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FULL PAPER

Physical characteristics, nutritional composition and phenolic compounds of some of the sorghum landraces obtained in South Africa

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Abstract

Sorghum is among the predominant food plants in sub-Saharan Africa with established dietary and health benefits. The purpose of this study was to evaluate the physical and nutritional characteristics and phenolic compounds of some of the sorghum genotypes grown in South Africa. The varieties investigated were white (Macia-SA), red (M48) and brown sorghum (M153). The Association of Official Analytical Chemists (AOAC) method was used for physical, nutritional and mineral examination and the Waters Synapt G2 quadruple time-of-flight (QTOF) mass spectrometer (MS) for the evaluation of the phenolic compound. The highest mineral content for the genotypes was potassium, in the range of 3599.24, 4248.04, and 4763.45 mg/kg; the highest value recorded was in the brown sorghum (SBrown) variety. The white sorghum (SWhite) variety had higher dry matter (DM), gross energy (GE) and starch contents compared to the red and brown types. Furthermore, higher ash, crude protein (CP) and ether extract (EE) values were observed in respect of the red sorghum variety. The most abundant phenolic compound in this study was caffeic acid, and this was more in the red sorghum. Naringenin-7-*O*-glucoside was the only quantified flavonoid, the highest content was reported in the red sorghum genotype. The Principal Component Analysis (PCA) showed that *p*-coumaric acid, chlorogenic acid, caffeic acid and naringenin-7-*O*-glucoside contributed largely to the clustering of the genotypes in component 1 (PC1), while feruloylquinic acid and ferulic acid contributed to the clustering of component 2 (PC2). High component loadings for PC1 were contributed by the red sorghum (SRed) variety. These results suggest that sorghum varieties grown under South African climatic conditions are rich sources of valuable nutrients and diverse phenolic compounds, with brown and red sorghum types being the outstanding varieties. Sorghum's unique phenolic profile qualifies it to be used to lessen oxidative stress and prevent diseases such as cancer. It has the potential to be utilized in the development of functional food additives.

1. Introduction

After maize, sorghum ("*Sorghum bicolor* (L.) Moench") is considered the grain of choice in sub-Saharan Africa and other developing countries Mabhaudhi *et al.* (2016), where it is used as the main staple food by the inhabitants of the region. It contains valuable nutrients considered essential for growth and development (Chan *et al*., 2007). For instance, the aleurone and germ layers have appreciable content of fat, which contribute up to 80% of the total fat (Rooney and Serna-Saldivar, 1991). A study by Shen *et al.* (2018) indicated that the different varieties of sorghum have different uses. For example, the white sorghum variety is normally utilized for cooking, while the brown and red sorghum varieties are utilized for feeding and beer production due to their content of bioactive compounds such as tannins (Shen *et al*., 2018). These compounds are beneficial to human health and are widely applied in many processed foods as functional ingredients. Due to the continuously degrading climatic conditions, coupled with the increase in populations around the globe, sorghum is seen as the "rescuer grain", because of its capability to survive in severe climates (Linder *et al*., 2017). It is also considered safe to use for celiac disease

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patients because it is free from gluten proteins (Kasarda, 2001).

Many pieces of research conducted on the nutritional content of sorghum, confirmed the richness of the grain with valuable minerals such as phosphorus, potassium, magnesium and calcium Afify *et al*. (2012), which are beneficial to humans and animals. Phosphorus is important in the mineralisation of bones and maintenance of the acid-base balance, while other minerals such as sodium, potassium and chlorine are useful in maintaining the osmotic balance in the body, calcium is essential in the formation and stability of cell walls and membrane structure; iron is essential for red blood cells function, and iron deficiency leads to anaemia (Soetan *et al*., 2010; Serna and Bergwitz, 2020). Gerrano *et al*. (2016) reported that the white sorghum genotype has high calcium content (279.85 mg/kg) in comparison to the other types. The variation in mineral content is believed to be influenced by the sorghum variety and the environment. In addition, Mabelebele *et al*. (2015) found that the tannin-free sorghum varieties contain less mineral concentration in comparison to other varieties. The inclusion of low tannin sorghum in guinea pigs' diets resulted in low cholesterol (Lattanzio, 2013). Studies by Topping (1991) and Warrand (2006) suggest that the presence of non-starch polysaccharides in sorghum improves bowel movement and lowers the level of cholesterol. Stefoska-Needham *et al*. (2015) reported a reduction in gastrointestinal cancer due to sorghum consumption.

Furthermore, phenolic compounds are secondary metabolites that are found in abundance in the plant kingdom (Afify *et al*., 2012). These *compounds are* found in nature and are considered rich in antioxidants, anti-inflammatory, anti-allergic, anticarcinogenic, antihypertensive, cardioprotective, anti-arthritic and antimicrobial activities (Lee *et al*., 2003; Dykes and Rooney, 2009; Bhuyan and Basu, 2017). The compounds, as defined by Dykes and Rooney (2007) contain benzene rings that have one or more hydroxyl groups. Sorghum grain is believed to have the widest variety of phenolic compounds (Dykes and Rooney, 2007). Xiong *et al.* (2019) reported that the phenolic compounds in sorghum consist of phenolic acids, 3-deoxyanthocyanidins and condensed tannins. These phenolic compounds are influenced by the type of sorghum and the climatic condition, as reported by Xiong *et al*. (2019). Furthermore, different studies suggest that sorghum contains most of the classes of phenolic compounds (Dicko *et al*., 2006). It is believed that the solution for micro-nutrient deficiencies may lie in recognising valuable ancestral grains which are left out, because of the bottlenecks imposed by domestication and reintroducing them into cultivated crops (Awika and Rooney, 2004). Afify *et al.* (2012) found that the red sorghum variety contained higher iron than other cereals. Sorghum could, therefore, be one of the grains that can aid in tackling malnutrition. The purpose of this research was to unearth the potential of the grain by profiling the nutritional and mineral contents and phenolic compounds of some sorghum varieties grown in South Africa.

2. Materials and methods

2.1 Reagents and chemicals

All chemicals were supplied by Merck (Kenilworth, NJ, USA) and Sigma-Aldrich (St. Louis, MO, USA) and were of analytical-reagent grade. Deionized water (obtained from Milli-Q® Type 1 Ultrapure Water Systems) was used throughout the experiment. To minimize contamination risk, glassware and other equipment were cleaned with 6.0 M nitric acid (HNO_3) and thoroughly rinsed with deionized water.

2.2 Sourcing of sorghum grains and preparation

The three different sorghum varieties used in this study were grown and sourced from the Agricultural Research Council Grain Crops Institute (ARC-GCI), which is situated in Potchefstroom, in the North West province, South Africa (coordinates: 26°43'43.16"S–27° 04'47.71"E). This area has an average temperature of 22–34ºC in summer and 2–20ºC in winter. The approval to conduct this research was granted by the Ethics Committee for Animal Research, College of Agriculture and Environmental Science, University of South Africa. The ethics clearance number is 2020/CAES_AREC/003. All three sorghum varieties were adapted to different types of soil, namely, sandy loam and sandy soils in short-season areas with an annual rainfall of between 350 and 750 mm. The sorghum was planted in a field that had the same environmental conditions in the summer season from November to April/May in the year 2019 to 2020. Sorghum M48, which is an open-pollinated variety and has a red kernel, was cross-bred using two sorghum lines that were selected through the pedigree breeding method. The height of this plant is around 1 to 1.2 m and it is purple and has excellent traits, which include high grain yield and pleasing resistance to aphids and stem borers. It takes around 110 to 120 days for this variety to reach maturity. The brown sorghum type, known as M153, is an open-pollinated variety selected through local collections in South Africa. This variety, like M48, is also purple but it has brown seeds. The height of this plant ranges between 1.5 and 1.7 m. This variety takes up to 130 to 140 days to reach maturity. It has been bred for better traits, such as grain yield, bird resistance and

resistance to aphids and stem borers. Macia-SA is a pure-line white sorghum variety that was selected at the ARG-GCI, Potchefstroom, from an ICRISTAT introduction M71 in the germplasm collection. This sorghum variety has been registered in numerous SADC countries, such as Botswana, Zimbabwe, Nambia, Tanzania and Mozambique, as well as the eastern African countries. The height of Macia-SA ranges between 1.2 and 1.5 m, and it takes this variety between 120 and 130 days to reach maturity. The good traits of this variety include early maturity, the ability to escape terminal drought and moderate resistance to aphids and stem borers.

