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The effect of sorghum type and processing on the antioxidant properties of African sorghum-based foods

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Abstract

This work determined the effect of sorghum type and different processing technologies of traditional African sorghum foods on total phenols, tannin content and antioxidant activity. The products were prepared by fermentation, conventional and extrusion cooking of whole and decorticated ground grain. The tannin sorghum types, had higher ABTS and DPPH antioxidant activities, compared to the types without tannins. Antioxidant activity was significantly correlated with total phenols and tannins ($r > 0.95$). Decortication, reduced antioxidant activity of both tannin and non-tannin sorghum by 82–83% due to the removal of the pericarp and the testa, which decreased phenols. Processing, generally decreased antioxidant activity, however, conventionally cooked porridges had higher antioxidant activity than the extrusion cooked products. The retention of antioxidant activity, particularly in fermented and unfermented porridges, means that whole tannin sorghum can be processed into foods with potential health benefits.
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Keywords: Sorghum-based foods; Antioxidant activity; Tannins; ABTS; DPPH; Total phenols

1. Introduction

Sorghum [*Sorghum bicolor* (L.) Moench] is a drought-resistant crop and thus an important food source in semi-arid regions of the world. World production of sorghum is about 57 million tons and ranks fifth, after maize, rice, wheat and barley (FAOSTAT data, 2005). Some varieties of sorghum are recognized as important sources of dietary antioxidants because of the phenolic compounds found in the grain (Awika & Rooney, 2004; Dykes & Rooney, 2006).

Phenolic compounds in sorghum occur as phenolic acids, flavonoids and condensed tannins (Serna-Saldivar & Rooney, 1995). Condensed tannins (proanthocyanidins) occur in sorghums with a pigmented testa which have dominant B_1B_2 genes (Waniska & Rooney, 2000). The tannins in sorghums have the highest levels of antioxidants of any cereal analyzed (Gu et al., 2004). Sorghum tannins are 15–30 times more effective at quenching peroxyl radicals than simple phenolics, thus they are potential biological antioxidants (Hagerman et al., 1998). Despite their possible beneficial effects as antioxidants, tannins have been linked to reduced protein digestibility of sorghum (Duodu et al., 2002), because they bind with proteins and inhibit enzymes (Scalbert et al., 2000). The evidence of possible benefits of tannins in the diet has led to research that focuses on sorghum tannins and health.

Abbreviations: ABTS, 2,2′-azinobis(3-ethylbenzothiazoline-6-sulfonic acid); DPPH, 2,2-diphenyl-1-picrylhydrazyl; CE, catechin equivalents; TE, Trolox equivalents; PPO, polyphenol oxidase; POX, peroxidase.

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In many parts of Africa, sorghum is milled as whole grain, or decorticated using traditional mortars and pestles or mechanical dehullers (Serna-Saldivar & Rooney, 1995). Decortication removes the grain's outer layers where the polyphenols are concentrated, which reduces overall tannin content (Taylor & Dewar, 2001). This improves product color, reduces astringency and improves digestibility. The milled sorghum is used for making fermented or non-fermented soft or stiff porridges. Sorghum is also used in the preparation of malted and fermented beverages such as *Mahewu*, in Zimbabwe (Bvochora, Reed, Read, & Zvauya, 1999), or sorghum beer (Taylor & Dewar, 2001). Special procedures, such as alkali treatment, are used to eliminate the negative effect of tannins on sorghum malt enzyme activity (Beta, Rooney, Marovatsanga, & Taylor, 2000).

The food industry in Southern Africa has also been exploring the use of sorghum in the production of ready-to-eat products, using extrusion cooking technology and gun-puffing. The tannin sorghums are used in many food products and are sometimes preferred in some areas of Africa. Special products are made from tannin sorghums. Some reports exist on antioxidant activity of fully processed products like cookies and bread containing sorghum bran, as well as extrusion cooked products (Awika, Rooney, Wu, Prior, & Cisneros-Zevallos, 2003).

