffed variant displayed a significant ($p \leq 0.05$) decline in the total flavonoid content in comparison to control flour. Range of total flavonoids of control and processed SOR flours lied between 68.96 mg RE/100g in the parled flour to 110.87 mg RE/100g in the control fraction. The lowest content being observed in the parled variant can be owed to the removal of outer bran layer in the process of parling, where these bioactive compounds are concentrated the most. The observation was also in line with the findings reported by Sreeramaiah and Goudar (2012) who observed a substantial reduction in the total flavonoid content in flaked sorghum grains. This decline was owed to the pre-processing applications like soaking, removal of bran and boiling before final pressing by the authors.

Total Antioxidant Capacity by DPPH (1,1 diphenyl-picrylhydrazyl/2,2-Diphenyl-1-picrylhydrazyl): Radical

Table 3. Effect of various treatments on bioactive compounds and antioxidant activity of and sorghum (dry matter basis)

Crop	Treatment	Total phenols (mg GAE/100g)	Tannins (mg/100g)	Total flavonoids mg RE/100g	DPPH TAC (mg TE/100g)	FRAP TAC (mg TE/100g)
SOR	C	142.21^{ab}±2.65	35.22^{a}±4.33	110.87^{a}±4.19	422.97^{a}±16.05	241.90^{a}±12.41
	T1	109.53^{c}±12.16	25.26^{b}±3.01	100.51^{ab}±2.89	493.54^{b}±7.34	356.77^{b}±1.07
	T2	126.47^{ac}±7.26	34.56^{a}±2.65	89.62^{b}±2.74	426.64^{a}±8.87	246.16^{a}±3.24
	T3	105.18^{c}±12.16	32.54^{a}±2.34	95.59^{b}±8.00	363.02^{c}±11.26	263.53^{a}±23.79
	T4	117.54^{ac}±15.86	33.89^{a}±4.79	96.44^{b}±2.37	350.67^{cd}±3.59	251.52^{a}±3.21
	T5	118.29^{ac}±5.92	32.80^{a}±3.04	109.46^{a}±3.03	498.67^{b}±9.74	320.09^{c}±14.80
	T6	156.51^{b}±13.98	30.10^{c}±5.51	100.05^{ab}±5.19	442.28^{a}±14.72	250.34^{a}±4.24
	T7	111.09^{c}±4.86	25.30^{b}±2.96	68.96^{c}±1.66	327.37^{d}±7.86	161.61^{d}±2.39

Mean values followed with different subscripts are significantly different ($p \leq 0.05$) using Tukey's test for different parameters [Total phenols, tannins, total flavonoids, total antioxidant activity (DPPH & FRAP)].

PM-1: Pearl millet FBC 16; PM-2: Pearl millet PCB 165; SOR: Sorghum PSC 4

C- control sorghum/ pearl millet flour, T1-germinated sorghum/ pearl millet flour, T2- soaked sorghum/ pearl millet flour, T3- blanched sorghum/ pearl millet flour, T4- roasted sorghum/ pearl millet flour, T5-puffed sorghum/ pearl millet flour, T6-milled sorghum/ pearl millet flour, T7-parled sorghum/ pearl millet flour

scavenging activity (Table 3) was studied by DPPH (1,1 diphenyl- picrylhydrazyl/2,2-Diphenyl-1-picrylhydrazyl) for control and processed fractions sorghum PSC 4 (SOR). Total antioxidant capacity of all the analysed samples was expressed as 'mg trolox equivalent/100g'. Statistically significant ($p \leq 0.05$) increase in the antioxidant activity was detected in germinated (493.54 mg TE/100g) and puffed (498.67 mg TE/100g) SOR flour. Although, blanching (363.02 mg TE/100g), roasting (350.67 mg TE/100g) and decortication (327.37 mg TE/100g) were found to significantly ($p \leq 0.05$) reduce the total antioxidant activity of the SOR flour. Revelation of comparable results was done by Singh et al., (2019) who noted a significant enhancement in the antioxidant activity post germination. The authors also demonstrated a positive correlation between duration of germination and its antioxidant activity (% inhibition of DPPH). The reported antioxidant activity rose from around 12 percent after twelve hours to about 40 percent at the end of 48 hours. Significant ($p \leq 0.05$) rise in the radical scavenging activity (by DPPH) post germination can be attributed to the induction of high levels of enzymes (superoxide-dismutases, glutathione-S-transferase, peroxidises and catalases) with antioxidative properties (Gupta et al., 2013).