2.3 Physical characteristics

In respect of each sorghum variety, 1000 sound kernels were weighed to determine the thousand kernel weight. The colour of each sorghum variety was observed visually. A total of 20 grain kernels were halved using a blade, for each of the sorghum types. The texture was assessed based on proportions of the corneous, intermediate and floury endosperm. A hunter lab test was also conducted to assess the colour of the grains using the procedure of Knievel *et al.* (2009). A scalpel was used to scratch the external coating (pericarp) of the three studied varieties and the presence of the pigmented testa was performed using a light microscope. The bleach test method of Taylor and Dewar–(2001) was used to detect grains with pigmented testa. Grains that were classified as tannin-containing were black over their entire surface and those that were classified as tannin free were either completely brown or white.

2.4 Chemical analysis

Proximate analysis was conducted to determine the dry matter (DM), ash, crude fibre, crude protein and ether extract. The method used was according to the specifications of the Association of Official Analytical Chemists (AOAC, 2008). Values of dry matter and moisture were determined after samples had been dried using a furnace at 105ºC to constant weight. Ash content was determined by means of heating at 550ºC for 6 hrs in a muffle furnace. Leco analyser equipment was used to perform a nitrogen analysis according to method 968.0 of the AOAC (2008) the percentage of nitrogen was multiplied by a factor of 6.25, to obtain the crude protein. Neutral detergent fibre corrected for nitrogen (NDFn) and acid detergent fibre corrected for nitrogen (ADFn) were determined using an ANKOM^{2000} Fibre Analyser (ANKOM Technology, New York) according to the method of Van Soest *et al*. (1991). The NDFn content was examined using heat-stable α-amylase (Sigma A3306, Sigma Chemical Co., St. Louis, MO, USA). The ADFn was examined by the method of Van Soest *et al*. (1991). The gross energy content was determined using an adiabatic bomb calorimeter (Gallenkamp, Autobomb, and London, UK). The extraction of starch was conducted using the *Amyloglucosidase/α-Amylase* method following an assay procedure. These determination methods were broadly grouped into acid hydrolysis or enzymic procedure.

2.5 Amino acids

Amino acids separation and detection were performed using a Waters ACQUITY ultra-performance liquid chromatography (UPLC) fitted with a photodiode array (PDA) detector. In this procedure, 1 µL of sample/ standard solution is injected into the mobile phase, which conveys the derivatised amino acids onto a Waters UltraTax C_{18} column (2.1 × 50 mm × 1.7 µm) held at 60° C (Hewitson *et al*., 2007). Elution of analytes off the column is performed by running a gradient. Analytes eluting off the column are detected by the PDA detector. Each amino acid comes off the column at a unique retention time. Fat and ether extract lipid content was estimated using Soxtec solvent extraction systems, as described by Anderson and Luthria (2004). Samples were extracted following three automatic steps of boiling, rinsing and recovering, with an estimated time of an hour.

2.6 Data and statistical analysis

The one-way analysis of variance (ANOVA) software (SAS Institute, 2012) was used to determine the variations in the nutritional composition of the sorghum varieties. The mean was separated through the least significant difference (LSD) at a significance level of $p<0.05$.

PCA was conducted to study the correlation among the phenolic compounds. A multivariate cluster analysis was carried out, using the commercial statistical package PAST (Pulliainen and Wallin, 1996).

2.7 Mineral analysis

Samples of the sorghum varieties were cleaned from impurities, dried, and milled using a two-roll into flour, which was then analysed to determine the mineral contents. To determine the minerals, three samples of the sorghum varieties were prepared in duplicate, and then analysed using the methods of the AOAC (2008). Acid digestion of samples was carried out on a heating block (pre-heated to 240°C). A 0.5 g of each ground grain sample was accurately weighed into the digestion tube, to which 25 mL of HNO_3 was added. For digestion, the heating block temperature was ramped to 240°C, on which the samples were left to boil for 15 mins. A 10 mL solution of perchloric acid ($HClO_4$) was then added to

the samples and further boiled for 35 mins. Digested samples were cooled under a fume cupboard, followed by the addition of deionized water. The samples were transferred into a 50 mL volumetric flask and made up to the mark with deionized water. Samples were transferred into polyethylene bottles for elemental analysis.

Phosphorus was determined by the method of Pulliainen and Wallin (1996), the samples were dry-ashed with zinc oxid, the content of phosphorus was then measured colorimetrically as molybdenum blue. Calcium, magnesium, copper, iron, manganese, zinc, sodium and potassium were determined by atomic absorption spectrophotometry using Varian SPECTRAA - 220FS (NJ, USA).

2.8 Phenolic compounds extraction

The extracts were prepared by using 2 g dry sorghum material and 15 mL of 50% methanol/1% formic acid in water with ultrasonication for 1 hr and standing overnight, followed by centrifugation and transfer of the supernatant to a glass vial ready for the LC-MS analysis.

2.9 LC-MS analysis

The samples were analysed by means of an LC/MS QTOF MS connected to a Waters Acquity UPLC (Waters, Milford, MA, USA) used for high-resolution UPLC-MS analysis. Electrospray ionisation was used in negative mode with a cone voltage of 15 V, desolvation temperature of 275°C, desolvation gas at 650 L/h, and the rest of the MS settings optimized for best resolution and sensitivity. Data were gathered by scanning from m/z 150 to 1500 m/z in resolution mode as well as in MSE mode. In MSE mode, two channels of MS data were acquired: one at low collision energy (4 V) and the other using collision energy ramp (20−60 V) to obtain fragmentation data as well. Leucine enkephalin was used as lock mass (reference mass) for accurate mass determination and the instrument was calibrated with sodium formate. Separation was achieved on a Waters HSS T3, 2.1×100 mm, 1.7 µm column. An injection volume of 2 µL was used and the mobile phase consisted of 0.1% formic acid (solvent A) and acetonitrile containing 0.1% formic acid as solvent B. The gradient started at 100% solvent A for 1 min and changed to 28% B over 22 mins in a linear way. It then went to 40% B over 50 s and a wash step of 1.5 mins at 100% B, followed by re-equilibration to initial conditions for 4 mins. The flow rate was 0.3 mL/min and the column temperature was maintained at 55°C.

3. Results and discussion

3.1 Physical characteristics

In this study, thousand kernel weight (TKW) differed between the three studied sorghum varieties (Table 1). The findings are similar to those reported by (Noori *et al*., 2004; Chiremba, 2012), who indicated that high TKW values indicate that large grains have a proportionally lower exterior than the lower ones. The bleach test results in the present study showed the presence of tannins only in the brown variety; the red and white varieties were tannin free. However, the reported findings differ from those of Selle *et al*. (2010), who showed that red sorghum contains more tannins than the white variety and that, based on this observation, the white variety is more suitable than the red type for feeding pigs and poultry. In the present study, the three sorghum types were also found to have different textures, where red sorghum was corneous, brown was intermediate and white was floury. These results correspond with the results obtained in the studies by Hikeezi (2010) and Shegro *et al*. (2012). It has also been reported that grains that have a high proportion of corneous endosperm tend to be more resistant to breakage than grains that have a high proportion of floury endosperm (Etuk *et al.*, 2012). In this case, the corneous red sorghum would be suitable to be used for developing high-quality sorghum products. In South Africa, sorghum is used to make sorghum meal (Mabele) for human consumption. The Hunter lab test showed that the red and brown sorghum varieties have the same lightness, redness and green colour although they have different visual kernel colours (VKC). According to Sedghi *et al.* (2012), sorghum grain colour might vary greatly because of pericarp colour, thickness and the presence of testa. They further note that the thinner the pericarp, the more it influences the testa. An analysis of nutritional composition provides extensive information regarding the vital components of food items and offers

Table 1. Physical characteristics of the three sorghum varieties.