Awika, Rooney, et al. (2003) and Dykes, Rooney, Waniska, and Rooney (2005), showed that in unprocessed sorghum grain, the content of total phenols was an excellent predictor of antioxidant activity measured by the ABTS, DPPH and ORAC methods. Fermentation reduced measurable tannin content of sorghum products (Hassan & El Tinay, 1995; Bvochora et al., 1999). The reduction in tannins by processing occurs by the interaction of tannins with proteins and carbohydrates (Mehansho, Butler, & Carlson, 1987). These tannin complexes are less extractable, and give reduced tannin levels. Sorghum tannins have strong affinity for proteins high in proline content, like the prolamins (Emmambux & Taylor, 2003). In aqueous environments, polymerization of tannins also occurs between tannin molecules or with other pigments such as anthocyanins (Remy, Fulcrand, Labarbe, Cheynier, & Moutounet, 2000), these complexes may however, not be detectable by the common tannin assay methods such as the vanillin-HCl method.

To date, there are limited reports on the effect of different processing methods on antioxidant activity of African sorghum-based foods such as fermented and unfermented porridges. The objective of this study was to evaluate the effect of traditional African processing and extrusion cooking, using a twin-screw cooker extruder, on total phenols, tannin content and antioxidant activities of products from different sorghum types. The products evaluated included porridges and extrudates made from whole and decorticated tannin and non-tannin sorghums.

2. Materials and methods

2.1. Materials

Two non-tannin sorghum types, Macia and NK 283, and three tannin types, Red Swazi, NS 5511 and Framida were grown in 2003. Four sorghum types originated from Zimbabwe and these were; Macia, Red Swazi, NS 5511 and Framida. NK 283 is a non-tannin sorghum type from South Africa; it has a red pericarp without a pigmented testa. Macia is a white food-type sorghum without a pigmented testa, while Red Swazi is a traditional variety and consisted of mixed red and white grains; over 70% of the kernels had a pigmented testa.

Catechin hydrate, DPPH (2,2-diphenyl-1-picrylhydrazyl) and potassium persulfate were obtained from Sigma (St Louis, MO). The Trolox (6-hydroxy-2,5,7,8 tetramethylchroman-2-carboxylic acid) was obtained from Acros Organics (Morris Plains, NJ), while 2,2′-azinobis(3-ethylbenzothiazoline-6-sulfonic acid) (ABTS) was obtained from TCI Kasei Koygo (Tokyo, Japan). The Total Starch Assay Kit was obtained from Megazyme International Limited (Ireland).

2.2. Analyses

2.2.1. The Bleach (Chlorox) test

The presence or absence of a pigmented testa in the sorghum grain was determined using the Bleach or Chlorox test (Waniska, Hugo, & Rooney, 1992).

2.2.2. Grain hardness

The hardness of the sorghum kernels was assessed visually on a scale 1–5 (soft) basis using the methods and illustrations from Rooney and Miller (1982). Hardness, was then measured using the Single Kernel Hardness Tester (SKHT) Perten SKCS 4100 (Perten Instruments Inc, Chatham, IL), and expressed as Hardness Index (HI).

2.2.3. Grain color

The sorghum kernel color was assessed visually and with a colorimeter Model CR-310 (Minolta, Osaka, Japan) to obtain the CIE L^* values.

2.2.4. Proximate composition of the grain

The moisture content of the milled grain was determined by oven drying at 135 °C for 2 h (AACC Method 44-19, 2000). Protein content was determined by combustion using a LECO FP-528 Nitrogen Analyzer (LECO Corporation, St Joseph, MI), while fat was extracted with petroleum ether. Ash content was determined by dry ashing using a muffle furnace at 550 °C (AOAC Method 923.03, 2002). Starch was determined by the AACC Method 76-13 (2000) using the Megazyme Total Starch Assay Kit.

