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Dry heat treatments of sorghum grains: influence on the flour storage stability and porridge sensory characteristics

by

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DECLARATION

I, Olalekan Jimi Adebowale declare that the thesis, which I hereby submit for the PhD in Food Science at the University of Pretoria, is my own work and has not previously been submitted by me for a degree at this or any other tertiary institution.

Olalekan Jimi Adebowale

October 2020

DEDICATION

This thesis is dedicated to the Glory of Allah (S.W.T.) for His grace, mercy and favour.

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ABSTRACT

Dry heat treatment of sorghum grains: influence on flour storage stability and porridge sensory characteristics

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Olalekan Jimi Adebowale

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Degree:	PhD (Food Science)

Sorghum, a climate-smart crop, is an important cereal food crop in Africa with a vital role in nutrition and food security. However, utilization of its flour is limited by its susceptibility to deterioration by lipid hydrolysis and oxidation during flour storage. These chemical changes are associated with the development of rancid off-flavours. Application of dry heat treatments of the grain could be a practical approach to stabilize the flours. This study evaluated the influence of dry heat treatments (microwaving and roasting) of sorghum kernels on the storage stability of the flour as evaluated based on the sensory characteristics of porridge prepared from the flour.

Firstly, the effects of microwaving (36 kJ/100 g-90 kJ/100 g) and roasting (150 ºC, 10 min-25 min) non-tannin and tannin sorghum grains on the physicochemical and functional properties of their flours (wholegrain and decorticated) were investigated. The results showed decreases in moisture content, lightness, fat acidity and pasting viscosity of the flour due to treatments at the extreme levels. With decortication, flour fat acidity was reduced further. The total phenolic content (TPC) and antioxidant activity (AOA) of flours decreased with increasing microwave energy inputs. Whereas the phenolic content of grain flours decreased significantly ($p < 0.05$) due to roasting of the kernels, the AOA increased.

Secondly, flours of non-tannin sorghum after heat treatments (microwaving with 30 kJ/100 g and 90 kJ/100 g inputs, roasting at 150 ºC, 10 min and 25 min) were tested under accelerated storage conditions (50 ºC with UV light-16 W/cm^2) for 6 weeks. The effects of heat treatments of sorghum grains on rancid-indicating parameters (fat acidity and anisidine value) of the stored flour and the texture, colour and descriptive sensory characteristics of porridge prepared from flour were investigated. Both microwaving and roasting resulted in a substantial reduction in the flour fat acidity and anisidine value throughout storage; the higher levels of both heating types being more effective. Microwaving of sorghum kernels made the porridges slightly more darker brown, with more specks, less cooked maize porridge but more intense sorghum aroma. With flour storage, porridge of control was characterized with more intense oily, fermented, rancid and painty aromas than those of the microwave-treated samples. Fat acidity of flour samples decreased due to heat treatments from 50.1 to 21.1 mgKOH/100 g at baseline (week 0). Sensory indications of porridge rancidity were identified less intensely and much later during flour storage for heat-treated samples.

With roasting, flour fat acidity of roasted kernels for shorter (10 min = 48.9 mgKOH/100 g) and longer (25 min = 34.4 mgKOH/100 g) duration was substantially lower than those unroasted (50.1mg KOH/100 g). The lower fat acidity indicates greater stabilization of the flour against lipolysis and oxidative rancidity. With flour storage, porridges from unroasted non-tannin wholegrain flours had dominant painty, oily, rancid and fermented aromas while those prepared from decorticated flours displayed rancid and fermented aromas, brown colour, visible specks and residual aftertaste. Roasting sorghum kernels for 25 min and decorticating was most effective at reducing fat acidity (lipolysis) from 50.1 to 3.3mgKOH/100 g and *p*AV (oxidation) from 80.2 to 38.2 units. The treatment therefore has potential to improve the flour stability but had an impact on sensory quality of products made from the flour. The treatments partially inactivated the flour lipases and consequently retarded free fatty acid oxidation. The treatments had no substantial adverse effects on other flour and porridge attributes. Microwave pretreatment of sorghum grain slows the development of rancidity and improves flour shelf stability, more so at 90 kJ/100 g than 36 kJ/100 g. Microwave treatment of sorghum could be recommended over roasting and thus be an effective technology to stabilize sorghum flour and thereby enhance its food product quality. Also, roasting operation showed to be rather promising.

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LIST OF ABBREVIATIONS

µmol	Micromoles
AACC	American Association of Cereal Chemists
ABTS	[(2, 2-azinobis (3-ethlybenzothiazoline-6-sulfonic acid)]
AOA	Antioxidant activity
AOAC	Association of Analytical Chemists’
BI*	Browning index
*C**	Chroma
CE	Catechin equivalent
db	Dry basis
DPPH	2,2′-diphenylpicryl hydrazyl free radical
FA	Fat acidity
FAO	Food and Agriculture Organisation
FFA	Free fatty acids
FV	Final viscosity
GAE	Gallic acid equivalent
GC	Gas chromatography
GC-MS	Gas chromatography mass spectroscopy
H	Microwave heat treatment at 90 kJ/100 g
H^o	Hue angle/value
HCl	Hydrochloric acid
ISO	International standards organization
kJ	kilojoules
KOH	Potassium hydroxide
kW	Kilowatt
L	Microwave heat treatment at 36 kJ/100 g
LC/MS	Liquid chromatography-Mass spectroscopy
LSD	Least significant difference
MASLT	Multivariate shelf-life test
mc	Moisture content
MHz	Megahertz

min	Minutes
mPa.s	Millipascal second
MS	Mass spectrometry
ºC	Degree Celsius
ORAC	Oxygen Radical Absorbance Capacity
*p*AV	para-anisidine value
PCA	Principal component analysis
PV	Peak viscosity
r	Pearson’s correlation
RH	Relative humidity
rpm	Revolution per minute
s	Seconds
SD	Standard deviation
SPME-GC-MS	Solid phase microextraction gas chromatography mass spectroscopy
TEAC	Trolox equivalent antioxidant capacity
TBARS	Thiobarbituric acid reactive species
TE	Trolox equivalent
TPC	Total phenolic content
U	Untreated samples
UV	Ultraviolet
v/v	Volume/volume
W	Watt
WAI	Water absorption index
WGF	wholegrain sorghum flour
WGK	Wholegrain sorghum kernels
WSI	Water solubility index

1.0 INTRODUCTION

Sorghum (*Sorghum bicolor* (L.) Moench) is the fifth most important cereal grain in the world, next to wheat, rice, maize and barley with world production estimated to be above 60 million tons in 2015 (FAOSTAT, 2017). An estimated 90 % of the world's sorghum production area lies in the developing countries, majorly in Africa and Asia. Sorghum is a staple food grain for about 500 million people in over 30 countries within the semi-arid areas of Africa and Asia (ICRISAT, 2018). With renewed interest in dietary modification, healthy and gluten-free food components, attention on sorghum for human nutrition purposes has increased (Awika, 2017). Grain sorghum is processed as flour, whole or decorticated, into products such as fermented bread (dosa), unfermented pancakes (chapati/roti), thin (ambali) or stiff (mudde or tuwo) porridge, various types of bread, cakes and cookies (Meera, Bhashyam, & Ali., 2011; Marston, Khouryieh, & Aramouni, 2016).

Like other cereal grains, sorghum grains can be stored for long periods without undergoing any noticeable changes in physical quality, provided the kernels remain whole (Meera et al., 2011). However, wholegrain sorghum flour is susceptible to lipid deterioration by lipolysis and lipid oxidation, limiting the shelf-life of the flour (Meera et al., 2011). Lipolysis involves the release of free fatty acids from triglycerides by the action of lipase enzymes (Meera et al., 2011). Lipid oxidation involves the reaction of the unsaturated fatty acids with molecular oxygen, resulting in the generation of volatile carbonyl compounds (Doblado-Maldonado et al., 2012). The effect is manifested as unpleasant off-flavour in flour, which adversely affects physicochemical properties and the sensory quality of products made from the flour (Zhang & Hamaker, 2005). Therefore, lipid deterioration in sorghum flour is a problem and has been of serious concern to the stakeholders in the value chain (Viscidi, Dougherty, Briggs, & Camire, 2004). The impact of the chemical changes could incur an economic loss for farmers and processors due the rancid nature of flour leading to low patronage or product rejection from consumers. Hence, it becomes essential to slow the activity of the lipase enzymes before milling sorghum grains to flour.

More recently, microwave heating or roasting treatments of cereal grains were demonstrated as potential strategies to suppress lipid oxidation and stabilize the flours (Ranganathan, Nunjundiah, & Bhattacharya, 2013; Qu, Wang, Liu, & Wang, 2017). Microwave heat treatment of cereal grains has been promoted as a 'green' technology for flour stabilization and food processing in industries (Qu et al., 2017). Besides the treatment does not leave any potential toxic residue on grains or products and it is also considered as an environmentally friendly process (Gautam, Islam, Sadistap, & Sarma, 2018). Unlike conventional heating methods, microwaves permit the transfer of electromagnetic energy throughout the volume of the food (material) resulting in instantaneous heating within a short duration (Qu et al., 2017). However, dry heat treatments of cereal grains may lead to changes or modification in the composition of some food constituents. For instance, starch granules are modified, proteins are denatured (Gómez & Martínez, 2016). A recent study has shown that microwave roasting of whole sorghum changed the colour of sorghum flours from light brown to dark brown, reduced flour peak, paste and breakdown viscosities, and improved the phenolic content and antioxidant properties (Sharanagat et al., 2019). Also, flour pasting characteristics, water absorption and solubility indexes were affected due to the impact of heat treatments on cereal kernels. (Ranganathan et al., 2013; Qu et al., 2017).

Keying, Changzhong, and Zaigu. (2009) reported that microwaving oat kernel inactivated lipase enzymes thereby improving the storage stability of the resulting flour. Qu et al. (2017) studied the effects of microwaving wheat kernels on the accelerated storage of the flours and found that microwave heating caused a significant decrease in the activity of lipase enzymes. The effects of using microwave heating or hot-air roasting treatments of sorghum kernels on whole or decorticated flour storage stability and sensory quality of resultant porridges have not been investigated. Microwave and/or roasting treatments of whole sorghum grains could potentially be used to control rancidity of whole grain sorghum flour, by inhibiting lipase and lipoxygenase activities, thereby slowing down the early steps of lipid breakdown. To further improve flour stability after treatments, whole sorghum grains could be decorticated to have a refined flour with less germ content. The extent of decortication was directly correlated with a reduction in fat content (Kebakile, Rooney, & Taylor, 2007).

However, there are insufficient studies in literature on the effects of dry heat treatments of sorghum grain using microwave heating and hot-air roasting to stabilize flour during storage. This study investigated dry heat treatments by microwaving and roasting wholegrain sorghum kernels as processing technologies for stabilization of sorghum flour, to improve flour storage stability and its products’ sensory attributes. The sorghum flour was subjected to an accelerated shelf-life test at elevated temperature and evaluated for indicators of lipolytic and oxidative rancidity during storage. Porridges prepared from the flours were used as a simple food vehicle for testing if the flour had been stabilized.

2.0 LITERATURE REVIEW

In this review, the structure and composition of whole grain sorghum kernels are covered. The storage stability of cereal flours and the mechanisms of lipid deterioration as it affects wholegrain and refined flours are reviewed. Potential strategies for stabilization of cereal grain flours using various treatment methods notably by the application of dry heat treatments including microwaving and roasting processes are reviewed in this chapter.

2.1 The value of sorghum as a human food

Sorghum **(***Sorghum bicolor (*L.) Moench) is the seed of a grass species, a monocotyledonous plant belonging to the family *Poaceae* (Stefoska-Needham, Beck, Johnson, & Tapsell, 2015). With an estimated world production of about 60 million tons per year, sorghum was ranked the fifth most important cereal crop in terms of production in 2015 (FAOSTAT, 2017). Major producers of sorghum include the United States (16 % of total world production), Mexico (12.2 %), Nigeria (9.8 %), Sudan (9.1 %), and India (7.8 %) in 2016 (FAOSTAT, 2017). Sorghum can thrive under harsher environmental conditions than other common cereals (Stefoska-Needham et al., 2015). This is because sorghum and some other cereals such as maize and millet are self-pollinating C_4 photosynthetic plants (Cruickshank, 2016). A C_4 photosynthetic plant has better adaptive features than the C_3 cereal plants (like rice and wheat) in dry situations with high intensity of light and extreme temperature (Wrigley, 2016).

As an important cereal that is grown globally, rich in nutrients and bioactive components, sorghum is still considered as a low value food for humans and mostly used as feed for animals (Stefoska-Needham et al., 2015). Hadbaoui, Djeridane, Yousfi, Saidi and Nadjemi (2010) was of the opinion that the notion that the utilization of sorghum is confined to regions where the populace earns a low income is misleading. They argued that sorghum production in the US and some other parts is mainly for animal feed and not human consumption. Sorghum however remains a staple food crop for about 500 million people in over 30 countries within the semi-arid areas of Africa and Asia (ICRISAT, 2018). Several food uses of sorghum have been established traditionally and/or commercialized (Aboubacar & Hamaker, 2000; Taylor, Belton, Beta, & Duodu, 2014; Rao, Kulkarni, & Kavitha, 2016), including porridges (Aboubacar, Kirleis, & Oumarou, 1999), couscous (Aboubacar & Hamaker, 2000), *injera* (a fermented, traditional flatbread in Ethiopia) (Yetneberk, de Kock, Rooney, & Taylor, 2004), beverages (fermented and non-fermented), cakes, cookies and biscuits (Rao et al., 2016), and *roti* (flatbreads in India). Many food products are developed from sorghum with success. Also, the recent surge of interest in dietary shifts, probably due to health-related issues and the attraction of alternative food ingredient sourcing, has resulted in the use of sorghum in many modern food products (Awika, 2017).