Variables	Sorghum variety		
	SRed	SBrown	SWhite
VKC	Red	Brown	White
TKW	3.59^{b}	1.89^{c}	4.59^{a}
Tannins	-	+	-
Texture	Corneous	Intermediate	Floury
Kernel colour (Hunter)			
L*	39.50±0.707^{b}	38.50±0.707^{b}	83.50±0^{a}
a*	14.00±1.414^{a}	14.50±0.707^{a}	8.50±1.414^{b}
b*	21.00±1.414^{b}	21.50±0.707^{b}	31.00±1.414^{a}

Values with different superscript within the same row are significantly different (p<0.05). TKW: 1 000 kernel weight (g), VKC: visual kernel colour, -: no tannins, +: tannins, L: lightness, a: redness, b: green colour value, SRed: Sorghum red, Sbrown: Sorghum brown, SWhite: Sorghum white.

energy values.

3.2 Nutritional composition

Table 2 shows a higher dry matter (DM) value in the white sorghum variety in comparison to the red and brown varieties. However, the values observed were lower than those obtained by Etuk and Ukaejiofo (2007). These variations could be associated with the differences in the cultivars used, which have been reported by Makokha *et al*. (2002) to have a significant effect on DM content. According to McDonald *et al*. (1991), the dry matter content of plants is an important factor in producing high-quality silage. Thus, the white sorghum variety in this study could be the better candidate for silage production, although it was reported by Shen *et al*. (2018) that the white sorghum varieties are more suitable for human consumption. It is also worth mentioning that most of the sorghum processed in South Africa, is used for human consumption. Esterhuizen (2018) reported that about 92% of sorghum produced in South Africa, is used for human consumption, while about only 5-10% is used for animal feed. The main uses of sorghum are beverages and sorghum meal (Esterhuizen, 2018). The ash content recorded in this study was higher in the red and brown sorghum types, although the values were lower compared to those recorded by (Rooney *et al*., 1996). Mohammed *et al*. (2019) reported that the mineral content of grains could be affected by the amount of ions available in the soil. Angelo (2018) reported the crude protein (CP) of sorghum to be between 8.9 to 15 g/100 g, depending on the variety. The reported CP was within the range of the findings of the current study for the three sorghum varieties but was higher than the requirements for the daily maintenance of (0.7 to 0.8 g/100 g) in humans. Kulamarva *et al*. (2009) reported that sorghum protein content may be affected by both genetics and environmental factors, which could be the cause of variations among the different types. The crude fibre (CF) results obtained in the current study were lower than the results reported by (Ayuba *et al*., 2020). The studied sorghum varieties were within the acceptable range (2.21–2.79 g/100 g), which makes them suitable for human feeding. However, Tona (2018) reported that CF should not exceed 0.001 to 0.0015 g/100 g of the diet because high fibre content in food has been linked with the cause of intestinal irritation and low availability of nutrients in humans (Mohammed *et al*., 2019).

The neutral detergent fibre (NDF) was higher in the red sorghum type, while the acid detergent fibre (ADF) was higher in the brown type. These findings are similar in respect of NDF but different in respect of ADF compared to the findings of Firdous and Gilani (2001), who recorded higher NDF and ADF in the red variety. According to Rasby and Martin (2008), NDF and ADF are very desirable and can be put to use in all sectors of the sorghum industry. The ether extract (EE) values recorded in this study were slightly lower compared to the results obtained by Etuk and Ukaejiofo (2007). Lipids are regarded as healthy dietary components that may lower the risk of chronic diseases and improve health in human bodies (Alabdulkarim *et al*., 2012). The values with respect to gross energy (GE) recorded in the present study were higher in the white variety but slightly lower in all three types when compared to the findings by Marin *et al*. (2016). The white sorghum type also had the highest starch content of the three types. Shegro *et al*. (2012) reported that the protein and starch in sorghum are beneficial to diabetic patients due to the slow digestibility of sorghum compared to other cereals.

Table 2. Nutritional composition (g/100 g) profile of South African sorghum varieties

Variables	Sorghum variety		
	SRed	SBrown	SWhite
Dry matter	88.57±0.00^{c}	89.14±0.007^{b}	90.07±0.000^{a}
Ash	1.62±0.007^{a}	1.56±0.007^{a}	1.35±0.070^{b}
Crude protein	11.97±0.007^{a}	10.37±0.007^{b}	9.35±0.007^{c}
Crude fibre	2.30±0.007^{b}	2.79±0.000^{a}	2.21±0.007^{c}
NDFn	7.07±0.007^{a}	8.14±0.007^{b}	8.14±0.007^{b}
ADFn	2.66±0.007^{b}	3.31±0.007^{a}	2.63±0.007^{c}
Ether extract	2.91±0.007^{a}	2.85±0.070^{ab}	2.74±0.007^{b}
Gross energy (mg/kg DM)	16.66±0.007^{c}	16.77±0.007^{b}	17.00±0.007^{a}
Starch	53.56±0.007^{b}	53.38±0.007^{c}	56.57±0.007^{a}

Values are presented as least squares means±SD. Values with different superscript within the same row are significantly different (p<0.05). NDFn: neutral detergent fibre corrected nitrogen, ADFn: acid detergent fibre corrected for nitrogen, SRed: Red Sorghum, SBrown: Brown Sorghum, SWhite: White Sorghum.

3.3 Mineral composition

The macro- and micro-mineral contents for the investigated sorghum varieties are shown in Table 3. The macro-mineral contents followed the sequence K > P > Mg > Na > Ca in the sorghum varieties. These results are consistent with data presented by Afify *et al*. (2012). The calcium content in the investigated sorghum varieties ranged from 4.74 to 7.25 mg/kg. The white sorghum (SWhite) variety had the highest *(p<0.05)* calcium content of 7.25 mg/kg; whereas the lowest *(p<0.05)* was found in the red sorghum, which was 4.74 mg/kg. Potassium was the highest mineral found across the sorghum varieties, with the highest value (4763.45 mg/kg) found in the brown sorghum (SBrown) variety. Thus, sorghum grain plays a role in supplementing the body with much-needed minerals, including potassium.

Phosphorus was the second abundant mineral in this

Table 3. Effect of sorghum colour on the mineral content of sorghum genotypes (mg/kg[1])

Macro-minerals					
	SRed	SBrown	SWhite	SEM	P value
Calcium	4.75[c]	5.55[b]	7.25[a]	0.05	0.0001
Magnesium	1445.86[b]	1423.54[c]	1479.82[a]	0.044	<0.0001
Potassium	4248.04[b]	4763.45[a]	3599.24[c]	0.045	<0.0001
Sodium	39.70[c]	47.72[b]	61.97[a]	0.005	<0.0001
Phosphorus	3486.85[a]	3486.85[a]	3219.54[b]	0.285	<0.0001
Micro-minerals					
	SRed	SBrown	SWhite	SEM	P value
Zinc	24.48[b]	27.64[a]	26.65[a]	0.005	<0.0001
Copper	4.99	4.99	4.99	0.007	0.8538
Manganese	13.05[b]	14.31[a]	13.25[b]	0.005	<0.0001
Iron	41.30[c]	46.46[a]	44.30[b]	0.005	<0.0001

Values with different superscript within the same row are significantly different (p<0.05). SRed: Red sorghum, SBrown: Brown sorghum, SWhite: White sorghum, SEM: Standard error of the mean.