Higher antioxidant activity in puffed variant can be due to the existence of higher total phenolic content in the flour. This statement was justified by Alothmanet al. (2009) who had defined direct correlation between percent DPPH inhibition and total phenols. The authors also attributed this outcome to the increased formation of Millard compounds due to high temperature exposure in a short time period. Additionally, the observation of the present study was in agreement with the findings reported by Pradeep and Guha (2011) that heat treatment was observed to increase the antioxidant activity of little millet by 95.5 percent as compared to germination which increased it by 91.7 percent.

Total Antioxidant Capacity by Ferric Reducing Antioxidant Power (FRAP)

Analysis of total antioxidant capacity by Ferric Reducing Antioxidant Power (FRAP) was expressed as 'mg Trolox equivalent/ 100g' (Table 3). Germination, puffing and decortication significantly ($p \leq 0.05$) affected the antioxidant power when analysed for FRAP. Germination and puffing significantly ($p \leq 0.05$) enhanced the antioxidant power by 47.5 and 32.3 percent respectively while decortication reduced it significantly ($p \leq 0.05$) by 33.2 percent owing to the removal of outermost bran layer holding phenols, flavonoids and antioxidants. Lowest to highest FRAP values of control and processed SOR flour ranged between 241.90 mg TE/100g in control to 356.77 mg TE/100g in germinated flour.

***In vitro* protein and starch digestibility:** The term *in vitro* suggests imitating a metabolic process outside of a living organism while the *in vitro* digestibility of nutrients account for the amount of nutrients absorbed and metabolized once ingested. The effect of processing treatments on *in vitro* protein and starch digestibility has been documented in Table 4. The *in vitro* protein digestibility of control and processed sorghum PSC 4 ranged between 49.81 to 56.44 percent with lowest digestibility was observed in blanched sorghum flour and highest in its germinated counterpart with a non-significant difference between them. This observation can be accredited to a myriad of hydrolytic enzymes released during processing especially due to germination. These enzymes have the potential to hydrolyse biopolymers (storage proteins) making it easily available for pepsin hydrolysis and it also degrades the anti-nutritional factors, thus, making the nutrients highly digestible.

Amid in vitro starch digestibility, sorghum PSC 4 flour displayed a significantly ($p \leq 0.05$) higher starch digestibility in roasted (42.03 mg maltose released per gram) and puffed (43.91 mg maltose released per gram) variants as compared to control (32.89 mg) while a significantly ($p \leq 0.05$) low digestibility was observed in blanched flour (27.57 mg maltose released per gram). This observation was however in line with the results reported by Roopa and Premavalli (2008) who revealed that puffing grains significantly improved the starch digestibility of finger millet. The results obtained in present investigation were in concordance with a study by Huang et al. (2018) who reported significant

Table 4. Effect of various treatments on dietary fiber and *in vitro* nutrient digestibility of sorghum (dry matter basis)

Crop	Treatment	*In vitro* starch digestibility (mg maltose released/g	*In vitro* protein digestibility (%)
SOR	C	32.89^{a}±1.31	51.12^{a}±18.24
	T1	37.77^{a}±0.90	56.44^{a}±7.98
	T2	35.78^{a}±1.83	51.42^{a}±1.42
	T3	27.57^{b}±1.67	49.81^{a}±10.56
	T4	42.03^{c}±2.48	52.74^{a}±8.80
	T5	43.91^{c}±0.29	50.05^{a}±1.71
	T6	34.22^{a}±3.38	53.41^{a}±8.47
	T7	34.34^{a}±1.22	55.06^{a}±2.85

Mean values followed with different subscripts are significantly different ($p \leq 0.05$) using Tukey's test for different parameters (*in vitro* nutrient digestibility).

PM-1: Pearl millet FBC 16; PM-2: Pearl millet PCB 165; SOR: Sorghum PSC 4

C- control sorghum/ pearl millet flour, T1-germinated sorghum/ pearl millet flour, T2- soaked sorghum/ pearl millet flour, T3- blanched sorghum/ pearl millet flour, T4- roasted sorghum/ pearl millet flour, T5-puffed sorghum/ pearl millet flour, T6-milled sorghum/ pearl millet flour, T7-parled sorghum/ pearl millet flour

increase in starch digestibility post puffing grains, owing to enhanced rate of hydrolysis probably due to starch gelatinization. Research evidence also described that higher degree of gelatinization create prospects for enzymes (amylases) to attack the starch causing its hydrolysis (Mishra et al., 2014).