The presence of specific bioactive compounds in sorghum, which may be lacking in some other cereals, confers another advantage to the crop. Wholegrain sorghum products are a source of bioactive compounds with promising potential to reduce the risk of diet-related diseases like obesity and diabetes (de Morais Cardoso, Pinheiro, Martino, & Pinheiro-Sant'Ana, 2017). Prominently among the beneficial bioactive compounds in sorghum are the polyphenols (especially flavonoids) and bioactive lipids (such as policosanols and phytosterols) (Girard & Awika, 2018). Trends have shown a renewed consumer interest in alternative 'ancient grains' including sorghum to substitute well-known food materials e.g. wheat and maize flour in food products (Taylor, 2016). Sorghum endosperm has also been demonstrated to display a slower starch digestible profile compared to other cereal grains, a property that can be related to glycemic index in humans.

2.1.1 Structure and composition of sorghum kernels

2.1.1.1 Characteristics of sorghum kernels

The sorghum kernel is a naked caryopsis. An average kernel has a weight of 20-30 mg (Awika, 2017), and a volumetric weight of 708 to 760 kg/m^3 and grain density from 1.26 to 1.38 g/cm^3 (Waniska, Rooney & McDonough, 2016) were reported for sorghum. A sorghum kernel consists of three distinct anatomical parts (Fig 2.1), being the pericarp (bran/outer layer), the endosperm (storage tissue) and the germ (embryo) (Chhikara, Abdulahi, Munezero, Kaur, Singh, & Panghal, 2018). These parts are protected by an inedible husk that protects the kernel from sunlight, pests, water and disease (Cruickshank, 2016). The bran is described as the multilayered outer skin of the kernel containing antioxidants, the B-vitamins and fibre.

2.1.1.2 Pericarp

The sorghum pericarp is rich in insoluble dietary fibre in the range of 4.3 % to 8.7 % (Wanniska & Rooney, 2000). The pericarp is sectionalized into three tissues, consisting of epicarp, mesocarp and endocarp (Taylor & Anyango, 2010). The epicarp is guided by a thin waxy layer and contains pigments which contribute to the colour of the grain. Hwang, Cuppett, Weller & Hanna (2002) described the surface of the pericarp as waxy containing nearly 46% fatty aldehydes, 7.5% fatty acids, 41 % fatty alcohols, 0.7 % hydrocarbons, 1.4 % wax and sterols esters, and 1 % triglycerides. The presence of some bioactive lipids, especially policosanols and phytosterols, as components of the waxes on the surface of the grain pericarp have also been reported (Girard & Awika, 2017).

A sub-coat (testa) existing between the pericarp and endosperm was reported to be present in some sorghum types. The testa layer is immediately beneath the endocarp, in which sorghums with pigmented testa contains condensed tannins (Taylor & Duodu, 2010). Recently researchers have demonstrated the potential of sorghum tannins as excellent antioxidants with proven health benefits (Girard & Awika, 2018). Sorghum tannins with effects on energy balance, glycemic control, lipids and cell-mediated immune responses have been reviewed extensively. For example, Stefoska-Needham et al. (2015) reviewed extensively on sorghum tannins and their impact on energy and glycemic control. These authors reported that regular consumption of wholegrain cereal-based foods could reduce the risk of heart disease and diabetes by up to 30 %, improve blood glucose regulation, control body weight and minimize the risk of certain types of cancer. Previously, other researchers have revealed the potential role of sorghum in human health and disease prevention (Taylor & Emmambux, 2010). If all these benefits ascribed to sorghum tannins is genuine and effective, there may be a role for sorghum grain-based diets to assist in the prevention of diseases such as diabetes, obesity and heart-related diseases (Stefoska-Needham et al., 2015). Awika & Rooney (2004) highlighted the presumed classification of tannin-sorghums into three types, designated as types I, II and III. These classifications are based on the medium of extraction of tannins using 1% acidified methanol and methanol alone and in-combination. Type III sorghums contain the highest amount of tannins compared to types I and II. The tannin contents reported for some sorghum cultivars were in the range of 2.3 to 67.2 catechin equivalents (CE) per 100 g and their antioxidant capacity ranged from 81.33 to 1122.54 μmol Trolox equivalents (TE) per gram bran (Kaufman et al., 2013).

2.1.1.3 Endosperm

The endosperm occupies the largest area consisting 82 % to 87 % of the kernel (Waniska et al., 2016) of which starch (81-82%) are abundant and protein (6-18%) contributes a small portion (Stefoska-Needham et al., 2015). A dense protein matrix and small starch granules are stored in the peripheral endosperm of the sorghum grain (Chhikara et al., 2018). At maturity, the grain endosperm consists of starch granules, spherical bodies which embed sorghum proteins or kafirins, and a protein matrix of glutelin (Cruickshank, 2016). These three components can be loosely packed to form floury (soft) endosperm or tightly packed in corneous (hard) endosperm (Elkhalifa, Schiffler, & Bernhardt, 2005).

Taylor & Anyango (2011) had explained that the degree of hardness of sorghum endosperm is related to the extent of grittiness in flour after milling. This relationship was attributed to the stronger interaction between the starch granules and the surrounding protein. Albumin, globulins, kafirins, cross-linked kafirins and glutenins are the major classes of sorghum proteins (de Mesa-Stonestreet, Alavi, & Bean, 2010). Of the sorghum proteins, kafirins are the main proteins. The kafirins are prolamin storage proteins with limited lysine (Stefoska-Needham et al., 2015). Cruickshank (2016) hypothesized that the interaction between kafirins and between kafirins and glutelins to form disulfide bonds possibly make the association resist digestion. Disulfide bonds involved in cross-linking of kafirins in the protein matrix forms a protective layer around the starch granules, possibly developing a resistance to hydrolytic breakdown which may be responsible for the reduction in digestibility of both protein and starch, especially in the tightly packed corneous (hard) endosperm (Cruickshank, 2016).

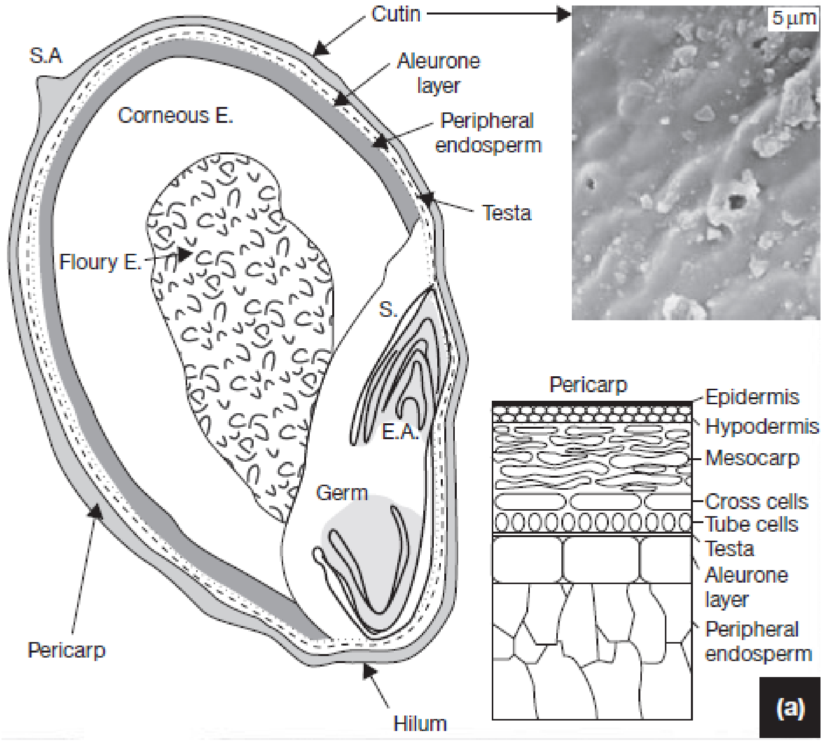

Figure 2.1 Longitudinal section of the sorghum kernel (Waniska et al., 2016)

2.1.1.4 Germ

The germ in a sorghum kernel consists of an embryonic hub and scutellum tissue containing an appreciable amount of oil, protein, enzymes, and minerals (Chhikara et al., 2018). However, the size of the different parts of the sorghum grain will depend on the variety and ecological situation. The germ is a lipid-rich part constituting about 28% and has a protein content of nearly 18 % by weight (Taylor & Anyango, 2011). The proteins in the germ of sorghum are mainly albumins and globulins. These proteins contain lysine and other essential amino acids (Taylor & Schüssler, 1986). Sorghum types have varying sizes of germ, yet germ size is linearly related to the size of the endosperm. With this assertion, the sorghum kernel could be high in oil content. It is a cumbersome process to remove the germ in sorghum (Meera et al., 2011), and the level of this hardship differs among sorghum types. Thus, sorghum flour unavoidably mixes with oil from germ during milling, which regularly causes rancidity issues in sorghum products (Waniska et al., 2016).

2.1.2 Composition of sorghum and sorghum flour

The composition of sorghum grains and its flour are reviewed.as:

2.1.2.1 Protein

The protein content of the sorghum grain varies from 11 to 13% depending on the grain cultivar, genotype, rainfall, soil fertility and ecological situations (Chhikara et al., 2018). Protein (8.7-13%) is the second most abundant component in sorghum kernels, next to starch (81.3-83%) in the endosperm (Serna-Saldivar and Rooney, 2019). The protein content varies in the anatomical parts of the grain (Table 2.1). The protein content is in the range 11.5-12.3% for the whole grain, 8.7-13% in endosperm, 17.8-19.2% in the germ and 5.2-7.6% in the pericarp (Serna-Saldivar & Rooney, 2019). Sorghum proteins can be grouped as prolamins and non-prolamins (de Morais Cardoso et al., 2017). However, the sorghum kafirins (a prolamin-type protein) are the major proteins in sorghum grain (de Mesa-Stonestreet et al., 2010), and are mainly present in the endosperm (Awika, 2017).

2.1.2.2 Sorghum lipids

As mentioned previously, sorghum lipids are contained predominantly in the scutellum section of the germ but also in the aleurone section of the kernel (de Morais Cardoso et al., 2017). The lipid content varies among sorghum types (Table 2.2) and in different anatomical sections of the kernel (Meera et al., 2011). The fat content in whole grain sorghum flour is typically 3.2-3.9 g/ 100 g (Meera et al., 2011; Serna-Saldivar and Espinosa-Ramirez, 2019), which is rather more than wheat

(2-3 g/100 g), rice (0.5-1.0 g/100 g) but less than maize (4-10 g/100 g) and oat (6-8 g/100 g) (Wrigley, 2016). The fat contains some 88% unsaturated fatty acids (Chhikara et al., 2018). Linoleic acid (C18:2; 42-58 wt. %) and oleic acid (C18:1; 21-27 wt. %) are the major unsaturated fatty acids, while palmitic acid (C16:0; 10-17 wt. %) is the most important saturated fatty acid reported in sorghum kernels (Day, 2016).

2.1.2.3 Vitamins and minerals

Wholegrain sorghum is a source of fat-soluble vitamins (D, E and K) and B-complex vitamins (thiamine, riboflavin and pyridoxine) with the exception of vitamin B_{12} (de Morais Cardoso et al., 2017). Sorghum grains are a source of minerals, typically phosphorus, potassium, zinc and iron. It is known that zinc availability varies between 9.7% and 17.1% and iron availability ranges from about 7% to nearly 16% (Afify, El-Beltagi, Abd El-Salam & Oman, 2011). However, the decortication (or dehulling) process has the tendency to lower the vitamin content as vitamins are stored in the aleurone layer and germ of sorghum kernels (Chhikara et al., 2018). The decortication process typically removes the greater parts of the aleurone layer and germ where vitamins are embedded, thus leading to loss of vitamins.

2.1.2.4 Starch

The chemical composition of sorghum grain is dominated by starch (Taylor & Duodu, 2017). Starch contents vary among anatomical sorghum fractions in the range 72.3-75.1% for wholegrain and 81.9-83% for endosperm, respectively (Table 2.2) Starch is a highly organized granular structure in which the two polymeric molecules, amylose and amylopectin are strongly linked by hydrogen bonding (Serna-Saldivar & Espinosa-Ramirez, 2019). Wang, Chen, Ren, and Guo (2014) theorized that amylose is essentially a linear chain consisting of glucose units that are linked by α-1,4-glycosidic bonds while amylopectin consists of glucose units linked by α-1,4-glycosidic bonds and α-1,6-branches.

The gelatinization temperature of sorghum starch varies among sorghum types (Taylor & Anyango, 2011) and it exists in the range of 66 ºC - 81 ºC which is higher compared to that of wheat and maize starch (Taylor & Emmambux, 2010).

Table 2.1 Distribution of different chemical components of the anatomical sorghum grain fractions

Components	Whole grain (%)	Endosperm (%)	Germ (%)	Pericarp (%)
Protein (%)	12.3	10.5	18.4	6
Range	11.5-12.3	8.7-13	17.8-19.2	5.2-7.6
Fat (%)	3.6	0.6	28.1	4.9
Range	-	0.4-0.8	26.9-30.6	3.7-6.0
Ash (%)	1.6	0.6	9.2	3.4
Range	1.6-1.7	0.3-0.7	3.9-10.4	2.0-3.8
Starch (%)	73.8	82.5	13.4	3.5
Range	72.3-75.1	81.3-83	-	-

Source: Serna-Saldivar and Espinosa-Ramirez (2019)

Table 2.2 Crude lipid content (g/100 g flour) of flours from different sorghum types and different anatomical sections

Anatomical section	Sorghum type		
	CSH9-13	CSH-5	M35-1
Germ	28.7	18.0	24.9
Endosperm	1.1	0.1	0.7
Pericarp	11.8	4.0	8.3
Whole	3.6	2.2	3.0

Source: Meera et al. (2011)

2.2 Wholegrain and refined flour from cereals

Wholegrain flour is the flour containing the bran, germ and endosperm in the same state and/or composition as when the grain was originally after harvesting from the field (Doblado-Maldonado et al., 2012). In other words, a wholegrain flour should also deliver almost the same nutrient composition as found in the native grain. Refined flour, on the other hand, has the outer germ and bran layers partially or completely removed through the dehulling operation.