investigation; the values ranged between 3219.54, 3486.85, and 3486.85 mg/kg for white, brown and red sorghum, respectively. These values are within the range of the results reported by Kasarda (2001). Calcium and phosphorus are considered very important minerals for strong bones and teeth (Yellen, 2002). The magnesium content varied from 1423.54 to 1479.82 mg/kg, with the white variety containing higher amounts (1479.82 mg/kg). Calcium was the least, with the content ranging between 4.75 and 7.25 mg/kg. There was a significant difference among the varieties (p<0.05). Sodium content varied at 39.70, 47.72 and 61.97 mg/kg, the highest was recorded in the SWhite variety. These values were higher than what was reported by Kasarda (2001). The copper content was equal for all the sorghum varieties (4.99 mg/kg), while the zinc values ranged from 24.48 to 27.64 mg/kg. The content of zinc in this study was higher than the reported values of 13.7 to 23.4 mg/kg (Rolfes *et al.*, 2009). The manganese and iron contents were 13.05, 13.25 and 14.31 mg/kg for the red, white and brown sorghum genotypes, and 41.30, 44.30 and 46.46 mg/kg for the red, white and brown sorghum genotypes, respectively. The values for the iron level were within the range reported by Rolfes *et al*. (2009) and Ng'uni *et al*. (2012). In addition, Mohammed *et al*. (2011) reported values of iron, zinc, and copper in sorghum flour as 2.24 mg/100 g, 0.75 mg/100 g and 0.61 mg/100 g, respectively. The values reported in their study were less than the values reported in this study. These differences in values could be attributed to the difference between the varieties of sorghum used.

The stacked bar chart of the sorghum varieties (Figure 1a) shows that the SBrown variety had the highest total macro-minerals, followed by the SRed variety. Calcium did not register in the graph while sodium had a trace representation, indicating their minute amounts in comparison to the other macro-minerals like potassium, magnesium and phosphorus. On the other hand, the micro-minerals content was in the order, Fe > Zn > Mn > Cu (Table 1) with SBrown variety still having the highest total micro-minerals but followed by the SWhite variety as revealed by the stacked bar chart (Figure 1b).

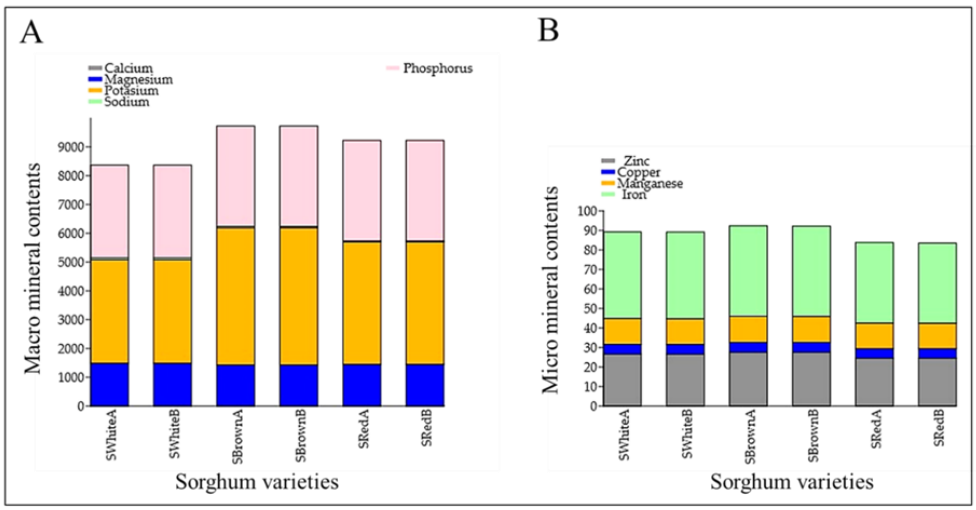

Figure 1. Stacked bar graph of macro and micro-mineral elements in sorghum varieties (mg kg[-1])

3.4 Pearson correlation between the mineral contents

The Pearson correlation (r) between the mineral contents is shown in Figure 2. There was a positive correlation between calcium, and the rest of the minerals, with the exception of potassium and phosphorus. There was a negative correlation between magnesium and most of the minerals. In addition, potassium had a negative correlation with magnesium and sodium but a positive correlation with phosphorus, zinc, manganese and iron. Sodium correlated positively with magnesium, zinc, manganese and iron and negatively with potassium and phosphorus. A strong negative correlation was also observed between phosphorus, magnesium and sodium, and a strong positive correlation with potassium (Figure 2). Potassium reserves its importance in that it is the major cation in intracellular fluid, which plays an important role in the regulation of acid-base balance, osmotic pressure and water balance (Pontieri *et al*., 2014). The micro-minerals, Zinc, manganese, and iron showed a positive correlation with calcium, potassium and sodium, but correlated negatively with magnesium and phosphorus). The various correlations explain the relationship of the minerals within the sorghum plant in terms of preferential cation exchange between sorghum root and the soil. Thus, preferred minerals impede the absorption of others giving rise to negative correlations. This is also applicable to competitive translocation from one part of the plant to another. However, minerals with similar cation exchange capacity (CEC) and rate of translocation show positive correlations.

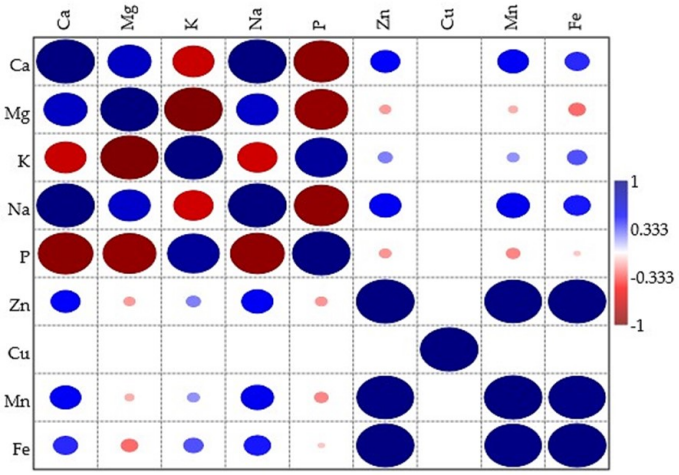

Figure 2. Pearson correlation plot for the mineral content in the sorghum varieties

The brown sorghum (SBrown) genotype appears to be a good candidate for future breeding because it contains higher levels of minerals in comparison to the other two genotypes. In addition, malnutrition related to the deficiency of micro-nutrients can be addressed by selecting grains that could correct deficiencies, particularly on the African continent. Sorghum is known to grow well in Africa, coupled with the fact that it contains valuable minerals as stated in this study, which could contribute to resolving the issues of malnutrition. Calcium content was seen to be low in the current study, as observed in some previous studies (Pontieri *et al*., 2014; Mabelebele *et al*., 2015; Stefoska-Needham *et al*., 2015), although contrasting a high value reported by Gerrano *et al*. (2016). Low calcium content has been associated with metabolic inhibitors and root cation exchange capacity (CEC) in which ions of magnesium, potassium and ammonium depress the uptake and distribution of calcium directly or indirectly (Wallace and Mueller, 1980; Yang and Jie, 2005). However, nitrate, being a complementary ion promotes the plant's calcium uptake. Therefore, a detailed understanding of calcium bioavailability in the sorghum cultivated soil in comparison with its root, stem and leaf concentrations is required to improve the grain calcium content through an appropriate technique such as biofortification. The large blue circles indicate a high and very high positive correlation, the large red circles indicate high and very high negative correlation, the medium blue and red circles indicate medium positive and negative correlation, respectively, and the small blue and red circles indicate small positive and negative correlation, respectively.