2.2.5. Determination of total phenols

The modified Folin Ciocalteu method of Kaluza, McGrath, Roberts, and Schroder (1980) was used to quantify total phenols. The milled samples were extracted for 2 h using 1% HCl in methanol while shaking at low speed in an Eberbach shaker (Eberbach Corp., Ann Arbor. MI). The extracts were centrifuged and the supernatant used for total phenols analysis. An aliquot of the extract (0.1 mL) was diluted with 1.1 mL water, and reacted with 0.4 mL Folin Ciocalteu reagent and 0.9 mL of 0.5 M ethanolamine. The reaction was carried out for 20 min at room temperature and the absorbance was read at 600 nm. Total phenols were expressed as mg catechin equivalents per g (mg CE/g).

2.2.6. Determination of tannin content

The tannin content was determined using the vanillin-HCl method as described by Price, Van Scoyoc, and Butler (1978). Blank determinations were used to counteract the effect of anthocyanins and other pigments in the samples. Tannin content was expressed as mg catechin equivalents per g (mg CE/g).

2.2.7. Antioxidant activity assay

Antioxidant activities of the sorghum extracts were determined using the ABTS and DPPH methods as described by Awika, Rooney, et al. (2003). For the ABTS assay, samples were extracted for 2 h with acidified methanol, while aqueous acetone (70%) was used as the extracting solvent for the DPPH assay. The standard used, was Trolox; antioxidant activity was reported as μmol Trolox Equivalent Antioxidant Capacity per g (μmol TE/g).

2.3. Sorghum processing

2.3.1. Decorticating and milling the grain

The sorghum grain was decorticated for 6–8 min to obtain extraction rates of 70–81% using a PRL dehuller (Rural Industries Innovation Center, Kanye, Botswana). The soft endosperm varieties, Framida and NS 5511, were decorticated for 6 min to avoid large losses due to endosperm fragmentation. The whole and decorticated grain was milled using a hammer mill.

2.3.2. Fermentation and preparation of the porridges

A traditional lactic acid starter culture was prepared by back slopping as described by Taylor and Taylor (2002). The starter was prepared from the natural micro-flora on the grain using decorticated, milled NK 283. The preparation involved suspending 100 g of flour in 90–100 mL boiled, cooled water, leaving the slurry at 25 °C, until the pH dropped to 3.6, which occurs after about 48 h. A portion (20 mL) of the fermented slurry was transferred to a fresh batch of sorghum flour slurry and the whole mixture was fermented at 25 °C for seven days. This procedure was repeated to maintain a natural inoculum.

The bulk starter culture was prepared by inoculating 500 g flour with the lactic acid starter, and fermenting to pH 3.6. Portions (20 mL) were taken from the bulk starter and added to 235 g milled grain suspended in 300 mL water, and the mixture fermented for 24 h or until the pH dropped to 3.6. The fermentation pH was determined at regular intervals, and the soured slurry was mixed with 1 L boiling water and cooked, with constant stirring, for 10 min. The unfermented porridge was prepared by suspending the sorghum flour in cold water, adding boiling water and cooking as described for the fermented porridge.

The fermented slurry and porridges were freeze-dried and analyzed for total phenols, tannins and antioxidant activity.

2.3.3. Extrusion cooking

Whole and decorticated sorghum was coarsely milled using screen size (≅1.58 mm) using a Hippo hammer mill (Precision Grinders Engineers, Harare, Zimbabwe). The milled grain was extruded in a Clextral BC92 twin-screw, co-rotating extruder (Clextral, FIRMINY Cedex, France). The feed rate was 550 kg/h, and moisture content of feed adjusted to about 18%, by injecting 45 L water per hour. The screw rotation speed was 230 rpm, and barrel temperature was maintained at 150 and 160 °C, and residence time was 30–90 s. The die diameter was 2 mm and the cutter speed set at 120 rpm. After extrusion, the sorghum extrudates were placed in containers and allowed to cool and equilibrate for a few hours (4–5 h).

2.4. Sample preparation

The processed and unprocessed sorghum samples, including the freeze-dried fermented slurries and porridges, were milled to pass through a 1 mm screen using the UDY cyclone mill Model 3010-030 (UDY Corporation, Fort Collins, CO.).