Phytochemicals with antioxidant potential have been reported for cereal grains such as sorghum and millet (Awika, 2017; Girard & Awika, 2018). With these properties, consumption of wholegrain sorghum and millet can potentially protect the human body against the risk of cancer, diabetes and cardiovascular disease (Beta & Duodu, 2016). However, many phytochemical compounds contained in whole grains are inherently bitter, which has led to limited consumer acceptability of food-based products made with wholegrain flours (Kebakile, Rooney, de Kock, & Taylor, 2008). The quality of food products such as sorghum and pearl millet porridge, made with wholegrain flours may be characterized with negative sensory attributes such as unpleasant or rancid flavour, dark or off-colour, dense/firm texture, gritty and astringent mouthfeel (Kebakile et al., 2008; Nantanga, Seetharaman, de Kock, & Taylor, 2008). It was proposed that wholegrain flour can produce foods judged as showing inferior or poor sensory quality compared to the refined flour (Doblado-Maldonado et al., 2012). Consumers' preference for products (such as bread) from refined flour due to its preferred sensory attributes is often the reason for the relatively low consumption of wholegrain-based food products (Heiniö et al., 2016).

2.3 Storage stability of whole grains

Doblado-Maldonado et al. (2012) reviewed extensively key issues affecting the storage stability of whole wheat flour. In the review, they established that wholegrain flour has relatively short storage stability compared to refined flour. This is because flour of wholegrain cereals is more susceptible to rancidity due to lipolysis and oxidation. When cereal grains are intact, triglycerides are compartmentalized in the oil organelles of the germ (Waniska et al., 2016). This prevents the interaction between lipid degrading enzymes and their lipid substrates. Processing operations, such as milling of grain to flour, result in the redistribution of the lipids and mix the enzymes with their substrates. This leads to an increase in the surface area of the flour and exposes the flour components to atmospheric oxygen, causing lipid deterioration and flour instability.

Generally, deterioration of lipids in cereal grain flours occurs due to lipolysis of the triglycerides and subsequent oxidation of the de-esterified unsaturated fatty acids, especially during storage at high humidity (Kolakowska, 2003). Lipolysis involves breaking of the ester bonds in triglycerides which link glycerol with fatty acids and can be brought about by heat or by the action of lipases. During the milling of cereal grain to flour, oil bodies in cells are ruptured and the active lipase enzymes are released (Doblado-Maldonado et al., 2012). The interaction between lipases and oils in the cereal flour results in hydrolysis of the triglyceride and a consequent increase in the content of free fatty acids (FFA) (Doblado-Maldonado et al., 2012). With flour storage, lipids in cereal flour may undergo further hydrolysis to produce more FFA and subsequently, oxidative deterioration commences when polyunsaturated FFA are oxidized.

Cereal flour lipid oxidation takes place though autoxidation of polyunsaturated fatty and acids probably to a lesser extent by lipoxygenase enzyme mediated oxidation of the polyunsaturated fatty acids; both involve the creation of fatty acid free radicals (Doblado-Maldonado et al., 2012).

Linoleic and oleic acids are the major unsaturated fatty acids, while palmitic acid is the most important saturated fatty acid reported in sorghum flour (Day, 2016).

Lipoxygenase has been identified as the major contributor to the rancid off-flavours in cereal flour (Qu et al., 2017). This is because lipoxygenase mediates the oxidation of polyunsaturated fatty acids to fatty acid free radicals, which in turn break down into to aldehydes and ketones, which are secondary oxidation products responsible for the many of the rancid off-flavours. More specifically, in the presence of oxygen, lipoxygenase oxidizes unsaturated fatty acids to conjugated hydroperoxidiene derivatives (Sissons, 2008). Lipoxygenase attacks the methylene group between two double bonds in non-esterified polyunsaturated fatty acids (Wang et al., 2017). Lipoxygenase is reportedly stable at a temperature of 50 ºC but can be rapidly inhibited at temperatures ranging between 65 ºC and 75 ºC (Sissons, 2008). The development of rancid off-flavours in wholegrain cereal flour can be controlled by rapid inactivation of lipase and lipoxygenase with heat (Keying et al., 2009; Qu et al., 2017).

Autoxidation is a non-enzymatic process which involves the creation of highly reactive ‘free radical’ species, whose formation can be enhanced by light, high temperature and certain metal ions (copper and iron) (Eskin & Przybylski, 2001). Free radicals generated from unsaturated fatty acids are further oxidized and form peroxy radicals, which subsequently form more fatty acid radicals and fatty hydroperoxides (Figure 2.4). Hydroperoxides react to form peroxy and alkoxy radicals, which in turn break down to form stable aldehydes and ketones (Wang et al., 2017). In both lipoxygenase- and autooxidation-catalyzed fatty acid oxidations, the final products are aldehydes and ketones (Doblado-Maldonado et al., 2012). The overall process of fatty acid oxidation involves three stages: initiation (fatty free radical formation), propagation (fatty acid free-radical increase by chain reaction), and termination (formation of stable non-propagating fatty acid products, mainly aldehydes and ketones) stages (Kamal-Eldin et al., 2003).

During the initiation stage, fatty acid radicals (L*) are formed from unsaturated fatty acids. At the propagation stage, these fatty radicals react with oxygen to form peroxy (LOO*) and alkoxy (LO*) radical species , which subsequently abstract a hydrogen atom from another fatty acid molecule (LH) to form hydroperoxides (LOOH) and another fatty radical (L*) The hydroperoxides are considered as the primary products of lipid oxidation, which are not stable and break down into a wide range of volatile and non-volatile non-propagating secondary oxidation products, (Figures 2.2 and 2.3) mainly aldehyde and ketones, alcohols (Kamal-Eldin, 2003; Wang et al., 2017).

There are some compounds in cereal grains that can obstruct the propagation stage of oxidation (Eskin & Przybylski, 2001). These compounds include phenolic compounds, which can deactivate the free radical species in the system by donating a hydrogen atom to the free radical, thus terminating propagation, by forming stable non-radical components (Girard & Awika, 2018).

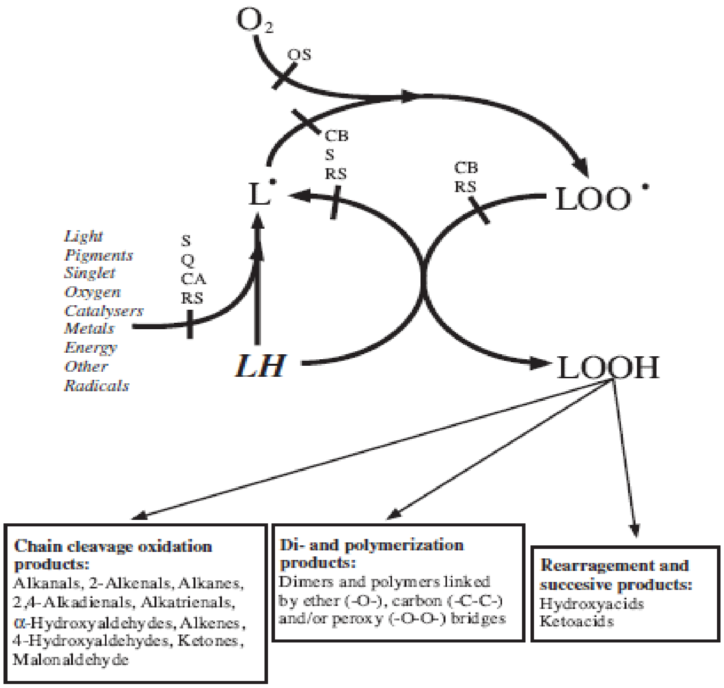

Figure 2.2 Possible mechanism of unsaturated fatty acid oxidation.

LH = fatty acid component; L = fatty radical; LOO = fatty acid peroxy radical; LOOH = fatty acid hydroperoxide. Antioxidants; OS = oxygen scavengers; CB = chain reaction breakers; S = synergists; Q = quenchers; CA = chelating agents; RS = radical scavengers (Eskin & Przybylski, 2001)

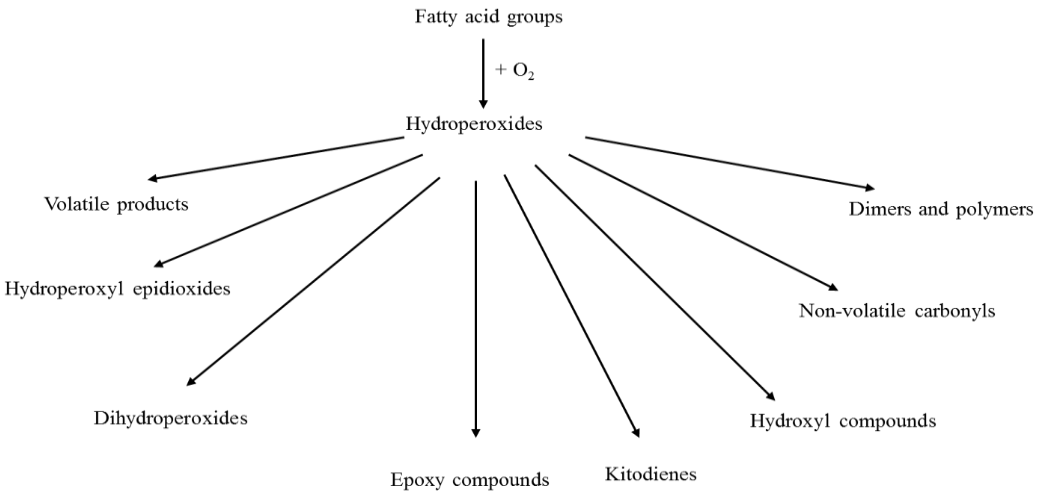

Figure 2.3 Illustration of the secondary decomposition products of hydroperoxides breakdown (Kamal-Eldin, 2003)

2.4 Technologies to improve the storage stability of cereal grain flour

Several treatments have been applied to cereal grains or flours with the aim to prevent the development of rancid off-flavours in flour during storage. These treatment strategies include decorticating the wholegrains (Abdelrahman, Hoseney, & Varriano-Marston, 1983) to remove partly or totally the germ from the kernel, the use of antioxidants (Kapoor & Kapoor, 1990), combination of heat treatment and fermentation of pearl millet grain (Tiwari, Jha, Pal, Sethi, & Krishan, 2014), application of dry heat to whole grain (Keying et al., 2009; Nantanga et al., 2008; Qu et al., 2017). Decortication processes and heat treatments (mainly dry heat treatments such as microwave heating and/or roasting) of cereal grain, specifically for sorghum and/or flour are of interest in the present study.

2.4.1 Decortication

The decortication process, also referred to as dehulling, involves mechanically peeling the outer layers of sorghum kernels mainly to remove the pericarp and improve the sensory appeal of the grains and grain-based products (Awika, 2017). The traditional sorghum grain milling process in most rural households of Africa usually include manual decortication in a wooden pestle and mortar to produce the meal (Kebakile, et al., 2008). Extraction rates are in the range of 72 to 86% with two steps, decorticating and hammer milling. However, with research advancement mechanized milling devices were developed, e.g., the Prairie Research Laboratory type abrasive dehuller and hammer mill. Kebakile et al. (2007) found out that sorghum cultivars with corneous endosperm are better for achieving a high extraction rate with hand pounding. Hand pounding thus produced coarse meals with low extraction rate (742 g/kg). During decortication, not all the germ is removed. Decortication can however reduce the triglyceride content of the resulting flour (Abdelrahman et al., 1983). Depending on the extent of decortication the process can also reduce the susceptibility to oxidative rancidity of cereal flour, thereby increasing the shelf stability of flour.

Lestienne, Buisson, Lullien-Pellerin, Picq and Trèche, (2007) established that decorticating pearl millet grains resulted to losses in fibre content and iron-binding phenolic compounds because the decortication process may have removed large parts of the outer bran or pericarp where fibre and phenolic compounds are embedded. Interestingly, decorticating sorghum could improve the physical appearance of flour and enhance consumer acceptability due to the removal of the pigmented or coloured outer layer. Also, these authors reported that decortication of sorghum grain could result in the reduction of phytate and polyphenols and thereby improve the bioavailability of minerals. Aboubacar, Yazici, and Hamaker (2006) found that the proper decortication level could substantially improve the colour and yield of couscous prepared from sorghum. The authors further proposed that decorticating sorghum at a level greater than 30% kernel removal caused a decrease in the yield of couscous. The decrease in the yield of couscous was attributed to greater starch concentration and rapid gelatinization. The authors concluded that decorticating sorghum is important to improve the colour and yield of couscous.

2.4.2 Dry heat treatments of cereal grains

The aim of dry heat treatment of cereal grains is to inactivate lipid-degrading enzymes, notably, lipase and lipoxygenase enzymes (Keying et al., 2009; Meera et al., 2011; Qu et al., 2017). Dry heat treatment processes that have been investigated include; hot-air oven treatment of pearl millet (Arora, Sehgal, & Kawatra, 2002), microwave heating of wheat kernels (Keying et al., 2009; Qu et al., 2017), hot-air oven heating of oat (Lehtinen, Kiiliäinen, Lehtomäki, & Laakso, 2003), and micronization of corn (Deepa & Hebbar, 2014).

2.4.2.1 Microwave heating and hot-air roasting technologies: mechanisms and application in cereal processing

Microwave heating is associated with the transmission of alternating electromagnetic field energy into thermal energy by affecting the polar molecules of the food material (Yadav et al., 2012).

Microwave heat treatment involves short time exposure of a material (such as cereal grains) to electromagnetic radiation in the wavelength ranging from as long as 1 m to as short as 1 mm, or to equivalently, with frequencies between 300 MHz and 300 000 MHz (Chandrasekaran, Ramanathan, & Basak, 2013). However, the frequencies ranging between 918 MHz and 2450 MHz have been recommended for safe use in food processing using microwave heating (Yadav, Anand, Kaur, & Singh, 2012). At this micro size wavelength, microwave energy was found to be highly efficient in achieving higher temperatures in a short time (Valadez-Carmona et al., 2017). Direct microwave heating of cereal grain is capable of inactivating lipase enzymes (Kermasha et al., 2007) by thermal denaturation of proteins and nucleic acids and thus limiting lipid degradation and oxidation in stored flour milled from cereal grain. This is because the microwave energy is delivered directly throughout the volume of the food materials due to its instant energy dissipation and could therefore achieve a rapid and uniform microwave heating (Chandrasekaran et al., 2013) of grains.