3.5 Amino acids

The profile of essential and non-essential amino acids in respect of the South African sorghum varieties is presented in Table 4. There was no variation ($P>0.05$) in tyrosine, methionine and isoleucine in the studied varieties. The values reported in this study were lower than the results obtained by Xiao *et al*. (2015), who recorded a higher histidine and threonine content in the red variety. In the present study, histidine was higher ($p<0.05$) in brown (0.37 g/100 g) sorghum than red (0.30 g/100 g) and white (0.24 g/100 g) sorghum. Histidine is regarded as one of the important amino acids and its deficiency has been associated with anaemia due to oxidative stress which plays a part in the aetiology of diseases (Kessler and Raja, 2019). The red sorghum exhibited higher lysine content than the brown and white types. These results differ from the results recorded by Makokha *et al*. (2002), which reported higher lysine content in fermented samples. There were variations in valine and leucine content between the three sorghum types. The red variety had a higher concentration of valine and leucine (0.71 and 1.95 g/100 g, respectively) than the brown (0.61 and 1.63 g/100 g) and white (0.52 and 1.42 g/100 g) types. Phenylalanine content was similar in red (0.89 g/100 g) and brown (0.87 g/100 g) sorghum compared to the white (0.74 g/100 g) variety. The recorded values were lower than the results obtained by Awadelkareem (2015), who evaluated two sorghum

varieties, and the results obtained by Okoh (1989), in malted samples. A study by Liu *et al*. (2013) showed that white sorghum grain had higher amino acid and starch digestibility than the red variety. Although previous studies are inconsistent regarding the correlation between the colour of sorghum and its nutritional value (Ebadi *et al*., 2019). Some consumers associate quality of sorghum or sorghum products with colour, texture and taste.

Table 4. Profile of essential and non-essential amino acids (g/100 g) of South African sorghum varieties

Variables	Sorghum variety		
	SRed	SBrown	SWhite
Essential amino acids			
Histidine	0.30±0.005^{b}	0.37±0.006^{a}	0.24±0.013^{c}
Threonine	0.84±0.031^{c}	1.51±0.122^{a}	1.21±0.058^{b}
Lysine	0.13±0.001^{a}	0.11±0.006^{b}	0.10±0.002^{b}
Tyrosine	0.47±0.044	0.53±0.036	0.44±0.000
Methionine	0.12±0.016	0.14±0.002	0.13±0.001
Valine	0.71±0.001^{a}	0.61±0.010^{b}	0.52±0.002^{c}
Isoleucine	0.68±0.117	0.59±0.018	0.54±0.041
Leucine	1.95±0.078^{a}	1.63±0.018^{b}	1.42±0.027^{c}
Phenylalanine	0.89±0.033^{a}	0.87±0.009^{a}	0.74±0.000^{b}
Non-essential amino acids			
Arginine	0.45±0.029	0.48±0.006	0.43±0.014
Serine	0.58±0.029^{a}	0.54±0.017^{ab}	0.48±0.018^{b}
Glycine	0.42±0.034	0.43±0.033	0.35±0.007
Aspartic	0.91±0.002^{a}	0.81±0.060^{a}	0.70±0.003^{b}
Glutamic	1.92±0.083^{a}	1.89±0.099^{a}	1.22±0.065^{b}
Alanine	1.15±0.032^{a}	0.96±0.010^{b}	0.83±0.003^{c}
Proline	0.94±0.001^{a}	0.84±0.013^{b}	0.74±0.018^{c}

Values are presented as least squares means±SD. Values with different superscript within the same row are significantly different (p<0.05). SRed: Red sorghum, SBrown: Brown sorghum, SWhite: White Sorghum.

Furthermore, findings regarding the non-essential amino acids in relation to the three South African sorghum varieties showed no variation (p>0.05) in arginine and glycine. Red (0.58 g/100 g) and brown (0.54 g/100 g) sorghum had a similar (p<0.05) serine content; the white type (0.48 g/100 g) exhibited a lower value. Also, red (0.91 and 0.81 g/100 g) and brown (1.92 and 1.89 g/100 g) sorghum exhibited higher (p<0.05) aspartic and glutamic values, respectively. Red sorghum had higher (p<0.05) alanine and proline (1.15 and 0.94 g/100 g) values than brown (0.96 and 0.84 g/100 g) and white (0.83 and 0.74 g/100 g) sorghum; white sorghum had lower alanine and proline values than the brown variety. These results were lower than those recorded by (Selle, 2011; Awadelkareem, 2015). The recorded variations could be associated with the presence of tannins since they have been reported to have a major anti-nutritive effect that can negatively influence the digestibility of amino acids (Brestenský *et al*., 2012). In addition, studied amino acids are very important components in human beings because improper intake can have detrimental effects (Miller, 2004).

3.6 Phenolic compounds

Sorghum varieties are known to contain an abundant and diverse range of phenolic compounds in comparison to other cereal crops, with the most dominant classes being simple phenolic acids, flavonoids and tannins (Rooney and Serna-Saldivar, 1991). The results of phenolic compounds detected in sorghum varieties, determined by means of the ultra-performance liquid chromatography-ultraviolet (UPLC-UV) method, are shown in Table 5. Structures of the compounds tentatively identified are given in Figure 3 while the representative chromatograms of the analysed sorghum genotypes are presented in Figure 4. Identification of the phenolic compounds suggests that the SRed variety contained slightly higher amounts of phenolic compounds than the brown and white varieties, as shown in Table 5 and Figure 5. A total of 18 compounds were detected, but only 16 of them were tentatively identified in the sorghum genotypes, six phenolic compounds were quantified. The phenolic compounds that were identified included phenolic acids and flavonoids. The amounts of

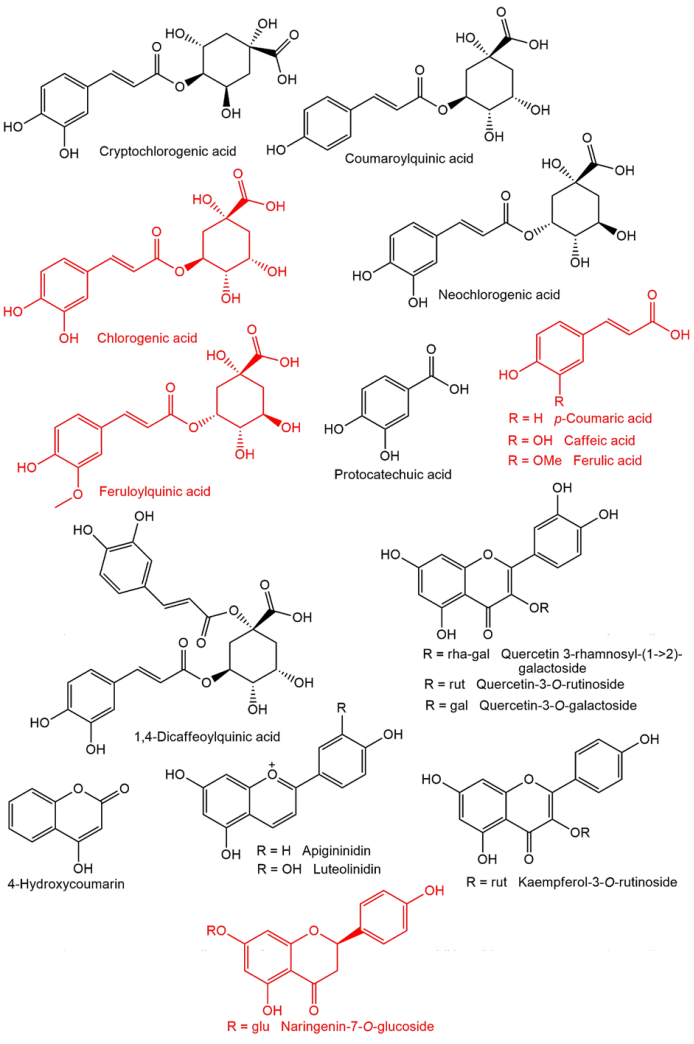

Figure 3. Structures of compounds identified in Sorghum genotypes. Quantified compounds are shown in red.