2.5. Statistical analyses

The statistical software SPSS version 11.5 (SPSS Inc. Chicago, IL) was used. Mean values of data were analyzed with one-way analysis of variance (ANOVA). The means were separated using Fisher's least significant difference (LSD) at $P < 0.05$. The correlations of total phenols and tannins with ABTS antioxidant activity, and that of ABTS and DPPH antioxidant activities were determined using Linear Regression.

3. Results and discussion

3.1. Effect of sorghum type, decortication and different processing methods on total phenols and tannin content

The grain properties are presented in Table 1. The Red Swazi was a blend of tannin and non-tannin sorghums. Tannin sorghums were softer than non-tannin sorghums

Table 1
Effect of sorghum type on grain quality of Macia, NK 283, Red Swazi, NS 5511 and Framida

Sorghum type	Pericarp color	L^* value	Bleach Test[A]	Kernel hardness score[B]	Kernel hardness index (HI)[C]	Kernel weight (mg)[C]	Kernel diameter (mm)[C]	% Decorticated grain yield
Macia	White	67.0 a	0	2.0	84.6 a	32.0 a	2.3 a	81
NK 283	Red	50.2 b	1	3.0	72.9 b	24.9 b	2.1 b	71
Red Swazi[D]	Red	49.0 c	77	3.5	63.7 c	24.7 b	2.2 b	75
NS 5511	Red	45.7 d	99	5.0	68.6 d	31.4 a	2.4 a	70
Framida	Red	45.8 d	99	5.0	44.0 e	29.6 c	2.2 c	72

Values within the same column with different letters are significantly different at $P < 0.05$.
[A] Number of kernels, out of a 100, with pigmented testa layer.
[B] Visual kernel hardness evaluated using a score of 1 to 5:1 is hard and 5 is soft or floury endosperm (Rooney & Miller, 1982).
[C] Kernel hardness, weight and diameter determined using the Single Kernel Hardness Tester (Perten SKCS 4100).
[D] Red Swazi, was a mixture of red and white grains.

which gave lower decorticated yield (average 72%) than Macia (81%). The soft kernels fragmented easily, resulting in higher endosperm loss to the bran (Beta, Rooney, Marovatsanga, & Taylor, 1999). The starch, protein, fat and ash contents (not reported here) were within the normal ranges reported for sorghum (Rooney & Waniska, 2000).

The total phenol levels differed significantly ($P < 0.05$) between the different sorghum types; (Table 2). Tannin sorghums had the highest total phenols, followed by NK 283 and Macia, which was lowest. The tannin content was highest for the sorghums with pigmented testa, while the red (NK 283) and white (Macia) sorghums did not have any tannins (Table 3). The antioxidant levels were correlated with total phenols and tannin content. Decorticating the grain significantly reduced the level of total phenols and tannins, when compared to the whole grain. The tannin sorghums had the greatest reduction in phenols. Macia, with the highest yield (81%), had total phenols reduced by 33%, while NS 5511, with a 70% decorticated yield, lost 77% of its phenols.

Decorticating the grain significantly reduced tannin content, by as much as 79–92%. The tannin content of decorticated NS 5511 and Red Swazi were not significantly different, 4.2 and 3.4 mg CE/g, respectively, while that of decorticated Framida was significantly higher (9.7 mg CE/g). The fermented slurries of both whole and decorticated tannin sorghums had significantly reduced total phenols when compared to that of the unprocessed

Table 2
Effect of different processing methods on total phenols[A] of sorghum

Sample	Raw grain		Fermented slurry		Fermented porridges		Extrusion cooked sorghum	
	Whole	Decorticated	Whole	Decorticated	Whole	Decorticated	Whole	Decorticated
Macia	2.7 b	2.2 a	2.2 a	2.5 b	3.3 b	2.9 b	1.8 a	2.3 a
NK 283	5.3 c	2.0 a	2.8 b	2.6 b	4.4 c	3.0 b	2.3 b	3.4 c
Red Swazi	19.7 j	6.6 e	9.5 g	4.3 c	8.7 f	NR[B]	6.0 e	2.5 b
NS 5511	22.4 k	4.7 c	10.1 h	5.2 c	9.1 f	3.6 c	6.7 e	4.1 c
Framida	24.5 l	8.5 f	16.3 i	7.5 e	NR	NR	5.3 d	3.7 c

Data values with different letters are significantly different at $P < 0.05$.
[A] Total phenols expressed as mg Catechin equivalents per g sample, dry basis (Folin Ciocalteu method).
[B] NR – no data value.