Two main mechanisms are involved by which microwaves generate heat, notably ionic polarization and dipole rotation. In most foods, the heat is generated as a result of internal resistance of molecular dipoles interacting with the rotating electric component of an electromagnetic field (Yadav et al., 2012). Rapid reorientation of water dipoles in food materials during non-ionizing electromagnetic radiation causes disruption of hydrogen bonds and molecular friction resulting in a rapid heating of food material and much energy efficiency. The heat is generated throughout the material creating a selective and volumetric heating resulting in more uniform.

The principle behind the volumetric heating of food material using microwaves is dielectric heating which depends on the electrical properties of the food (Chandrasekaran et al., 2013). With the application of an electric field, the bipolar molecules behave like microscopic magnets and tend to align themselves with the field (Yadav et al., 2012). As the electrical field rotates in millions of times per second (e.g., 2450 MHz), these molecular magnets are unable to withstand the forces retarding their movements. The resistance to the rapid movement of the bipolar molecules creates friction and results in heat dissipation in the part of food material exposed to the microwave radiation (Yadav et al., 2012). The most important requirement for application of microwave heating is that the material to be heated must be able to absorb microwave energy and transmit or convert it into heat. Industrial applications of microwave processing include cooking, drying, pasteurization and preservation. For cereal grains in particular, microwave heating technology has been used for disinfestation of grains to reduce post-harvest losses and also in drying and heating pretreatments in order to improve milling efficiency (Yadav et al., 2012). Nowadays, microwave drying is used mainly for drying of pasta and post-baking of biscuits (Bøaszczak, Gralik, Klockiewicz-KaminÂska, Fornal & Warchalewski, 2002). Bøaszczak et al. (2002) found that microwave heating of wheat grains adversely affected both technological properties and kernel microstructure, when the grain temperature exceeded 64 ºC, notably is protein denaturation changes, as well as deformation of starch granules when viewed under a scanning electron microscope or light microscope.

Microwave heating had more efficient energy savings and reduced processing times of food materials which results in enhanced overall product quality (Valadez-Carmona et al., 2017). Despite the importance of microwave heat-induced changes for understanding and controlling flour stability, a comprehensive study on the changes in sorghum grain which can, in turn, affect products' sensory quality, is still missing. That is why research on induced changes in sorghum grain caused by microwave heating and roasting remains an important and interesting challenge.

2.4.2.2 Effects of dry heat treatments of cereal grains on the storage stability of flour

Keying et al. (2009) applied microwave treatment to pre-conditioned (11% moisture level) whole oat kernels and found that microwave heat treatment (800 W) for 45 s inactivated lipase enzymes by nearly 99%, thereby stabilizing oat flour against triglycerides lipolysis. Light is one of the initiators of autocatalytic oxidation reaction in unsaturated free fatty acids in fat and oils. Unsaturated free fatty acids present in wholegrain cereals are susceptible to autoxidation when exposed to air, with the reaction proceeding by free radical mechanism. The reaction may result in production of stable non-propagating products that contribute to off flavour rancid note in wholegrain cereal based foods.

Nantanga, et al. (2008) toasted (at 120 ºC for 16 h) whole pearl millet grain with the aim to extend the flour shelf life. The authors found that the fat acidity of flour from fresh untoasted grain increased by almost ten-fold compared to that of toasted samples, suggesting increases of de-esterified fatty acids in the control sample due to lipolysis after grain milling. Reduced fat acidity of the freshly toasted grain flours was attributed to the inhibition of lipase caused by the heat treatment before milling the grains. Further, the toasted sample also showed significantly lower peroxide value than the untoasted sample. This probably showed that the toasting process could have led to the formation of Maillard-type products with potential antioxidant properties. These Maillard products could scavenge radical species that are known to promote the formation of hydroperoxides. However, with storage, the peroxide value of the control decreased. This was attributed to a decrease in hydroperoxides. The hydroperoxides are not stable and are transformed into secondary oxidation products (Wang et al., 2017). Consequently, Nantanga et al., (2008) reported that porridges prepared from the flour of untreated pearl millet grain were rancid, whereas porridges of flours from heated grains were not. The finding was based on the results obtained from the descriptive sensory evaluation of porridge samples.

Meera et al. (2011) investigated the effectiveness of hydrothermally treated sorghum grains on flour storage stability. The authors exposed whole sorghum grain types to moist heat (97 ºC) for 5, 10, 15 and 20 min. They found that sorghum grain exposed to moist heat for 15 min inhibited lipase activity and retarded hydrolytic rancidity, thus extending storage stability of flour to nearly eight months compared to 15 days for the control sample. However, the authors reported slight alteration in the physicochemical properties (such as reduction in WSI, increases in WAI and damaged starch) in flours from 15 min heat-processed grains when compared to flours from untreated grains.

Ruge, Changzhong, and Zaigui (2012) investigated the effects of the differently heat-treated oat kernels on the storage properties and sensory qualities of oat flour. The authors used hot-air roasting, steaming, infrared roasting and microwave heating, and they found that the free fatty acid values of oat flour increased by ten-fold with infrared roasting and by two- to three-fold with other heat treatments at the end of 8-week storage (40 ºC, 80% RH). Except for infrared, all other treatments were able to extend the storage stability of oat flour. This is because, with infrared-treated samples, the residual lipase activity was significantly higher than for those samples treated with other treatments (Hu, Wei, Ren & Zhao, 2009). With infrared roasting heat transfer to the core of the oat kernel was probably inefficient to inhibit lipase activity (Ekstrand, Gangby, Akesson, Stollman, Lingnert, & Dahl, 1993). Ruge et al. (2012) suggested that microwaving of the oat kernel was an advantage over infrared treatment in terms of efficiency and effectiveness for inactivation of lipase enzymes. Microwaves rendered a slower and more gradual heating process capable of causing less physical and chemical damage to the oat lipid components, allowing a higher heating efficiency for improving flour storage (Grant, 1999).

Yadav et al. (2012) investigated the effects of microwave treatment of pearl millet grain with the aim to improve flour stability. The authors treated pre-conditioned (15, 18, 21 and 24% moisture levels) pearl millet grains with 900 W microwave power for 40 to 100 s. They found that the grains conditioned at 18% moisture content had the least lipase activity after 100 s microwave treatment. In order words, a reduction of nearly 93% in lipase activity. The decrease in lipase activity of flour was attributed to elevated seed temperature (≈108 ºC).

Ding, Zhang, Wang, Qian, Qi and Xiao (2015) studied the effect of drying systems (ambient air, hot air and infrared drying) on rough rice with the intent to improve shelf-life of brown and milled rice. The authors found that the free fatty acid contents exceeded the limit in hot air, and ambient air-dried samples but remained less than 10% in infrared dried rice after 10 months of storage. Similar effects were also reported by Qu et al. (2017). The authors reported that microwaving of wheat kernels using 700 W for 30 s effectively caused a decrease in the activities of lipase and lipoxygenase enzymes in the flour. The decrease in enzyme activities was attributed to the microwave treatment that changed the structures or conformations of lipase and lipoxygenase enzymes, possibly through denaturation. Thus, suggesting that microwaving of wheat kernels can inactivate lipase and lipoxygenase enzymes. The authors concluded that microwaving of whole wheat grains at 700 W for 30 s significantly retarded the development of rancidity in flour during storage and extended flour shelf-life to about 4 weeks at 35 ºC.

Further, Deepa and Hebbar (2017) evaluated the effect of micronizing (200 ºC for 4 min) maize grain on flour shelf-life. The authors found that the treatment time resulted in inactivation of peroxidase enzyme and a reduction in lipase activity of maize flour to nearly 84 %. Flours of control samples under accelerated (38 ºC/90 % RH) and at ambient (25 ºC/65 % RH) storage conditions showed a significant increase in FFA content whereas flour from micronized grain showed no significant changes in FFA content. The authors found that flours of micronized grain displayed a shelf-life of 60 days under accelerated and 120 days at ambient conditions, while raw maize flour under the same storage conditions had a shelf-life of 15 and 30 days, respectively.

Rekas, Wroniak and Scibisz (2017) found that progress in lipid oxidation can be determined by spectrophotometric analyses (at 232 nm and 268 nm) and be expressed respectively as conjugated dienes and conjugated trienes. Conjugated dienes measure the primary oxidation compounds of lipids formed during storage (Wang et al., 2018). Conjugated dienes are formed by the rearrangement of double bonds during the formation of hydroperoxides from unsaturated fatty acids, while conjugated trienes are produced when polyunsaturated fatty acids with three or multiple double bonds under oxidation (Gertz, Klostermann, & Kochlar, 2000). Additionally, in the absence of descriptive sensory tests to predict and/or ascertain the level of lipid oxidation in the oxidised flour, findings above may be inconclusive.

Several studies investigated the storage stability of cereal grain flours and the efficiency of the stabilization methods have been documented. However, until now, application of microwave heating and/or roasting treatments of whole grain sorghum kernels with the aim to stabilize the flour has not been studied.

2.5 Sensory shelf-life testing of foods

Real-time storage studies can be difficult to perform because a long time period is required for highly stable food to deteriorate (Qu et al., 2017). In view of this, accelerated storage tests were developed to increase the rate of deterioration and shorten the time required to achieve significant changes in quality, thus enabling estimation of deteriorative rates to the expected storage temperature. During storage tests, indicatory parameters are measured to determine the rate of lipid deterioration during storage. Analytical tests during an accelerated shelf-life test must be based on the mode of deterioration of the test product in order to be valid indicators of degradation (Yadav et al., 2012). Choice of test should be established based on what is reported in the literature. Testing includes specific chemical analyses including fat acidity, peroxide and anisidine values, and sensory evaluation to determine the end of shelf-life (Keying et al., 2009).

The expectations of consumers are that high food quality will be maintained from the time of purchase and during consumption (Kilcast & Subramaniam, 2000). Coupled with these expectations is the primary requirement that such food should remain safe and also the need to reduce to the barest minimum any unwanted changes in sensory quality (Kilcast & Subramaniam, 2000). There is a finite length of time for a food after production, to retain a required level of sensory quality and/or remain safe under the specific conditions of storage. This period can be generally defined as the shelf-life of the food product. The sensory characteristics of most foods deteriorate throughout storage, though they may remain safe, but a degree of change is evidently tolerable to consumers (Kilcast & Subramaniam, 2000).

The use of sensory evaluation techniques is required to measure the changes in eating quality of food on storage (Kilcast & Subramaniam, 2000). On this, the choice of testing methods for shelf-life measurement will depend on the objective of the assessment and also on the pattern by which the sensory changes are to be interpreted in terms of shelf-life (Kilcast & Subramaniam, 2000). Shelf-life testing methods in some cases may be highly sophisticated and could warrant using a time-temperature computer system to monitor food product quality. The success or failure of a food product in the marketplace requires a knowledge of why such product deteriorates after manufacture, how it occurs and how it can be prevented or retarded from deteriorating. A definite level of change can be used as a reference if quantitative measures of sensory attributes are made (Kilcast & Subramaniam, 2000).

For shelf-life studies, variables that can be considered include: the nature of the food, its composition, the ingredients, the processing it went through, the packaging used for its protection, storage conditions, distribution, and handling-both by retailers and the consumer (Hough, 2010). When dealing with shelf-life of foods, ideally the focus is about sensory shelf-life (Hough, 2010). Sensory shelf-life is effectively determined by the consumer's rejection or reluctance to repurchase a food product if those sensory attributes observed on first consumption are lacking. In the design of sensory shelf-life tests, some parameters are critical for the success of the test, including temperature, maximum storage time, and time intervals (Hough, 2010).

For experiments dealing with product storage, two designs are usually considered, notably are the basic storage and the reversed storage designs. Unlike the basic storage design, where samples are stored at the desired temperature and periodically removed from storage for evaluation, the reversed storage design involves all samples being stored at the desired temperature with different storage times but samples are all available for evaluation on the same day (Hough, 2010). One major drawback with the reverse storage design is the issue of storing control (fresh) samples. In conducting sensory shelf-life studies, it is critical to compare samples of different storage times with a sample that is considered fresh.

2.6 Sensory evaluation of foods

Sensory evaluation is a scientific discipline that comprises a set of techniques used to evoke, measure, analyze, and interpret human reactions to those characteristics of foods as they are perceived by the five senses, notably sight, smell, taste, touch, and hearing (Stone & Sidel, 2004).

Sensory testing provides data on which sound decisions can be made, by producing a description attributes such as the appearance, aroma, flavour and texture of food and quantifying the nature and intensity of these attributes. A reliable sensory test should be bias-free. Three types of sensory testing are commonly used, each with a different goal and each using participants selected using different criteria (Lawless & Heymann, 2010). These test methods in sensory evaluation of foods are classified broadly as: difference (or discrimination), descriptive and affective testing. A summary of the three main types of testing is given in Table 2.3. Difference tests are designed to detect discernible differences while affective tests are used to determine differences in acceptability or preference between food products. The descriptive tests provide information on the specific food sensory characteristics and quantifies the sensory differences.