Table 5. Phenolic compounds identified in the extracts of sorghum genotypes using LC-MS methods

No	RT (min)	(M-H m/z)	Fragments	UV	Tentative identification
1	4.81	353.0872	353, 191, 179, 135	Nd	Cryptochlorogenic acid
2	6.04	337.0925	163, 119	Nd	Coumaroylquinic acid
3	6.98	353.0873	353, 191, 179, 135	Nd	Chlorogenic acid
4	7.96	153.019	153, 109	258,294	Protocatechuic acid
5	10.07	353.0884	353, 191, 179, 135	Nd	Neochlorogenic acid
6	12.64	367.1045	193	307	Feruloylquinic acid
7	12.99	179.0000	135,134	Nd	Caffeic acid
8	13.64	253.0713	161, 135, 133	Nd	Hydroxycoumarin
9	14.79	609.1461	609, 300, 271, 255	254,350	Quercetin-3-*O*-rhamnosyl () galactoside
10	15.26	609.1445	609, 300, 271, 255	Nd	Quercetin-3-*O*-rutinoside
11	16.22	463.0872	463, 300, 271, 255, 243	254,351	Quercetin-3-*O*-galactoside
12	16.87	463.0872	270, 254 211, 181	254,351	Luteolinidin
14	17.30	593.1505	593, 284, 255, 227	265,346	Kaempferol-3-*O*-rutinoside
13	17.24	433.1128	271, 151	281	Naringenin-7-*O*-glucoside
15	18.39	447.0918	118, 181, 211, 254	346,265	Apigininidin
16	19.17	515.1192	515, 353, 335, 255, 191, 173, 179, 135	Nd	1,4-Dicaffeoylquinic acid
17	19.17	515.1194	515, 375, 353, 191, 179, 135 (30)	Nd	Unknown
18	21.72	515.1183	515, 375, 353, 191, 179, 173, 135	Nd	Unknown

Nd: Not detected

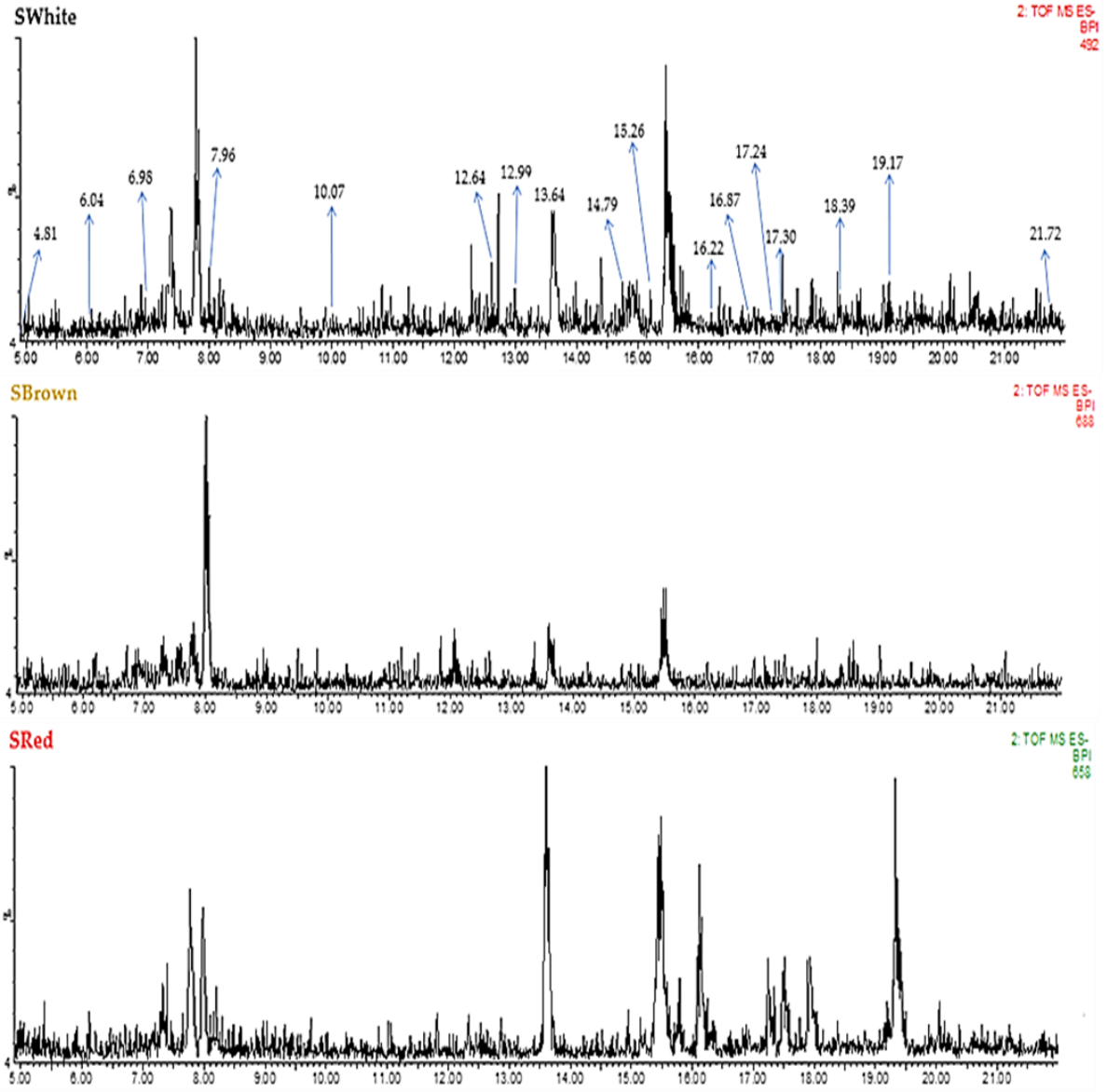

Figure 4. Chromatograms of the sorghum varieties

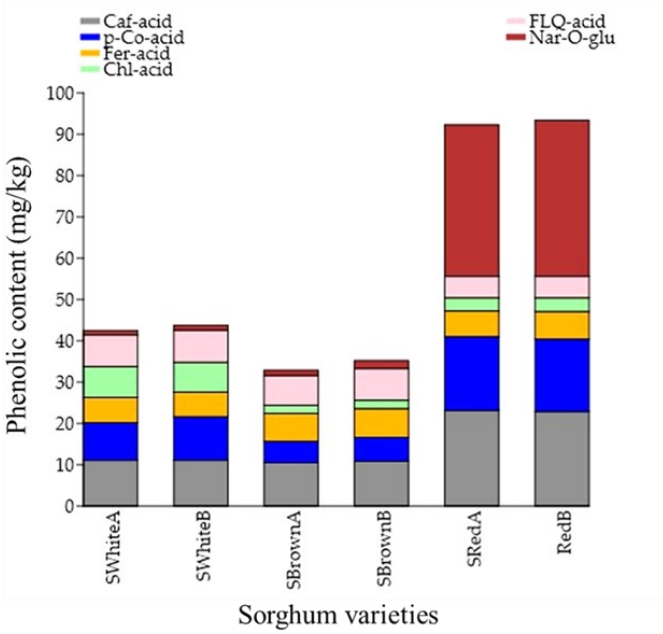

Figure 5. Stacked bar graph of phenolic compounds in sorghum varieties (mg/kg). Caf-acid: caffeic acid, p-Co-acid: p-coumaric acid, Fer-acid: ferulic acid, Chl-acid: chlorogenic acid, FLQ-acid: feruloylquinic acid, Nar-O-glu: naringenin-7-O-glucoside.

quantified phenolic compounds varied with the genotypes of the sorghum. The SRed variety had the biggest share of the compounds, followed by the SWhite variety, as shown in Figure 5 and the SBrown variety had the least quantity. These results agree with those of Dicko *et al*. (2006), who found that sorghum grains with pigmented testa and red plants had a higher content and diverse phenolic compounds. Furthermore, Lee *et al*. (2010) indicated that phenolic compounds in soybeans varied according to seed colour. Kang *et al*. (2016) found that the brown sorghum grain contained higher amounts and a greater variety of phenolic compounds when compared with the red and white types. Dykes and Rooney (2006) drew attention to the fact that the phenolic compound types and levels were related to the pericarp colour and the pigmented testa. These outcomes suggest that the diversity and occurrence of phenolic compounds are influenced by the colour of the crop.