Table 3
Effect of different processing methods on tannin content[A] of sorghum

Sample	Raw grain		Fermented slurry		Fermented porridges		Extrusion cooked sorghum	
	Whole	Decorticated	Whole	Decorticated	Whole	Decorticated	Whole	Decorticated
Macia	ND[B]	ND	ND	ND	ND	ND	ND	ND
NK 283	ND	ND	ND	ND	ND	ND	ND	ND
Red Swazi	33.6 g	3.4 b	11.4 d	ND	2.0 a	NR	0.9 a	ND
NS 5511	49.1 i	4.2 b	15.5 e	ND	4.5 b	ND	1.9 a	ND
Framida	47.8 h	9.7 c	24.0 f	3.9 b	NR[C]	NR	0.4 a	ND

Data values with different letters are significantly different at $P < 0.05$.
[A] Tannin content expressed as mg Catechin equivalents per g sample, dry basis (Vanillin-HCl method, blanks subtracted).
[B] ND – not detected.
[C] NR – no data value.

whole and decorticated grains. The cooked fermented porridges from whole tannin sorghum, had a slight reduction in total phenols compared to that of the fermented slurries. Extrusion cooking significantly reduced measurable total phenols and tannins for both whole and decorticated tannin sorghums. Fermentation, porridge making and extrusion cooking did not significantly affect the level of total phenols in processed NK 283 and Macia.

3.2. Effect of sorghum type, decortication and different processing methods on antioxidant activity

The tannin sorghums, Red Swazi, NS 5511 and Framida, had significantly higher ABTS and DPPH antioxidant activity when compared to sorghums without a pigmented testa layer, Macia and NK 283 (Table 4, Fig. 1). Framida had the highest ABTS antioxidant activity [427 μmol Trolox equivalents per g (μmol TE/g)], and DPPH antioxidant activity (305 μmol TE/g). Macia, a white non-tannin sorghum, had the lowest ABTS and DPPH antioxidant activities, (22 and 3 μmol TE/g respectively).

Decortication, significantly reduced antioxidant activities of both tannin and non-tannin sorghums by 73–87%. The ABTS antioxidant activity of Framida was reduced from 427 to 93 μmol TE/g, while that of Macia was reduced from 22 to 6 μmol TE/g. Decorticated Macia did not show significant change in DPPH antioxidant activity, while that of the other sorghums was significantly reduced. The ABTS antioxidant activities of decorticated Red Swazi and NS 5511 were not significantly different from that of whole NK 283.

The whole fermented slurries of tannin and non-tannin sorghums had reduced ABTS and DPPH antioxidant activities when compared to that of the raw grain. Processing into fermented porridges further reduced the antioxidant activities of whole tannin sorghum porridges, whilst those of non-tannin sorghums did not change significantly. Decorticated fermented porridges had significantly lower antioxidant activity than whole grain porridges. Extrusion

Table 4
Effect of different processing methods on antioxidant activity[A] of sorghum

Sample	Raw grain		Fermented slurry		Fermented porridges		Extrusion cooked sorghum	
	Whole	Decorticated	Whole	Decorticated	Whole	Decorticated	Whole	Decorticated
Macia	22 b	6 a	6 a	1 a	6 a	3 a	4 a	4 a
NK 283	52 c	7 a	25 b	3 a	20 b	4 a	12 ab	18 b
Red Swazi	359 h	51 c	102 e	15 ab	68 d	NR[B]	48 c	13 ab
NS 5511	384 i	49 c	147 f	20 b	74 d	13 ab	58 cd	22 b
Framida	427 j	93 e	200 g	46 c	NR	NR	53 c	19 b

Data values with different letters are significantly different at $P < 0.05$.
[A] ABTS antioxidant activity expressed as μmol Trolox equivalent antioxidant capacity per g sample (μmol TE/g), dry basis.
[B] NR – no data value.