Table 2.3 Classification of test methods in sensory evaluation

Class	Question of interest	Type of test	Panellist characteristics
Discrimination	Are products perceptibly different in any way	“Analytic”	Screened for sensory acuity, oriented to test method, sometimes trained
Descriptive	How do products differ in specific sensory characteristics	“Analytic’’	Screened for sensory acuity and motivation, trained or highly trained
Affective	How well are products liked or which products are preferred	“Hedonic”	Screened for products, untrained

Source: Lawless and Heymann (2010)

2.6.1 Descriptive sensory evaluation

Descriptive sensory evaluation can be defined as the identification, description and quantification of the sensory attributes of a food material or product using human subjects who have been specifically trained for this purpose” (Einstein, 1991). This type of evaluation consists of a group of highly trained assessors working together with a common term of reference to give the vocabulary needed to provide accurate descriptions of food samples. With descriptive analysis training methods, extensive training is required before a panel becomes a reliable sensory instrument. Examples of descriptive tests include flavour profile analysis, quantitative descriptive analysis, texture profile analysis and the sensory spectrum technique. A study done by Chambers, Allison, and Chambers (2004) looked at some traditional panel training methods and reported 60 to 65 hours of training were required before the panel was able perform with minimal variance. Descriptors that are more difficult to scale could require up to 125 h of training (Chambers et al., 2004). This extensive amount of time for training can make using the descriptive panels rather cumbersome. However, research has been conducted to improve panel training methods, by utilizing information derived from research on psychological learning techniques (Castura, Findlay & Lesschaeve, 2005). Findlay, Castura and Lesschaeve (2007) have reported that panels trained using Compusense® Feedback Calibration Method (FCM®) can be trained in a product area within 20 hours.

Compusense® FCM® uses information from category-learning research to provide feedback to panellists within 2.5 seconds of making a choice (Findlay et al., 2007). As important as timing is for category-learning, the frequency with which feedback is given is equally important. Findings have shown that intermittent, immediate, computerized feedback acts as a reward for correct decisions helping train new panels and improve already proficient panels, while reducing training time (Findlay et al., 2007). Using this approach, immediate computer feedback has been successfully used in training descriptive sensory panels (Findlay et al., 2007).

2.6.2 Effect of heat treatments of cereal grain on the sensory characteristics of porridge

Porridges (thick or thin types) could be made from maize, sorghum (Kobue-Lekalake, Taylor, & Kock, 2007; Kebakile et al. 2008) and millet (Nantanga et al., 2008) and these cereals are commonly consumed staples in many African countries. The main difference between thin and thick porridges is mainly the total solid content used in the preparation of the porridges (Aboubacar et al., 1999). In addition, it is traditional in many communities to eat the thick porridges with the bare hand because they are ‘solid-like’ while the thin porridges are fluid like and consumed by drinking in the morning or as a snack-type meal during the day time (Moussa et al., 2011). Porridges from whole grains can confer health benefits to humans and high sensory acceptance is important for such porridge (Heiniö et al., 2016). Good taste, flavour, texture and colour are the most important sensory criteria and an essential quality requirement for food products to remain in the market. A lexicon for sorghum porridge is presented in Table 2.4.

Kebakile et al. (2008) evaluated the effectiveness of different milling approaches (hand-pounding, roller milling, and abrasive decortication-hammer milling) and sorghum type on quality of meal extracted. They found that the milling processes imparted more variation to porridge sensory characteristics than sorghum type. For example, porridge of flour from roller-milled grain appeared darker, had more visible specks, intense astringent taste, and an intense branny aroma. Porridge of flour from hand-pounded grains were stiffer and coarser with intense unpleasant flavour and earth-like odour. Porridge stiffness was attributed to the particle size of the meal among other things. Also, Kebakile et al., (2007) previously suggested that the particle size profiling of the meals was influenced by the endosperm texture of the sorghum kernel. With abrasive decortication and hammer milling of grains, porridge appeared lighter and had more intense cereal aroma and flavour. Sorghum with pigmented pericarp and soft endosperm produced porridges with dark, specky, bran-like aroma, bitter with an intense astringent taste. Sorghum with light-coloured hard grains produced porridges with a light colour and more intense cereal flavour and aroma (Aboubacar et al., 2006).

Drewnowski and Gomez-Carneros (2000) in a review highlighted the causes of bitter taste in foods. The authors pointed out that bitter taste can be noticed at remarkably low threshold level. Kebakile, et al. (2008) found that sorghum types with coloured pigments and a higher concentration of flavonoids were more bitter. This perception of bitter taste was more in the porridge of flour from roller milled grains. This might be because of an additional increase in flavonoid levels due to possible higher extraction rates associated with roller milling. The authors suggested that light-coloured hard grain could be subjected to abrasive decortication followed by hammer milling in order to have a high-quality sorghum porridge. Kebakile et al. (2008) and Aboubacar et al. (1999), reported that consumers preferred a lighter colour than darker sorghum porridges.

Aboubacar et al. (1999) also found that the textural characteristic of stickiness in the mouth and cohesiveness were the most important sensory attributes of sorghum porridge, followed by taste and aroma. In studying different sorghum types, the starch properties were associated with the texture of sorghum porridge (Fliedel, 1995). As mentioned earlier, starch is the main carbohydrate in sorghum grain which is embedded in a protein matrix. When starch granules are heated in the presence of water, amylose molecules are released into the solution, and upon cooling the amylose molecules re-associate quickly by cross-linking with each other through hydrogen bonding to form a gel.

Nantanga et al. (2008) reported that cooked porridge, burnt and sweet/fruity aromas, with peanut/toasted flavour were the sensory descriptors of porridges from thermally treated pearl millet grain flour, while rancid, soapy/dirty dishwater-like aroma, rancid off-flavour, bitter taste and bitter aftertaste were associated with porridge from the untreated pearl millet flour. Parker, Hassell, Mottram and Guy (2000) suggested that cooked oat porridge flavour is related to volatile compounds such as 2-methylpropanal due to non-enzymatic reactions occurring during the cooking process. Sweet, fruity and peanut/toasted flavours could be attributed to flavour compounds such as 2-furfuryl alcohol and acetylpyrazine from Maillard-type reaction and caramelization during heating. Rancid and soapy aromas are often associated with volatile aromatic compounds formed as secondary products of oxidation of unsaturated fatty acids. Parker et al. (2000) reported octanal, nonanal and/or decanal as volatile secondary oxidation products related to soapy aroma.

Ruge et al., (2012) investigated the effectiveness of hot-air roasting, steaming, infrared roasting and microwave heating of oat kernel on the sensory properties and sensory quality of the flour. Oat kernel was conditioned to 20% moisture level before being subjected to different heat treatments including hot-air roasting (100 ºC, 20 min), infrared roasting (550 ºC, 45 s), microwave heating (800 W, 45 s) and steaming (121 ºC, 15 psi for 10 min). The results showed that hot-air roasting and infrared roasting displayed better sensory quality (flavour) than other treatments. Indicating that hot-air roasting >> infrared roasting >> microwave heating >> steaming treatments of oat kernels as the potential trend of oat kernel flour stability measured based on the sensory quality. The authors found that hot-air roasting of oat kernels gives a more favourable sensory quality of oat flour, and the process could be appropriated for improving flour storage stability.

While several studies have reported consumer preference for specific types of sorghum porridges (Abuobacar et al., 1999; Abuobacar & Hamaker, 2000; Kebakile et al., 2008), studies reporting the application of microwave treatment and/or roasting process to sorghum kernels to stabilize the fat in the flour has not been studied.

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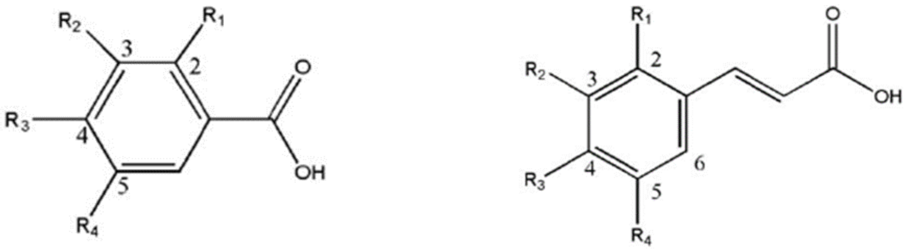
Table 2.4 A lexicon for sorghum porridge

Attribute	Definitions	Reference to clarify and rate perceived sensation	Rating Scale
Appearance			
Colour	Perceived colour intensity of porridge from white (light) to dark brown/purple (dark)	Maize meal porridge (rated 1) and Mmabaitse porridge made from HP meal (rated 8)	Light = 1 Dark = 9
Speck	Quantity of dark-coloured specks visible on porridge	None	
Texture			
Cohesiveness	Degree to which the chewed porridge held together	LARSVYT porridge (20% solids) made from HP meal (rated 6)	Not cohesive = 1 Very cohesive = 9
Stiffness	Force required to compress a spoonful of porridge between the tongue and palate	Marupantsi porridge 10% solids (rated 2) and Segaolane porridge (20% solids) made from ADHM meal (rated 6)	Not stiff = 1 Very stiff = 9
Stickiness	Force required to remove material adhering to teeth and palate during normal eating	Segaolane porridge (20% solids) made from HP meal (rated 4)	None Not coarse = 1 Very coarse = 9
Coarseness	Extent to which grittiness or graininess of porridge caused by small particles could be perceived	None	Not sticky = 1 Very sticky = 9
Aroma			
Branny	Cereal Intensity of aroma associated with cooked cereals	Segaolane porridge (20% solids) from HP meal (rated 5)	Not intense = 1 Very intense = 9
Cabbage (humus)	Intensity of aroma associated with bran	Marupantsi porridge made from ADHM meal with 5% fine bran added (rated 6)	Not intense = 1 Very intense = 9
	Intensity of odour typical of cooked cabbage	Lekgeberwa porridge (20% solids) made ADHM meal (rated 5)	Not intense = 1 Very intense = 9
Taste			
Bitterness	Fundamental taste of which caffeine is typical	Marupantsi porridge (20% solids) made ADHM meal (rated 3)	Not intense = 1 Very intense = 9
Astringent	Chemical sensation associated with puckering of tongue caused by substances such as tannins	Marupantsi porridge (20% solids) made from ADHM meal (rated 3)	Not intense = 1 Very intense = 9
Cereal (starchy) flavor	Intensity of flavour associated with starchy products off-flavour	Segaolane porridge (20% solids) made from HP meal (rated 6)	Not intense = 1 Very intense = 9
Painty (rancid)	Paint like off-flavour, typical of rancid oil	Segaolane porridge made from HP meal with 2% added rancid sunflower oil (rated 7)	Not intense = 1 Very intense = 9

Source: Kebakile et al. (2008)

2.7 Phenolic compounds in sorghum grains

Phenolics are not equally distributed in grains but are found to be concentrated in the outer layers, notably, the aleurone layer, testa and pericarp, which form the principal components of the bran (Devi et al., 2011). Sorghum, like millet, contains a wide range of phenolic compounds (Girard & Awika, 2018). The major classes of phenolic compounds in sorghum are phenolic acids, flavonoids, and proanthocyanidins or condensed tannins (Stefoska-Needham et al., 2015; Salazar-lópez, González-aguilar, Rouzaud-sández, & Robles-sánchez, 2018). The phenolic acids are presumably the most abundant and well characterized group of polyphenols, such that both benzoic and cinnamic acid derivatives (Figure 2.6) are dominating (Awika, 2017). However, after profiling some non-pigmented white and pigmented sorghum types, those with pigmented testa were reported to possess higher levels of phenolic compounds and antioxidant activity (AOA) (Wu, Johnson, Bornman, Bennett, & Fang, 2017). The polyphenols are considered as the main contributors to the AOA (Dykes & Rooney, 2007).



Hydroxybenzoic acids

Hydroxycinnamic acids

	R_1	R_2	R_3	R_4
Gallic acid	H	OH	H	CH
Gentisic acid	OH	H	H	CH
Salicylic acid	OH	H	H	H
p-hydroxybenzoic acid	H	H	H	OH
Syringic acid	H	OCH_3	OH	OCH_3
Protocatechuic acid	H	OH	OH	H
	R_1	R_2	R_3	R_4
Caffeic acid	H	OH	OH	H
Ferulic acids	H	OCH_3	OH	H
o-coumaric acid	OH	H	H	H
p-coumaric acids	H	H	H	H
Sinapic acid	H	OCH_3	OCH_3	OCH_3
Vanillic acid	H	OCH_3	OCH_3	H

Figure 2.4 Basic structures of some major phenolic compounds in sorghum (Awika, 2017)

The polyphenols found in sorghum grains do exert important bioactive properties not related to their actual AOA, which may provide superior health benefits (Awika, 2017). The antioxidant compounds in some sorghum cultivars are gaining attention of researchers due to their active roles as lipid stabilizers and ability to retard excessive oxidation of living cells which often lead to cancers and aging (Apea-Bah, Minnar, Bester, & Duodu, 2016). The stable radical intermediates of the antioxidant compounds can prevent the oxidation of some food ingredients, especially unsaturated fatty acids (Devi, Vijayabharathi, Sathyabama, Malleshi, & Priyadarisini,2011). The efficacy of phenolic compounds to show antioxidant tendencies emanates from their ability to release hydrogen atoms through hydroxyl groups or benzene rings to electron-deficient free radicals and to consequently form a resonance-stabilized and less reactive phenoxyl radical species (Devi et al., 2011)

Consumption of sorghum-based foods that is polyphenol-rich may play a positive role in ameliorating the risk of some terminal or diet-related diseases such as diabetes, cancer and cardiovascular disease (Stefoska-Needham et al., 2015). The mechanism of action of the antioxidant in wholegrain cereals may involve direct free radical scavenging or Fe chelation. Indirect antioxidants such as Fe, Zn, Cu, and Se act as cofactors of antioxidant enzymes (Beta & Duodu, 2016).