Total Minerals and their *in vitro* Bioavailability

Iron: Analysis of control and processed SOR flour revealed variant results (Table 5). It was observed that milling (6.67 mg/100g), puffing (6.37 mg/100g), roasting (6.18 mg/100g) and germination (5.75 mg/100g) significantly ($p \leq 0.05$) improved the iron content of SOR flour (5.40 mg/100g) while blanching (4.86 mg/100g) and soaking (4.82 mg/100g) significantly ($p \leq 0.05$) reduced the content. Research analysis also reported a significant increase in mineral extractability of pearl millet between 23 to 70 percent post application of domestic processing like germination. This observation could owe to the reduction in phytic acid contents which otherwise would make complexes with minerals leaving it unabsorbed (Coulibalyet al., 2011).

Calcium and zinc: Calcium content of SOR flour was observed to reduce significantly ($p \leq 0.05$) post processing application from 21.46 to 10.88 mg/100g (Table 6). The lowest content was observed in parled (10.88 mg/100g) flour due to removal of outer bran and germ which holds these minerals. The least reduction in calcium content of SOR flour was observed in its milled variant (20.02 mg/100g). However, other processing treatments had calcium content in order of germination > puffing > roasting > soaking > blanching (19.23, 19.17, 18.60, 18.17, 16.87 mg/100g, respectively). Similar

Table 5. Effect of various treatments on total and bioavailable iron of and sorghum (dry matter basis) (calculation)

Crop	Treatment	Iron		
		Total (mg/100g)	Percent Ionizable iron at pH 7.5 (X)	*In vitro* iron bioavailability (Y) (% iron absorption in adults)
SOR	C	$5.40^{a}\pm0.29$	$2.37^{ab}\pm0.46$	$1.60^{ad}\pm0.22$
	T1	$5.75^{ab}\pm0.29$	$3.76^{bc}\pm0.68$	$2.25^{bc}\pm0.32$
	T2	$4.82^{c}\pm0.06$	$2.15^{a}\pm0.32$	$1.50^{ad}\pm0.15$
	T3	$4.86^{c}\pm0.20$	$2.83^{ab}\pm0.55$	$1.82^{abd}\pm0.3$
	T4	$6.18^{bd}\pm0.07$	$4.21^{c}\pm0.57$	$2.46^{c}\pm0.26$
	T5	$6.37^{d}\pm0.13$	$2.97^{bc}\pm0.71$	$1.88^{bcd}\pm0.34$
	T6	$6.67^{d}\pm0.14$	$2.36^{ab}\pm0.34$	$1.59^{ad}\pm0.16$
	T7	$4.13^{e}\pm0.33$	$1.99^{a}\pm0.47$	$1.42^{ad}\pm0.22$

Mean values followed with different subscripts are significantly different ($p \leq 0.05$) using Tukey's test for different parameters (total and bioavailable iron).

PM-1: Pearl millet FBC 16; PM-2: Pearl millet PCB 165; SOR: Sorghum PSC 4

C- control sorghum/ pearl millet flour, T1-germinated sorghum/ pearl millet flour, T2- soaked sorghum/ pearl millet flour, T3- blanched sorghum/ pearl millet flour, T4- roasted sorghum/ pearl millet flour, T5-puffed sorghum/ pearl millet flour, T6-milled sorghum/ pearl millet flour, T7-parled sorghum/ pearl millet flour

Table 6. Effect of various treatments on total and bio available calcium and zinc of pearl millet and sorghum (dry matter basis)