The representative chromatograms of the sorghum genotypes in Figure 4 show an almost identical pattern of peaks, perhaps indicating that there was not a big difference among the genotypes in terms of the phenolic compounds. Compound 1 was identified as cryptochlorogenic acid based on the precursor ion $[M-H]^-$ at m/z 353.0872 with product ions at m/z 353, 191, 179, 135. Whereas compound 2 had a precursor ion $[M-H]^-$ at m/z 337.0925 with product ions at m/z 163, 119 was tentatively identified as coumaroylquinic acid and was present in red sorghum, brown sorghum and white sorghum. In addition, diverse phenolic compounds were tentatively identified, revealing the abundance of these compounds in some of the sorghum varieties grown under South African conditions. The phenolic compounds such as apigeninidins and luteolinidins, found in this study, are considered unique to sorghum (Awika *et al*., 2004). These compounds are used as natural food colourants as reported by Noori *et al*. (2004). Feruloylquinic acid (compound 6 with $[M-H]^-$ at m/z 367.1045) and caffeic acid (compound 7 with $[M-H]^-$ at m/z 415.1243) yielding product ions at m/z 193 and 179, respectively, were both identified and found to be present in all the sorghum varieties. A few studies reported that ferulic acid was the amplest phenolic compound in sorghum (Hahn *et al*., 1983). Chandrasekara and Shahidi (2011) reported that ferulic acid and *p*-coumaric acid were the most dominant in maize grains. However, in this study, caffeic acid was the most abundant. It was also noted that most of the quantified phenolic compounds were phenolic acids (Table 5).

Compound 8 was identified as hydroxycoumarin based on precursor ion $[M-H]^-$ at m/z 253.0713 with product ions at m/z 161, 135, 133. Feruloylquinic acid and hydroxycoumarin derivative, coumaroyl quinic acid, ferulic and *p*-coumaric acids were also identified. Several compounds identified in this analysis were reported to have health benefits for both humans and livestock. The sorghum grain cultivated in South Africa has shown the possession of health-beneficial bioactive phenolic compounds known to have the ability to reduce the risk of infection with many chronic diseases. The study by Khan *et al.* (2015), showed that pasta containing red whole grain sorghum has resulted in a significant improvement of antioxidant status by increasing plasma polyphenols, antioxidant capacity, and superoxide dismutase activity.

The *p*-coumaric acid, which is an isomer of coumaric acid, is believed to have the ability to eliminate reactive oxygen species in the human lung (Salinas-Moreno *et al*., 2017). Furthermore, Mohammed *et al*. (2011) reported the synergistic effect of the caffeic acid or *p*-coumaric acid mixture, which suggests their chemopreventive activity in chronic diseases and cancers. Bouzaiene *et al*. (2015) reported that caffeic and *p*-coumaric acids were the two most common hydroxycinnamic acid derivatives in grains. Previous studies confirmed the importance of caffeic acid and its analogues as anti-inflammatory, antibacterial, antiviral and antitumor (Van Hung, 2016; Shahidi and Yeo, 2018). Furthermore, hydroxycinamic acids were acknowledged by Bouzaiene *et al*. (2015) as constituting about 60% of the phenolics in sorghum. The sorghum varieties investigated in the current study, have shown the presence of caffeic and *p*-coumaric acids. In addition,

chlorogenic acid was reported in the current investigation. This esterification product of caffeic and quinic acids is also considered an important natural inhibiter of protein tyrosine phosphatase 1B, which could be a therapy for diabetes, obesity and cancer (Gomes *et al*., 2003). These findings are therefore indicative of the nutraceutical significance of Sorghum varieties accessed in this study.

Furthermore, hydroxycoumarin derivative has the retention time of 13.64 (as shown in Table 5), which corresponds with high peaks in the chromatograms shown in Figure 4. The benzoic acid in sorghum always registered a noticeable presence; however, in this study, no benzoic acid was detected in any of the sorghum genotypes. This difference could be attributed to genotypes, growth or environmental conditions. It could also be due to the complexity of the bounded sites of these acids, as mentioned by Zhang *et al*. (2010). The last two compounds detected (RT; 19.17 and 21.72, respectively) were assigned unknown. However, the similarity of their parent ion mass (515.1194 and 515.1183) with that of 1, 4-dicaffeoylquinic acid (515.1192) suggests they are probably isomers. This is further justified by their common diagnostic fragments. According to Clifford *et al.* (2005), compounds 17 and 18 may be tentatively assigned 3, 5-dicaffeoylquinic acid and 4,5-dicaffeoylquinic acid, respectively. This study further confirms the earlier report that LC-MS can conveniently differentiate derivatives and isomers of chlorogenic acid (Clifford *et al*., 2005).

The structural relationship among the identified phenolic compounds is shown in Figure 3. The compounds can be grouped into phenolic acid derivatives and flavonoids. The phenolic acid derivatives are all based on hydroxycinnamic acid except for protocatechuic acid (a dihydroxybenzoic acid). Although phenolic acids may occur in free or conjugated forms, the majority of those found in grains are either esterified or etherified with polysaccharides in the cell wall (Călinoiu and Vodnar, 2018). This provides a reason for the esters accounting for six out of nine whose structures are based on hydroxycinnamic acid, as reported in this study. Eight flavonoids were identified, consisting of four glycosylated flavonols, a flavanone glycoside, two 3 -deoxyanthocyanidins and a coumarin. Sugar moieties are known to be a key determinant in the absorption of dietary flavonoids in man (Hollman *et al*., 1999). Thus, the dominance of flavonoid glycosides over aglycones in this study further provides credence to the claim of sorghum's nutraceutical potential. Flavonol glycosides contribute to pollen's yellow colour but deeper colours are associated with anthocyanins (Křen, 2008). Sorghum is considered a good source for 3-deoxyanthocyanidins, which could be used as commercial natural colourants for foods (Xiong *et al*., 2019). Furthermore, apiginidin is reported to have diverse pharmacological activities and has demonstrated antioxidant and anticarcinogenic properties (Fratianni *et al*., 2007). The presence of these important phenolic compounds in the investigated sorghum varieties, further advocate for their candidacy as grain for food, feed and health. The extended conjugated systems of most flavonoids' architecture make the molecules absorb light in the visible region of the electromagnetic spectrum and thus reflect the colour that is observed. This phenomenon is further enhanced by "sandwich stacking" effect imposed by glycosyl moieties attached to the flavonoid skeleton, resulting in colour deepening and stabilization. This may be one of the factors responsible for the observation of SRed having a far higher amount of flavonoid glycoside (Table 6).