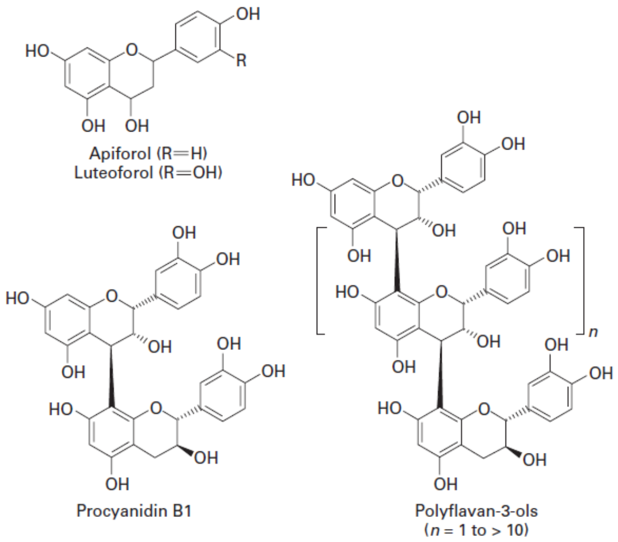


Figure 2.5 Characteristic structure of phenolic antioxidants in sorghum (Kamal-Eldin, 2003)

2.7.1 Effect of dry heat treatments of cereal grains on phenolic content and antioxidant of the resulting flours

Xiong, Zhang, Luo, Johnson and Fang (2019) studied the effect of processing white colour sorghum types on the total phenolic content (TPC), antioxidant activity (AOA) and volatile compounds. The authors found that roasting (150 ºC for 60 min) slightly increased the TPC and AOA compared to the control (Table 2.5). The result was similar to earlier findings reported for red sorghum grain. Wu, Huang, Qin and Ren (2013) found that TPC and AOA of roasted (150 ºC for 1 h) sorghum grain flour increased compared to a control. Proposed reasons for the increase in TPC in roasted samples were attributed to: (1) the release of bound phenolic acids from the degradation of cellular constituents and cell walls (Randhir, Kwon, & Shetty, 2008); (2) phenolic acids became more extractable in roasted sorghum grain flour (Taylor & Duodu, 2015); and (3) some conjugated polyphenolics such as tannins may have been degraded at elevated temperatures to simple phenolics including extractable single phenolic acids (Taylor & Duodu, 2015).

Also, de Morais Cardoso et al. (2014) evaluated the effects of processing sorghum, using dry heat, on the antioxidant profile and observed that most of the phenolic compounds in sorghum were stable to thermal processing and so their benefits may be retained in food products after cooking (Table 2.5). The protection of phenolics by other food components such as proteins or poor sensitivity of the assay procedure employed could have led to no significant changes in phenolic content detected during or after processing (Duodu, 2014).

Sharma and Gujral (2011) studied the effects of sand roasting (280 ºC for 20 s) and microwave cooking (900 W for 120 s) of barley on AOA of flour. It was reported that antioxidant properties increased due to roasting whereas the TPC decreased. The authors also found that barley subjected to roasting displayed higher AOA compared to microwave cooked barley. The decrease in the content of total phenolics after roasting could be attributed to the breakdown of heat labile and/ or free phenolic compounds (Randhir et al., 2008). Sharma and Gujral (2011) explained further that microwave cooking has the potential to inactivate the polyphenol oxidase activity in barley. This was attributed to the volumetric heating and intense penetration power of the microwaves.

However, there are discrepancies in the values reported for the TPC of sorghums by different researchers, particularly when the Folin-Ciocalteu method was used. This might be because the assay measures not only polyphenolic compounds but also detect other biological compounds that are formed during heat treatments of cereal grains (Wani, Gani, Tariq, Sharma, Masoodi & Wani, 2016). These compounds, such as melanoidins, are formed during the roasting process for instance, and presumably possess reducing or antioxidant properties (Zou et al., 2015). Thus, roasting might have partially contributed to an elevated apparent concentration of total phenolics in some of these studies.

Table 2.5 Effect of thermal treatment of cereal grains/fractions on phenolic compounds of flour

Cereal type	Thermal treatment	Changes in polyphenols	References
Rice, brown	Hydrothermal	A decrease in total phenolic and flavonoid contents	Zeng Hu, McClements, Luo, Liu, Gong and Huang (2018)
Red, non-tannin Sorghum, flour	Microwave heating (middle power, 4 min)	Increase in total phenolics.	de Morais Cardoso et al. (2014)
	Wet cooking (450 ml of water, 100 °C, 25 min)	A decrease in anthocyanidins, total phenolic compounds, and AOA.	
	Oven heating (121 °C, 25 min)	No change in total phenolics	de Morais Cardoso et al. (2014)
Oat	Sand roasting (280 °C, 15 s)	A decrease in the TPC	Gujral, Sharma and Rachna (2011)
Barley	Sand roasting 180 °C, 5, 10, 15, 20 min) Microwave cooking (900 W for 120 s)	A decrease in the TPC with an increase in AOA	Sharma, Gujral and Rosell (2011)
Sorghum, grain	Roasting (150 °C, 60 min)	Increase in the TPC and AOA	Wu et al. (2013)
Sorghum, grain	Roasting (150 °C, 60 min)	Increase in the TPC and AOA	Xiong et al. (2019)

TPC = total phenolic content, AOA = antioxidant activity

2.7.2 Effect of dry heat treatment of cereal grain on the content of damaged starch, pasting and functional properties of flour

Qu et al. (2017) studied the effects of microwave heating (700 W for 0-60 s) of wheat kernels on the flour functionality. They found significant gradual increases in the damaged starch content after 20 s of the treatment. Thus, microwaving of wheat kernels could be responsible for the mechanical damage (disruption) of the starch in the wheat flour through depolymerization thereby weakening the starch granular structures. This is because microwave heat treatment disrupted the intermolecular forces between the starch and proteins and increased the content of damaged starch.

The peak viscosity (PV) of pasted flours or starches significantly decreased due to microwave heating of wheat and corn (maize) flours and/or starches (Lewandowicz, Jankowski, & Formal, 2000). Pinkrova et al. (2003) also observed a reduction in the PV of rice flour due to an increase in microwave energy input on the rice grains. The PV could reflect the maximum swelling of starch granules before the disruption of starch granules (Shah, Gani, Ashwar, shah, Wani, & Masoodi, 2016). The reduction in PV of starch was attributed to the disruption of the starch granule structure leading to a decrease in the water absorption capacity and reduced ability of starch to swell (Luo, He, Fu, Luo, & Gao, 2006). In addition, Luo et al (2006) attributed the reduction in PV to the incremental change of inter- and intramolecular hydrogen bonding due to the association of starch chains during microwave heat treatment of maize starches from different varieties.

The changes observed in the pasting profiles of starch from millet caused by microwave heating was attributed to the moisture content of the starch (Li, Hu, Wang, & Zheng, 2019). Considering the microwave field, polar constitutes like water molecules vibrate at a very high frequency (2450 MHz) and then the spontaneous friction, collision and vibration between the water molecule and the starch granules could generate heat within a short time (Venkatesh & Raghavan, 2004). The heat generated during microwaving could cause the physical damage of starch granules and degradation of starch structures. Also, the polar groups including the hydroxyl and carbonyl groups can be affected such that the original hydrogen bonds are broken and there is the formation of new hydrogen bonds between water and starch chains, hence loss of double-helix (double-stranded) order (Brasvoveanu & Nemtanu, 2014).

Further, the pasting process could promote the formation of amylose-lipid complexes (Wokadala, Ray, & Emmambux, 2017). The complexes are formed by the interactions between amylose and lipids forming a layer of amylose-lipid complexes on the granular surface of starch (Sharma & Gujral, 2019). The presence of a lipid layer on the granular surface of starch may have formed a protective cover that prevents water uptake due to the hydrophobic nature of lipids (Sharma & Gujral 2019). The protective layer presumably reduces the ability of starch granules to imbibe water, thus leading to reduced PV. Similarly, Singh and Adedeji (2017) found that the complexation of amylose and lipids causes a reduction in the extent of water uptake and swelling of starch, restricting amylose leaching thus resulting in lower PV.

Huang et al. (2015) reported that starch with high amylose contents displayed reduce PV due to limited swelling of starch granules. Further, the phenolic compounds could also influence starch during pasting by competing with starch molecules for water binding (Wu et al., 2016). This competition between phenolics and starch for water may reduce the available water in the system during pasting for swelling of starch.

During pasting, the breakdown value of starch/flour indicates the extent of the disruption of starch granules while the setback value expresses the tendency of starch/flour against retrogradation (Trung, Ngoc, Hoa, Tien, & Hung, 2017). A lower setback value suggests that a weaker strength gel network structure has formed during the cooking phase due to the disruption of starch granules (Li et al., 2019). With microwave heating of millet grain, Li et al. (2019) reported that an increase in the moisture content of millet flour resulted in more severe damage to the starch granules based on PV, breakdown and setback values.

2.8 Gaps in research

Research has been conducted on the effectiveness of thermal treatments of cereal grains including sorghum, with the aim of extending the storage stability of flour. Although the researchers used different thermal processing methods to improve flour storage stability, most of these methods are time-consuming and in some instances like hydrothermal treatment, an additional drying step is needed to bring the moisture content of treated grain to safe levels. Such additional drying of grains could incur more energy and additional processing cost. Also, the previous studies did not consider testing the stabilized flour using a convenient food vehicle to evaluate with trained descriptive sensory panels whether the flour retained its functionality and sensory quality. The researcher did not find any study that reported on the effects of dry heat treatments (using microwave treatment and/ or roasting process) of sorghum grains on the flour storage stability. The effects of microwave heat and/or roasting treatment applied to sorghum kernels with subsequent processing (e.g. decortication, milling to flour and storage) has not been reported.

Sorghum processed to flour and consumed as porridge may be used to produce baked products such as cake, biscuits or bread. Sorghum flour is sensitive to rapid deterioration by lipolysis (of triglycerides by lipase) and subsequent oxidation of de-esterified fatty acids (by lipoxygenase or autoxidation). The deterioration is manifested by the development of rancid off-flavour. Studying the influence of dry heat treatments of sorghum grain on the physicochemical and functional properties of the resulting flour would be important to understand the flour stability and the sensory characteristics of porridge from stored flour.

3. HYPOTHESES AND OBJECTIVES

3.1 Hypotheses

3.1.1 Microwave and roasting treatments of wholegrain sorghum kernels will stabilize the flour milled from the whole and decorticated grains. In comparison to flours from untreated kernels, the flours from heat-treated whole sorghum kernels will remain fresher for longer periods without traces of unpleasant or rancid off-flavour in the product prepared from the stored flour.

This is because heat treatments when applied to sorghum kernels could denature or inactivate lipid-degrading enzymes, notably lipase and lipoxygenase enzymes (Keying et al., 2009). Nantanga et al. (2008) studied the effects of thermal treatments to partially pre-cook and improve the shelf-life of whole pearl millet flour and reported a reduction in fat acidity of flour from freshly heated whole pearl millet grains. The reduction in fat acidity was attributed to the inhibition of lipase enzyme due to heat treatment before milling the grains. This inhibition will prevent both the lipolytic reaction or hydrolysis of triglycerides and subsequent lipoxygenase-catalyzed oxidation of any eventual de-esterified unsaturated fatty acids (Deepa & Hebbar, 2017). Nantanga et al., (2008) reported that thermal treatment of whole pearl millet kernels produced a change in the sensory attributes of porridges prepared from the thermally-treated pearl millet kernel flour, notably appearance, aroma, texture, taste and flavours. Lipase activity could promote instant lipid rancidification of unsaturated fatty acids in whole flour resulting in an unpleasant or a rancid aroma. Heiniö, Lehtinen, Oksman-Caldentey and Poutanen (2002) found that accumulation of both free fatty acids and the volatile lipid oxidation products appears to favour the development of undesired sensory properties such as rancidity and bitterness. The authors concluded that rancidity and bitterness were highly positively correlated with each other and with the amount of free fatty acids. Qu et al. (2017) found that microwaving wheat kernels caused a substantial decrease in lipase and lipoxygenase activities, resulting in a shelf-life extension of over 4 weeks for wheat flour.

3.1.2 Although it is hypothesized that microwave or roasting treatment of sorghum kernels will stabilize the resultant flours, the treatment levels that stabilize flours will however affect the physicochemical, particularly colour and functional properties, notably flour paste profile or viscosity and WAI. The extent of the energy input in sorghum kernels will be inversely proportional to the extent of change in physicochemical and functional properties of the resultant flours.

Roasting sorghum kernels changed the colour (decreased the lightness L*) and browning index (increased the brownness a*) of the resulting flours (Ranganathan et al., 2013). The decrease in L* was attributed to a lower moisture content due to the heat treatment and development of a glazed-like appearance after grinding the treated kernels to flour. Darkening of the flour was attributed to the production of brown pigments from Maillard reaction. The authors reported a significantly lower ($p < 0.05$) pasting profile of the sorghum flour due to the heat treatment of the kernels. This is because the formation of a harder endosperm texture or structure due to the heat treatment might have resulted in case hardening in treated samples such that flour water absorption was reduced and the ability of starch granules to swell was limited.

Sharanagat et al. (2019) reported an increase in TPC of sorghum flour upon microwave roasting of sorghum kernels. This is because the heat treatment caused the release of bound phenolics from the cell walls, which could become more extractable in aqueous ethanol and acetone, or hydrolysable tannins or high molecular weight phenolic compounds are degraded to smaller units thus contributing to an increase in TPC (Taylor & Duodu, 2015). The increase in AOA may be partially attributed to the generation of Maillard-type products such as melanoidins which could behave and react like Trolox, a vitamin E analogue.

3.2 Objectives

3.2.1 To determine the effect of the level of microwave heating of tannin and non-tannin sorghum grains on the physicochemical (colour, moisture and fat acidity, TPC and AOA) and functional properties (pasting properties, WAI and WSI) of the whole and decorticated grain flours (unstored) milled from the grains.

3.2.2 To determine the effects of level of microwaving non-tannin wholegrain sorghum kernels on storage stability (using fat acidity and *p*AV of flour as indexes) of whole flours (stored at 50 °C for 6 weeks, 24 h fluorescent light) as evaluated based on the sensory characteristics of porridge prepared from stored flours.

3.2.3 To determine the effects of roasting tannin and non-tannin wholegrain sorghum kernels on the physicochemical and functional properties of whole and decorticated grain flours, and storage stability (using fat acidity and *p*AV of flour as indexes) of whole and decorticated grain flours (stored at 50 °C for 6 weeks, 24 h fluorescent light) as evaluated based on the sensory characteristics of porridge prepared from stored flours.