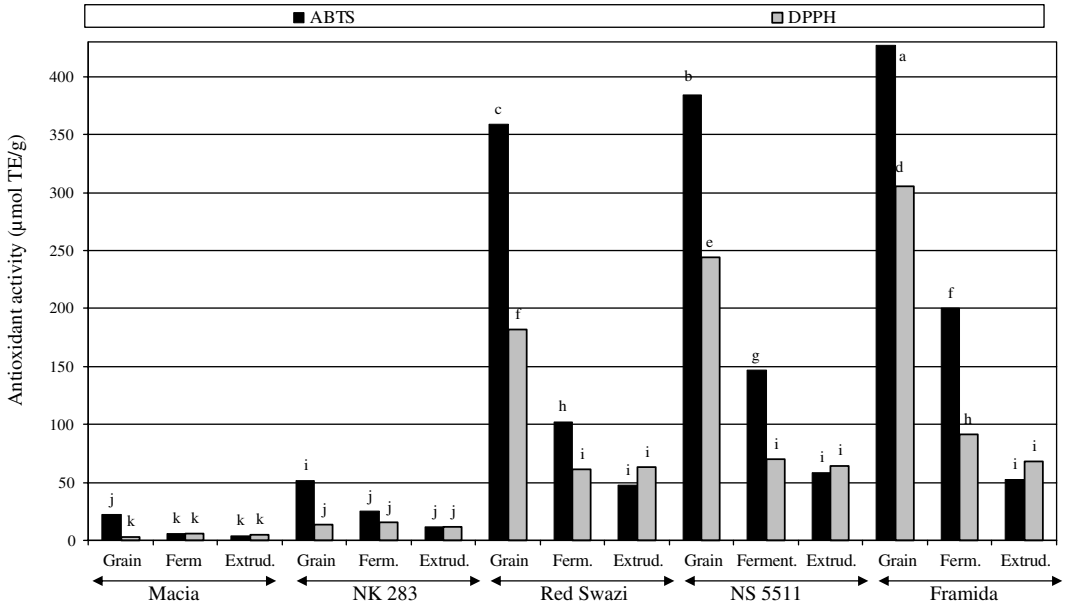

Fig. 1. Comparison of ABTS and DPPH antioxidant activity of whole sorghum grain and products. Abbreviations: Ferm. – fermented slurry; Extrud. – extrudates.

cooking, significantly reduced antioxidant activity, by up to 86%, compared to that of the unprocessed grain. The antioxidant activities of extrudates produced from decorticated NK 283, Red Swazi, NS 5511 and Framida, did not differ significantly. Macia decorticated extrudates had the lowest antioxidant activity.

The sorghum types with pigmented testa layers, had higher total phenols content as well as higher antioxidant activity than non-tannin sorghum types. Dykes et al. (2005) and Dicko, Gruppen, Traore, van Berkel, and Voragen (2005) reported similar results. The total phenols and tannin content of grain and processed samples were highly correlated to antioxidant activity, R-square = 0.96 and 0.94 respectively for the ABTS assay; while for the DPPH assay, correlation with total phenols was R-square = 0.94 and that with tannin content was 0.92. Antioxidant activity, determined by the ABTS method, was higher than that determined by the DPPH method (Fig. 1), although the two methods were highly correlated, (R-square = 0.93). Awika, Dykes, Gu, Rooney, and Prior (2003) and Awika, Rooney, et al. (2003) demonstrated that the ABTS and DPPH methods were highly correlated with the oxygen radical absorbance capacity (ORAC) method. The lower values for the DPPH assay, may be due to differences in the extracting solvents; work done in our laboratory showed that acidified methanol extracted higher amounts of total phenols than aqueous acetone. Acidified methanol was used as the extracting solvent for the ABTS assay, while aqueous acetone was used for the DPPH assay. According to Arnao (2000), lower DPPH values may also be due to interference from other grain pigments such carotenoids and anthocyanins, which also absorb at the wavelength used for the DPPH assay (515 nm). The ABTS assay is carried out at 734 nm, which is outside the absorption range of most grain pigments.