In addition, few of the phenolic compounds were quantified (as shown in Table 3). The caffeic acids were 10.5, 11.1, and 23.2 mg/kg. The highest amount was recorded in the SRed type. These quantities were found to be within the range of 3.49±0.13 to 8.17±0.20 mg/100g, as reported by the United Nations Food and Agriculture Organization (FAO), and 1.14 to 3.81 mg/100 g, as reported by Dykes *et al*. (2009) in decorticated brown sorghum. Caffeic acid is characterised by anti-carcinogenic action which is mainly associated with its antioxidant property (Magnani *et al*., 2014). In addition, p-coumaric acid was recorded at 5.2, 9.1 and 17.8 mg/kg for SBrown, SWhite, and SRed varieties respectively. However, the quantities of ferulic acid of 6.1, 6.7 and 6.2 mg/kg were almost similar across the three sorghum varieties. Chlorogenic

Table 6. Quantified individual phenolic compounds in sorghum varieties (mg/kg)

Samples	SWhite	SBrown	SRed	SEM	Probability
Caffeic acid	11.1^{b}	10.5^{c}	23.2^{a}	0.145	0.0010
p-coumaric acid	9.1^{b}	5.2^{c}	17.8^{a}	0.419	0.0006
Ferulic acid	6.1	6.7	6.2	0.166	0.0967
Chlorogenic acid	7.5^{a}	2.0^{c}	3.2^{b}	0.095	0.0010
Feruloylquinic acid	7.6^{a}	7.2^{b}	5.2^{c}	0.138	0.0019
Naringenin-7-*O*-glucoside	1.1^{c}	1.3^{b}	36.7^{a}	0.373	0.0010

Values with different superscript within the same row are significantly different (p<0.05). SRed: Red sorghum, SBrown: Brown sorghum, SWhite: white sorghum, SEM: Standard error of the mean

acid registered the lowest quantity in the SBrown variety (2.0 mg/kg), followed by the SRed variety (3.2 mg/kg), while the highest quantity was registered in the SWhite variety (7.5 mg/kg), as shown in Table 3 and Figure 5. Feruloylquinic acid was 5.2, 7.2 and 7.6 mg/kg for the SRed, SBrown, and SWhite varieties, respectively. The quantity of naringenin-7-*O*-glucoside was 1.1, 1.3 and 36.7 mg/kg for SWhite, SBrown, and SRed respectively. The highest amount was recorded in the SRed genotype. There were significant differences ($p<0.05$) among all the phenolic acids for the sorghum genotypes; the only exception was the ferulic acid. The quantities of caffeic and ferulic acids reported in this study were lower than in the reports of Zhang *et al*. (2010). The difference could be attributed to genotypes or environmental factors. In their study, Wu *et al*. (2017) reported the influence of variety on the phytochemical content of rice.

3.7 Principal component analysis

The Principal Component Analysis (PCA) method was utilized to group the sorghum varieties into components that accounted for two significant principal components which had eigenvalues of more than 1. They cumulatively added to 99.9998% (Table 7). According to Shao and Bao (2015) and Zhou *et al*. (2020), eigenvalues are considered significant if they are more than 1 and component loadings are meaningful if they are more than±0.30. This study, therefore, considered the first two components (PC1 and PC2). The importance of the PCA technique is to emphasize differences among the varieties; it is considered valuable in finding traits that contribute the most to the total amount of variation (Chatfield and Collin, 1980). The first principal component (PC1), which on its own explained 98.042% of the variation, had an eigenvalue of 2.32444 (Table 4). The total variability among the sorghum genotypes was mainly due to variations in caffeic acid, *p*-coumaric acid and naringenin-7-*O*-glucoside (Table 7 and Figure 7).

Table 7. Principal component analysis of the phenolic compounds in sorghum varieties, showing their percentage contribution to the total variations

	PC1	PC2
Caffeic acid	0.30698	0.02540
P-coumaric acid	0.26186	0.51964
Ferulic acid	0.00373	-0.13885
Chlorogenic acid	-0.03493	0.83329
Feruloylquinic acid	-0.06416	0.01666
Naringenin-7-*O*-glucoside	0.91205	-0.12410
Eigenvalue	2.32444	1.01123
% Variance	98.0420	1.95780
Cumulative %	98.0420	99.9998

Figure 6 displays a loading of *p*-coumaric acid, chlorogenic acid, caffeic acid, and naringenin-7-*O*-glucoside in the same area on the right side of the score plot, where the SRed genotype was plotted, suggesting a possible link between these phenolic compounds and confirming that the SRed variety indeed contained more phenolic compounds, as shown in Figure 5. The high component loadings for PC1 were contributed by the SRed variety. Similarly, feruloylquinic acid and ferulic acid were grouped on the left side of the plot. Ofosu *et al*. (2020) revealed that individual polyphenols varied among the sorghum genotypes.

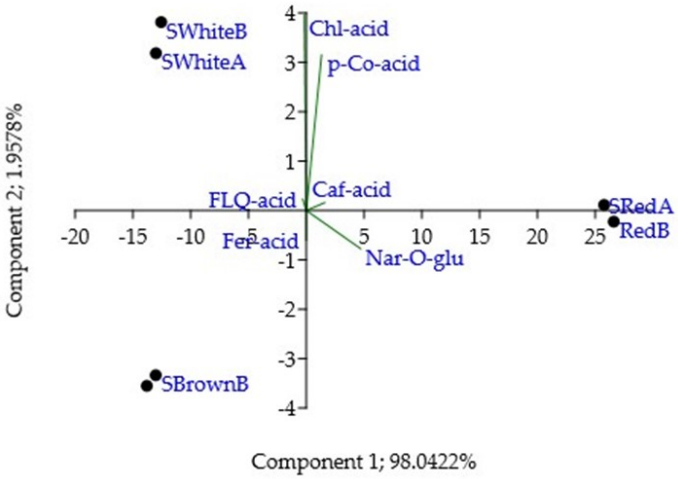

Figure 6. PCA scatter plot of the phenolic compounds in sorghum. Caf-acid: caffeic acid, p-co-acid: p-coumaric acid, Fer-acid: ferulic acid, Chl-acid: chlorogenic acid, FLQ-acid: feruloylquinic acid, NO-gluco: naringenin-7-O-glucoside.

The second principal component (PC2) accounted for 1.9578% of the total variation, with an eigenvalue of 1.01123 (Table 7). The variation was predominantly a function of *p*-coumaric acid and chlorogenic acid (Table 7). The sign of the loading is an indication of the direction of the relationship between the components and the variables, as stated by Chatfield and Collin (1980).

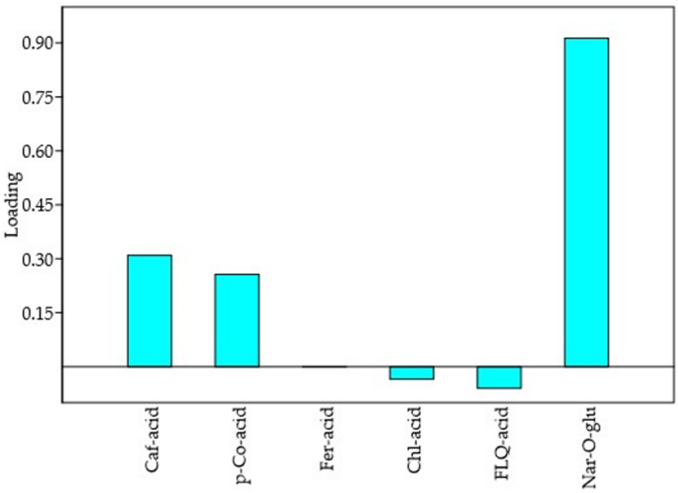

Figure 7. Loadings plot of the phenolic compounds and their percentage contribution to the total variations in sorghum genotypes. Caf-acid: caffeic acid, p-co-acid: *p*-coumaric acid, Fer-acid: ferulic acid, Chl-acid: chlorogenic acid, FLQ-acid: feruloylquinic acid, NO-gluco: naringenin-7-*O*-glucoside.

Ferulic acid was shown to have no contribution to the variation among the sorghum varieties (Figure 7).

4. Conclusion

The varieties of Sorghum grain grown in South Africa have been demonstrated through this study to encompass a substantial amount of nutritional elements, amino acids, minerals and possess nutraceutical potentials as demonstrated by the content of valuable phenolic compounds. These characteristics qualify the sorghum varieties to be used as alternative grains for nutrition, as well as health benefiting grains for humans and livestock. The varieties studied can therefore be used to build resilience in the South African food system. It can therefore be suggested that the studied sorghum varieties deserve attention in terms of future research and inclusion in the consumer market using different processing and packaging. It can be processed into commercially available products such as bread, cereal, cereals and livestock feed.

This study has contributed to the available knowledge on the phenolic compounds of some sorghum varieties grown under the climatic conditions of South Africa. Conclusion drawn in this study contributes to attracting the South African consumers to the importance of South African sorghum varieties as alternative grains in human diets and livestock feed.

Conflict of interest

The authors declare no conflict of interest.

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