Crop	Treatment	Calcium			Zinc		
		Total (mg/100g)	Bioavailable (mg/100g)	Percent bio-availability	Total (mg/100g)	Bioavailable (mg/100g)	Percent bio-availability
SOR	C	$21.46^{a}\pm0.67$	$5.23^{abc}\pm0.56$	$24.35^{a}\pm1.81$	$3.12^{a}\pm0.17$	$0.24^{abd}\pm0.03$	$7.62^{ab}\pm0.39$
	T1	$19.23^{bc}\pm0.38$	$5.69^{bc}\pm0.31$	$29.61^{ab}\pm2.65$	$3.26^{a}\pm0.04$	$0.30^{b}\pm0.02$	$9.16^{b}\pm0.61$
	T2	$18.17^{d}\pm0.22$	$4.93^{abc}\pm0.35$	$27.14^{ab}\pm1.71$	$2.51^{bc}\pm0.07$	$0.19^{ac}\pm0.02$	$7.50^{ab}\pm0.81$
	T3	$16.87^{e}\pm0.31$	$4.20^{ad}\pm0.46$	$24.93^{a}\pm3.13$	$2.58^{c}\pm0.06$	$0.14^{c}\pm0.05$	$5.33^{a}\pm2.00$
	T4	$18.60^{bd}\pm0.33$	$4.57^{abd}\pm0.42$	$24.53^{a}\pm1.85$	$2.63^{c}\pm0.13$	$0.21^{acd}\pm0.07$	$8.06^{ab}\pm0.51$
	T5	$19.17^{bc}\pm0.34$	$5.51^{ab}\pm0.47$	$28.78^{ab}\pm1.48$	$2.31^{bd}\pm0.04$	$0.21^{acd}\pm0.01$	$9.14^{b}\pm0.47$
	T6	$20.02^{c}\pm0.32$	$4.87^{abc}\pm0.61$	$24.34^{a}\pm2.26$	$3.85^{a}\pm0.19$	$0.28^{bd}\pm0.01$	$7.36^{ab}\pm0.39$
	T7	$10.88^{f}\pm0.16$	$3.57^{d}\pm0.31$	$32.81^{b}\pm3.13$	$2.18^{d}\pm0.06$	$0.19^{ac}\pm0.06$	$8.80^{ab}\pm2.91$

Mean values followed with different subscripts are significantly different ($p \leq 0.05$) using Tukey's test for different parameters (total and bioavailable calcium and zinc).

PM-1: Pearl millet FBC 16; PM-2: Pearl millet PCB 165; SOR: Sorghum PSC 4

C- control sorghum/ pearl millet flour, T1-germinated sorghum/ pearl millet flour, T2- soaked sorghum/ pearl millet flour, T3- blanched sorghum/ pearl millet flour, T4- roasted sorghum/ pearl millet flour, T5-puffed sorghum/ pearl millet flour, T6-milled sorghum/ pearl millet flour, T7-parled sorghum/ pearl millet flour

revelation was observed in a study by Afify et al., (2012) who reported significant reduction in the calcium content in three sorghum varieties post soaking (26.74, 18.90 and 16.51 mg/100g), cooking (13.15, 16.74 and 14.58 mg/100g) and germination (12.50, 12.50 and 18.79 mg/100g) when compared to their control (33.09, 26.59 and 22.91 mg/100g) counterparts. Significantly ($p \leq 0.05$) higher absorption of available calcium was observed in parled (32.81%) SOR flour, followed by germinated (29.61%) SOR flour. Other processing treatments also proved to significantly ($p \leq 0.05$) enhance the absorption percentage of calcium content in the order of puffing > soaking > blanching > roasting > milling (28.78, 27.14, 24.93, 24.53, 24.34% respectively).

Total zinc content was also observed to reduce significantly ($p \leq 0.05$) by application of processing treatment to SOR flour owing to leaching in soaking medium. The zinc content of control and processed SOR flour ranged between 2.18 mg/100g in parled flour and 3.26 mg/100g in germinated SOR flour. Afify et al. (2012) also reported the zinc content of processed (soaked, cooked and germinated) sorghum flours to range between 3.12 mg/100g and 3.78 mg/100g. The observation of the above-mentioned study validated the observation of the present study. A significant ($p \leq 0.05$) enhancement in the percent bioavailability was observed in processed SOR flours as compared to control flour. Maximum zinc absorption was established by germinated (9.16%) and puffed (9.14%) SOR flours followed by decortication, roasting, soaking and milling (8.80, 8.06, 7.50 and 7.36 % respectively). However, percent bioavailability of zinc was significantly reduced in blanched (5.33%) SOR flour.

CONCLUSION

The major constraint for wide utilization of sorghum being its low availability and acceptability attributing to its fat content and undesirable flavour can be countered by applying conventional processing. Germination and puffing considerably retained and increased the crude protein and total dietary fiber, respectively while reducing the fat content. *In vitro* starch digestibility was improved by processing too. Iron content improved substantially by thermal processing while calcium and zinc were lost by heat treatments and parling. However, germination and puffing showed affirmative relationship with iron, calcium and zinc absorption. Therefore, germination and puffing resulted in desirable nutritional characteristics of sorghum cultivar and these treatments at household level are instrumental in popularizing these grains for value addition and enhanced nutrition and can be regarded as the most viable applications for household processing to combat food and nutritional security.

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