Decortication, reduced total phenols, tannins and antioxidant activity because the process removes the grain's pericarp and most of the testa layer, where the polyphenols are concentrated (Hahn, Rooney, & Earp, 1984). Decortication is favored in the production of tannin sorghum food products in Africa because it reduces astringency, and produces lighter colored products (Taylor & Dewar, 2001). Product color is a major quality criteria of sorghum-based products (Kebakile et al., 2003).Thus, the antioxidant benefits of the sorghum is often lost during processing.

The reductions in *in vitro* antioxidant activities of fermented slurries (or fermented milled grain) and porridges were caused by changes during processing that affected the extraction of total phenols and tannins. These changes probably involved associations between the tannins, phenols, proteins and other compounds in the grain. These results confirmed previous studies, where fermentation reduced tannin levels, and improved *in vitro* digestibility of protein (Hassan & El Tinay, 1995; Osman, 2004). Hassan and El Tinay (1995) reported tannin reduction of 61% to 63%, while Osman (2004) found tannin reductions ranging from 15% to 35%. In our study, tannins in whole fermented slurries were reduced by 49% to 68%. Several conflicting explanations were given for the apparent reduced tannin content after fermentation. One suggestion, is that in aqueous environments such as fermentation, tannins tend to bind with protein and other components, reducing their extractability (Scalbert et al., 2000). Another explanation, is that during fermentation, tannins may be degraded by microbial enzymes (Towo, Matuschek, & Svanberg, 2006). Polyphenol oxidase (PPO) reduced phenolic content in tannin sorghums (Towo et al., 2006). In plants, PPOs may synergistically act with peroxidases (POX) during enzymatic browning. PPO and POX activity was detected in the leaves and grains of sorghum; generally, red sorghum varieties with high phenolic content had high PPO and low POX activities (Dicko et al., 2002).

Extrusion cooking significantly reduced ABTS antioxidant activity by 83% to 87%, for the sorghum products when compared to that of the raw grains. Thus only 13% to 23% of antioxidant activity of the original raw or unprocessed grain was extracted from the products. These retentions are significantly lower compared to those of sorghum extrudates produced with a single screw friction type extruder (Awika, Dykes, et al., 2003); where 70–100% of the antioxidant activity was retained. We used a steam heated, co-rotating twin-screw cooker extruder where the feed was tempered to 18% moisture prior to extrusion. The higher moisture content probably promoted phenolic and tannin polymerization (Remy et al., 2000), which affected extractability of phenols and tannins, and reduced antioxidant activity. In contrast, the low moisture (<15%), high shear and high temperature extrusion conditions of the single screw extruder may cause depolymerization of the condensed tannins and convert them into low molecular weight oligomers that are more extractable (Awika, Dykes, et al., 2003). The observed higher antioxidant activity of extruded NK 283 (18 μmol TE/g), compared to raw decorticated grain (7 μmol TE/g) may result from increased extractability of phenols from the grain cell walls and proteins.

4. Conclusion

The significant reduction in antioxidant activity in cooked high tannin sorghum products can be attributed largely to the interaction of tannins with prolamins (Emmambux & Taylor, 2003). Protein denatured by cooking, had open loose structures which promoted tannin–protein interactions. Riedl and Hagerman (2001) found that tannin–protein complexes retained their antioxidant activity, and thus had potential to act as free radical scavengers in the gastrointestinal tract. Deprez et al. (2000) demonstrated *in vitro* breakdown of large tannin polymers by microbial flora in the colon. Thus, the protein–tannin polymers may be broken down, and the tannins released. This is an area that requires significant research to clarify the kind of complexes formed and whether they are released during

digestion in the gastrointestinal tract by pepsin and other enzymes.

Clearly decorticating the sorghum drastically reduced the antioxidant activity and the health benefits therein. In the cooked, ready-to-eat whole grain products, the porridges had higher antioxidant activity than the extrudates.

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