4.0 RESEARCH CHAPTERS

The research, which tested the hypothesis stated in Chapter 3 (Hypotheses and objectives), is separately presented into four different sub-chapters with each chapter presented as proposed for publication.

4.1 Effects of microwave heat treatment of tannin and non-tannin sorghum grains on the physicochemical and functional properties of the milled flours (unstored)

4.2 Stabilization of wholegrain sorghum flour and consequent potential improvement of food product sensory quality by microwave treatment of the kernels.

4.3 Effects of hot-air roasting of tannin and non-tannin sorghum grains on the physicochemical, functional properties of their unstored flours, and stabilization of non-tannin stored flours based on improvement of food product sensory quality.

4.1 Effects of microwave heat treatment of tannin and non-tannin sorghum grains on the physicochemical and functional properties of their unstored flours

4.1.1 Abstract

Sorghum, when milled to flour, cannot be stored for a long duration because of its susceptibility to lipid deterioration resulting in the development of rancid off-flavours. The effects of the extent of microwaving of non-tannin and tannin sorghum grains on physicochemical (moisture content, fat acidity, total phenolic content (TPC), antioxidant activity (AOA) and colour) and functional properties (pasting, water absorption index (WAI) and water solubility index (WSI)) of their flours (wholegrain and decorticated) were investigated. Generally, moisture, fat acidity, TPC and AOA of flour from treated grains decreased with a concomitant increase in microwaving energy (from 36 kJ/100 g to 90 kJ/100 g) applied to 500 g grains when compared with untreated samples. The highest AOA (54.8 µmolTE/g) was in untreated (raw) wholegrain, tannin flour. The lightness (L*) of flour decreased slightly for whole tannin (76.9-75.7), decorticated tannin (92.2-86.7), whole non-tannin (83.0-82.1) and decorticated non-tannin (92.4-91.6) samples while increases in redness (*a**) and yellowness (*b**) colour values were observed upon microwaving. During pasting, control flours exhibited higher PV compared to those of microwave-heated samples. However, microwaving sorghum kernels led to a decrease in WAI and WSI. Decrease in flour fat acidity values with increasing microwave energy input on sorghum grains shows the potential of the treatment to stabilize sorghum flour.

Keywords sorghum, microwave energy, flour, whole grain, decorticated grain

4.1.2 Introduction

Sorghum is a staple food crop for a large segment of the population in sub-Saharan Africa and Asia (ICRISAT, 2018). Like other cereal grains sorghum can be stored for long periods without undergoing deterioration provided the grains remain whole and intact (Meera et al., 2011). However, sorghum flour is susceptible to lipid deterioration due to lipolysis (hydrolytic rancidity) and/or autoxidation (when flour is damp). The chemical changes are associated with subsequent oxidation of the unsaturated fatty acids leading to the development of rancid off-flavours (Arora, Sehgal, & Kawatra, 2002). This may affect some of the physicochemical and functional properties of flours and sensory qualities of the food products of flour (Zhang & Hamaker, 2005). In such situations where the lipids in flours are oxidised, food product rejection by the consumer may arise.

Generally, application of heat treatments to cereal grains can inactivate lipid-degrading enzymes to retards lipolysis and/or prevent rancidity caused by lipase and lipoxygenase and reduce moisture content, thereby extending the shelf-life of cereal flour (Bucsella, Takács, Vizer, Schwendener, & Tömösközi, 2016). Microwave processing of cereal grains is a 'green' technology utilizing a non-polluting energy source, have been a viable strategy that can potentially improve the stability of cereal flour (Keying et al., 2009; Qu et al., 2017). The fundamental cause of the improvement in the shelf-life of whole flour when kernels are microwave-heated, is volumetric heating of food components (like fat/water) such that higher energy efficiency can be achieved on sample under the treatment compared to conventional heating (Qu et al., 2017). This mechanism of heating could wholly or partially inactivate the activity of lipid-degrading enzymes and delay or halt lipolysis. Microwaves cause dipolar rotation of water molecules due to the polar field of microwave radiation and generate heat by molecular friction. Qu et al. (2017) reported that microwaving wheat grains (700 W for 30 s) potentially reduced the activities of lipase and lipoxygenase enzymes in flour stored under accelerated condition (35 ºC). The authors found that there was a decline in the enzyme activity which was attributed to microwave heating effects which changed the structural conformation of lipase and lipoxygenase enzymes.

The presence of phenolic compounds in sorghum grains, especially tannin types may offer antioxidant properties to the food-based products made from the flour (Awika & Rooney, 2004). This is because tannins are powerful antioxidants (Girard & Awika, 2018). Dietary phenolic compounds such as phenolic acids that are distributed in sorghums also have potential AOA (de Morais Cardoso et al., 2014) through their ability to scavenge free radicals (Apea-Bah et al., 2014). Shahidi and Zhong (2015) also hypothesized that phenolic antioxidants play a vital role in food preservation by inhibiting lipid oxidation. Therefore, sorghum flour with higher concentrations of phenolics may potentially display more AOA (Shen et al., 2017). Wholegrain sorghum particularly those of tannin types have a higher concentration of phenolics compared to tannin-free sorghum types (Awika & Rooney, 2004). The decortication process removes a large proportion of the bran (outer covering of grain) containing the phenolic compounds which are mostly concentrated in the bran (Dykes & Rooney, 2006). Decorticating whole grains sorghum before milling to flour can possibly improve flour stability and could reduce rancidity in cereal flour. This could be because the decortication process partially or wholly removes the lipid-rich germ region from the whole grain, making little or no lipid available to undergo deterioration.

Limited information is available in literature about the effects of microwaving sorghum kernels on the physicochemical and functional properties of their flours. This study was conducted to evaluate the effects of extent of microwaving of tannin and tannin-free sorghum kernels on physicochemical (moisture content, fat acidity and, TPC, AOA and colour) and functional properties (pasting characteristics, WAI and WSI) of flours obtained from whole and decorticated grains.

4.1.3 Materials and methods

4.1.3.1 Materials

4.1.3.1.1 Description of raw materials (tannin and non-tannin sorghum types)

Red tannin (54.1 mg CE/g- a blend of sorghum cultivars PAN 8616 and PAN 8625) and non-tannin sorghum grains (a blend of cultivars but primarily PAN 8816) were used as raw materials for this study, supplied by Tiger Brands (Pty) Ltd., South Africa. The grains were manually cleaned to remove broken grains, empty kernels and other foreign particles. Cleaned grains were stored in plastic buckets at -20 °C until needed for further use. All reagents used for chemical analysis were analytical grade and procured from Merck (Pty) Ltd. (Johannesburg, Gauteng, South Africa).

4.1.3.2 Methods

4.1.3.2.1 Microwave heat treatment of wholegrain sorghum kernels

A pilot-scale commercial microwave oven (Delphius Commercial and Industrial Technologies, Centurion, South Africa) capable of generating 900 W power at 2,450 MHz was used for microwaving sorghum grains. Each batch of 500 g, previously cleaned sorghum grains and conditioned to 14 % moisture content was placed on a flat glass plate and microwaved for 40, 60, 80 and 100 s resulting in energy outputs of 36, 54, 72 and 90 kJ [i.e., Energy (kJ) = Power (kW) x Time (s) respectively (Table 4.1.1). The temperature of microwaved grains was immediately measured after heating using a non-contact infrared thermometer (Fluke 62 mini, Wantitall (Pty) Ltd., Linbro Park, Gauteng, South Africa). Microwaved grains were cooled for 5 min at room temperature (20-22 °C) by spreading on aluminium trays, packaged in zip-lock bags and then stored at - 20 °C till required for analyses.

Table 4.1.1 Sample treatment based on time-power combination with increasing order of microwave energy transmitted

Treatment	Treatment time (s)	Microwave energy (kJ) (Time *Power)
T_1 (Control)	0	0
T_2	40	36
T_3	60	54
T_4	80	72
T_5	100	90

4.1.3.2.2 Decortication of kernels and milling

Decortication was carried out with a Tangential Abrasive Dehulling Device (TADD, Venables Machine Works, Saskatoon, Canada), according to the procedure described by (Dlamini, Taylor, & Rooney, 2007). Raw grains (9.2 % and 10.1 % moisture content) served as controls. Half of the grains were decorticated, and the remaining half kept whole. Grain (50 g) was placed in the TADD cups (at a time, 4 samples in duplicate were decorticated) and closed prior to decortication for 6–8 min. The decorticated grain was recovered from the cups using vacuum suction and weighed. Extraction rates of approximately 80-82 % by weight. A laboratory hammer mill (Falling Number Laboratory Mill 3100, South Africa) fitted with a 500 µm opening screen was used to mill the whole decorticated grain. Milled samples were immediately put into zip-lock bags and stored at -20 °C until needed for analyses.

4.1.3.3 Analyses

4.1.3.3.1 Determination of moisture content and fat acidity

AACC (2000) method 44-19 was used to analyse moisture content of flours, using a forced-air circulation oven (Model FSOE, Labdesign Engineering (Pty) Ltd., Roodepoort, Gauteng, South Africa). Ground sorghum flour samples (2-3 g) were dried at 103 °C for 3 h, and weight loss was calculated as the % moisture content. Fat acidity was determined using AACC (2000) method 02-01A for small grains and calculated as mg KOH required to neutralize FFA from 100 g flour on a dry weight basis. All measurements were carried out in triplicate.

4.1.3.3.2 Total phenolic content

4.1.3.3.2.1 Extraction of phenolic compounds

Extraction of phenolic compounds was carried out using the modified extraction procedure described by Apea-Bah et al. (2014). Exactly 1 g of flour was extracted with 10 ml 1 % (v/v) concentrated HCl in a methanol solution under magnetic stirring (Labcon MS20 magnetic stirrer, Laboratory Marketing Services Cc., Randburg, South Africa) for 2 h at a low speed, followed by centrifugation using a universal centrifuge (Z366K, Hermle Labortechnik GmbH, Wehingen, Germany) at 2000 x g, at 4 °C for 10 min. The residue was then extracted with two additional 10 ml volumes of the same solvent for 30 min each. It was then centrifuged, and the supernatant collected as before. Supernatants were pooled together into centrifuge tubes wrapped with aluminium foil to prevent exposure to light and stored at -20 °C for analysis of TPC and antioxidant properties.

4.1.3.3.2.2 Determination of total phenolic content

The TPCs of sorghum flour extracts were determined by using the Folin-Ciocalteu phenol reagent following the modified method described by Apea-Bah et al. (2014). Exactly 0.1 ml (100 µL) extract was mixed with 7 ml (700 µL) of distilled water and 0.5 ml (500 µl) Folin-Ciocalteu phenol reagent. The mixture was swirled to mix and left for 8 min to equilibrate at ambient temperature followed by addition of 1.5 ml (1500 µ l) 20 % sodium carbonate. The volume of the mixture was made up to 10 ml, shaken to mix well and then incubated in the dark at ambient temperature for 2 h. Thereafter, absorbance was read at 765 nm in a spectrophotometer (Lambda EZ150, Perkin-Elmer, Massachusetts, USA). The standard curve of (+)-catechin (0.1-0.5 mg/ml; R^2 = 0.99) was used to quantify the phenolic acid content. The TPCs were expressed as milligram catechin equivalent per gram (mg CE/g) flour, dry weight basis. The analyses were carried in triplicate.

4.1.3.3.2.3 Determination of antioxidant

The free radical scavenging activity of sorghum extract was determined using ABTS* [(2, 2-azinobis (3-ethlybenzothiazoline-6-sulfonic acid)] assay described by Awika et al. (2003). Exactly 190 µl of previously incubated (12-16 h) ABTS* stock solution was added to 10 µl sorghum extract in a 96-well microplate. The reacting mixture was then incubated in the dark for 30 min and absorbance was read at 734 nm in a spectrophotometer. A standard curve for Trolox (0.05-0.8

µmol/L; $R^2 = 0.99$) was used to quantify the AOA and results were expressed as micromole Trolox equivalent per gram (µmol TE/g flour), dry weight basis. The test was performed in triplicate.

4.1.3.3.3 Colour determination

The colour of flours (unstored) was determined by the tristimulus colorimetry method using a Minolta colorimeter (Chroma meter CR-400C, Konica Minolta, Osaka, Japan) in CIElab scale L* a* b* (B. Sharma, Gujral, & Solah, 2017). A white tile from the manufacturer was used to do the calibration (CIE L*= 96.63, a* = 0.22, b = 2.28) of the colorimeter. Flour was filled into petri dishes. The colour of flours was taken at three separate spots (randomly chosen) and then averaged. Hue value (H*), colour saturation/treatment intensity (Chroma, C*), the total colour difference (ΔE*) and browning index (BI*) were estimated from L*, a* and b* values and then compared to those with control. The equations below were used to calculate all these parameters:

Chroma, (C*) = $\sqrt{a^2 + b^2}$ and Hue angle (H*) = (b/a)

Total colour difference (ΔE*) = $\sqrt{(\Delta L*)^2 + (\Delta a*)^2(\Delta b*)^2}$

Differences of $L*$, $a*$ and $b*$ [Equations (1) – (3)] were used to calculate the changes in different colour attributes of samples.

$$\Delta L* = L* - L \qquad (1)$$

$$\Delta a* = a* - a \qquad (2)$$

$$\Delta b* = b* - b \qquad (3)$$

Where, L, a, b is colour component values of control. The following values were used to determine if the total colour difference was visually obvious (Biaxal et al., 2008).

ΔE* < 1 = colour differences are not obvious for the human eye

1 < ΔE* < 3 = colour differences are not appreciative by the human eye

ΔE* > 3 = colour differences are obvious for the human eye.

Brown Index (BI*) = $\frac{100\,(x - 0.31)}{0.17}$

Where, x = $\frac{a* + 1.75\,(L*)}{5.645\,(L*) + a* - 3.012\,(b*)}$

4.1.3.3.4 Pasting properties

Pasting properties were determined using an Anton Paar Rheometer with Rheoplus software® (Physica MCR 301, Ostfildern, Germany). Sorghum flour (1.5 g) was suspended in distilled water and adjusted to a total weight of 15 g. The suspension was mixed manually in a cup and stirred to avoid lumps forming prior to measurement. The pasting regime was initialized, and the slurry stirred (960 rpm), at 50 °C for 30 s. Thereafter stirring was held at 160 rpm for the remainder of the cycle. The suspension was heated from 50 °C to 91 °C at a heating rate of 5.5 °C/min and held at 91 °C for 15 min before cooling down to 50 °C (at a cooling rate of 5.5 °C/min). The test was performed in triplicate.

4.1.3.3.5 Water absorption and solubility indexes

Water absorption (WAI) and (WSI) solubility indexes were determined according to the procedures described by Gujral and Singh (2002). Into a 50 ml centrifuge tube, exactly 2.5 g flour was dispersed in 30 ml of distilled water at 30 °C and incubated in a shaking water bath (OLS26 Aqua Pro, Grant Instrument Ltd., Wehingen, Germany) for 30 min at 30 °C with mixing every 5 min by a vortex. The solution was centrifuged using a universal centrifuge (Z366K, Hermle Labortechnik GmbH, Wehingen, Germany) at 4500 rpm for 15 min and the supernatant was decanted carefully into a moisture tin of known weight and dried at 100 °C overnight. The WAI was recorded as the weight of gel obtained per gram of dry ground sample. The amount of dry solid recovered after evaporating the supernatant in an oven was expressed as dry solid in 2.5 g sample and defined as WSI

$$\text{WAI} = \frac{weight\ of\ gel}{weight\ of\ flour\ sample}$$

$$\text{WSI} = \frac{weight\ of\ supernatant\ after\ drying}{weight\ of\ flour\ sample}$$

4.1.3.3.6 Light microscopy

Light microscopy of tannin and non-tannin sorghum flours from microwaved and untreated (whole and decorticated) preconditioned sorghum kernels were performed. Exactly 5.0 mg (dry basis) of flour sample was dissolved in 1 mL of 30% glycerol solution. The flour suspensions were also stained with and without iodine solution. About 0.3 mL of 30 % glycerol solution was added to the suspension and mixed. Samples were observed using a Light Microscope (Nikon Optiphot, Tokyo, Japan) fitted with appropriate illumination sources and filters for normal with iodine staining and cross polarisation.

4.1.4 Statistical analysis

The effect of sorghum type and milling fraction on the characterization of physicochemical properties of sorghum flour was determined with one-way analysis of variance (ANOVA). Also, the effect of microwave energy level applied to each of the two types of sorghum grains on moisture, fat and fat acidity contents, TPC and AOA, WAI, WSI, lightness (L*), redness (a*) and yellowness (b*) values for either decorticated or whole kernel flours were determined using four separate (wholegrain tannin, decorticated grain tannin, wholegrain non-tannin and decorticated grain non-tannin) one-way ANOVA models. The means for each respective microwave energy level were compared with Fisher's Least Significant Difference (LSD) test at $p < 0.05$ using XLSTAT® (Addinsoft^{TM}, New York, US). A separate two-way ANOVA model was applied to determine the effects of microwave energy (36 kJ to 90 kJ), sorghum type (tannin and non-tannin) and processing (decortication and wholegrain) and their 2-factor interactions effects as independent factors on dependent variables Pearson's correlation coefficient was used to analyze linear relationships between TPC, AOA, fat acidity, moisture content, Hue angle, and browning index of flours.

4.1.5 Results and discussion

4.1.5.1 Effect of sorghum type and milling fraction on the characterization of physicochemical properties of sorghum flour

Sorghum types had a significant ($p < 0.05$) effect on all flour parameters except fat acidity (Table 4.1.2). Similarly, processing had a significant ($p < 0.001$) effect on all flour parameters except WSI. The interaction of sorghum types and processing was significant ($p < 0.05$) for most parameters except yellowness, chroma, browning index and WAI of flour.

Table 4.1.2 Effect of sorghum type and milling fraction on the characterization of physicochemical properties of sorghum flour

Flour parameters	Sorghum types		p-value	Processing		p-value	Sorghum type x processing				p-values
	Tannin	Non-tannin		Wholegrain	Decorticated		Non-tannin* wholegrain	Tannin* wholegrain	Non-Tannin* decorticated	Tannin* decorticated	
Moisture content (%)	8.4^{b}	10.1^{a}	0.000	9.8^{a}	8.6^{b}	0.000	10.1^{a}	9.4^{b}	9.8^{ab}	7.4^{c}	0.000
Fat acidity (mg KOH/g)	18.1	18.3	0.125	19.9^{a}	16.5^{b}	0.000	20.1^{a}	19.6^{a}	16.4^{c}	16.6^{c}	0.009
TPC (mg CE/g)	12.8^{a}	4.9^{b}	0.000	12.7^{a}	5.1^{b}	0.000	5.6^{bc}	19.8^{a}	4.3^{c}	5.9^{b}	0.000
AOA (µmol TE/g)	36.0^{a}	17.1^{b}	0.000	37.9^{a}	15.3^{b}	0.000	19.8^{b}	55.9^{a}	14.4^{d}	16.1^{c}	0.000
Lightness (L*)	81.5^{b}	87.1^{a}	0.000	79.4^{b}	89.2^{a}	0.000	82.5^{c}	76.3^{d}	91.6^{a}	86.7^{b}	0.039
Redness (a*)	4.3^{a}	2.4^{b}	0.000	4.8^{a}	1.9^{b}	0.000	3.9^{b}	5.6^{a}	0.9^{d}	3.0^{c}	0.004
Yellowness (b*)	7.2^{b}	8.9^{a}	0.000	8.4^{a}	7.7^{b}	0.001	9.2	7.6	8.6	6.8	0.459
Chroma (C*)	8.4^{b}	9.2^{a}	0.000	9.7^{a}	7.9^{b}	0.000	10.0	9.4	8.4	7.4	0.283
Hue value (H°)	59.9^{b}	75.5^{a}	0.000	60.1^{b}	75.3^{a}	0.000	66.8^{b}	53.4^{c}	84.3^{a}	66.4^{b}	0.000
Browning index (BI*)	13.0^{a}	12.7^{b}	0.000	15.3^{a}	10.4^{b}	0.000	15.0	15.5	10.4	10.5	0.423
WAI	3.3^{a}	3.2^{b}	0.001	3.9^{a}	2.7^{b}	0.000	3.7	3.9	2.7	2.7	0.456
WSI	0.029^{a}	0.026^{b}	0.040	0.028	0.026	0.154	0.025^{b}	0.032^{a}	0.027^{b}	0.025^{b}	0.024

4.1.5.2 Moisture contents of sorghum flour

Table 4.1.3 shows the moisture content values of flour obtained from sorghum kernels (pre-conditioned (14% moisture content) prior to treatment at varying levels of microwave energy. The moisture contents of flours from microwaved grains were significantly lower ($p < 0.05$) compared to flours from untreated sorghum. With concomitant increasing microwaving energy input to kernels, the moisture contents of the flours decreased gradually resulting in 16.5 % to 24.4 % moisture loss.

4.1.5.3 Fat acidity

Table 4.1.3 presents results for fat acidity of flours from untreated (not conditioned) and microwaved sorghum (pre-conditioned). There was a significant decrease ($p < 0.05$) in fat acidity of flours as the energy level of the microwaving process was increased. A reduction of about 37.8% in fat acidity was observed between 20.1 mg KOH/100 g to 12.5 mgKOH/100 g (Tables 4.1.3). The decrease was more for flours obtained from milled wholegrain (tannin-free) than the decorticated. This is because decortication (extraction rates ≈80-82 % by weight) partially removed the germ from wholegrains, thereby reducing the triglyceride content (released via lipolysis) which may be available for lipid deterioration in the resulting flour (Abdelraham et al., 1983). The extent of decortication can also reduce the susceptibility to oxidative rancidity of cereal flour, thereby potentially increasing the storage stability of flour (Doblado-Maldonado et al., 2012). Highest and lowest fat acidity was recorded in flours from microwaved non-tannin wholegrain sorghum and the decorticated (tannin) grain at 36 kJ and 90 kJ, respectively. Non-tannin (wholegrain) sorghum kernels are potentially more susceptible to fat oxidation than tannin types. This could be that tannin types are rich in phenolic compounds with potential antioxidant tendency than non-tannin types. The antioxidant compounds in tannin types are reportedly to play active roles as lipid stabilizers. The stable radical intermediates of the antioxidant compounds have the ability to prevent the oxidation of unsaturated fatty acids in foods (Devi et al., 2011). A strong correlation was found between the fat acidity and fat contents ($r = 0.56$, $p < 0.05$); and, between fat acidity and antioxidant capacity ($r = 0.71$, $p < 0.05$).

Table 4.1.3 The effect of microwave energy applied to tannin or non-tannin sorghum grains on moisture, and fat acidity of whole and decorticated grain flours (unstored)

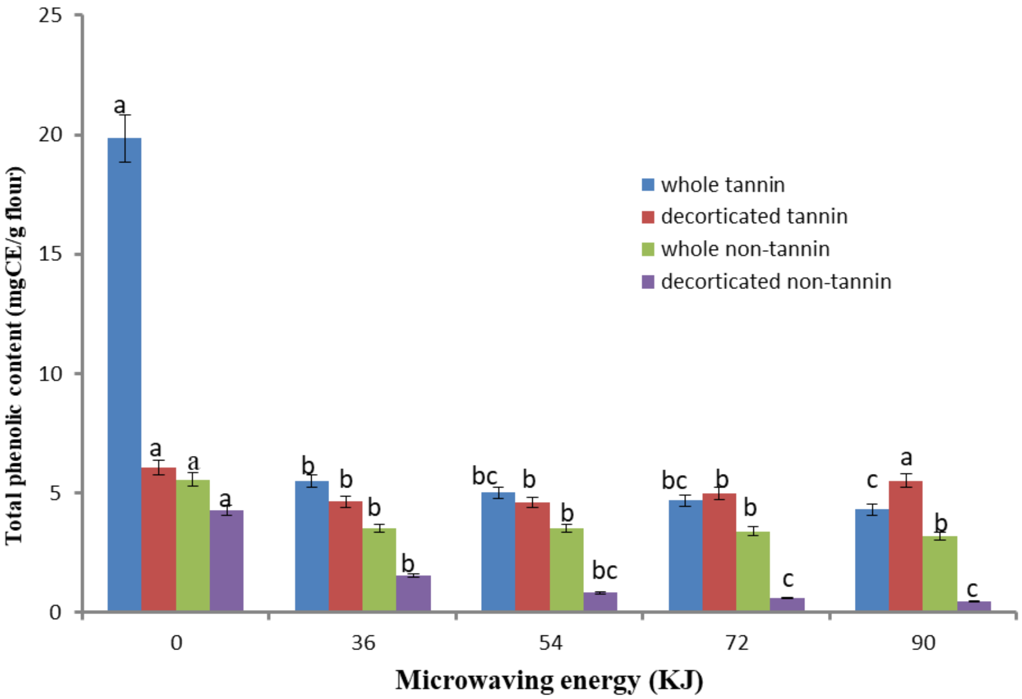
Microwave energy (kJ)	Sorghum type/processing	Moisture (%)	Fat acidity mg KOH/g †
0	Tannin (wholegrain)	9.4(0.1) ^{a}	**19.6(0.3)^{a}**
36		8.9(0.1)^{ab}	19.8(0.3)^{a}
54		8.3(0.1)^{b}	19.6(0.3)^{a}
72		7.6 (0.1)^{c}	17.9(0.2)^{b}
90		7.1(0.1)^{c}	17.3(0.3)^{c}
0	Tannin (decorticated grain)	7.3(0.1)^{b}	**16.6(0.1)^{a}**
36		7.2(0.1)^{a}	15.5(0.1)^{b}
54		7.2(0.1)^{a}	14.9(0.2)^{c}
72		7.2(0.1)^{b}	13.9(0.1)^{d}
90		7.1(0.1)^{b}	12.5(0.2)^{e}
0	Non-tannin (wholegrain)	10.1^{a} (0.2)	**20.1(0.3)^{a}**
36		9.0(0.1)^{b}	20.1(0.2)^{a}
54		8.7(0.1)^{bc}	16.3(0.1)^{b}
72		8.4(0.1)^{cd}	15.9(0.1)^{b}
90		8.1(0.1)^{d}	15.5(0.2)^{b}
0	Non-tannin (decorticated grain)	9.8(0.1)^{a}	**16.4(0.2)^{a}**
36		8.9(0.2)^{b}	15.4(0.1)^{b}
54		8.5(0.2)^{bc}	14.6(0.1)^{c}
72		8.1(0.2)^{cd}	13.9(0.1)^{d}
90		7.6(0.2)^{d}	13.3(0.2)^{e}

For each sorghum type/processing, mean values in columns for different microwave energy levels with different superscripts differ significantly ($p < 0.05$). Results are expressed as the mean ± standard deviation of three replicate determinations. †expressed on a dry weight basis. Flour fat acidity of the respective grains/treated samples at baseline are printed bold

4.1.5.4 Total phenolic content of sorghum flour

There was a decrease in the total phenolic content (TPC) of flour extracts from treated sorghum grains when compared with those from untreated sorghum kernels (Figure 4.1.2). The TPC decreased (19.85-0.47 mgCE/g dry basis) in comparison with the flour from untreated sorghum kernels as the levels of microwaving increased. Also, after microwaving sorghum (36-90 kJ/100 g energy inputs), the TPC of the resulting flours from the decorticated grains showed significant differences ($p < 0.05$) when compared with the treated whole kernels.

The highest TPC (19.85 mg CE/g sample db) was recorded in flour from raw whole tannin sorghum flour. A strong positive correlation between TPC and antioxidant activity (AOA) of flours ($r = 0.87$, $p < 0.05$) was observed (Figure 4.1.2).

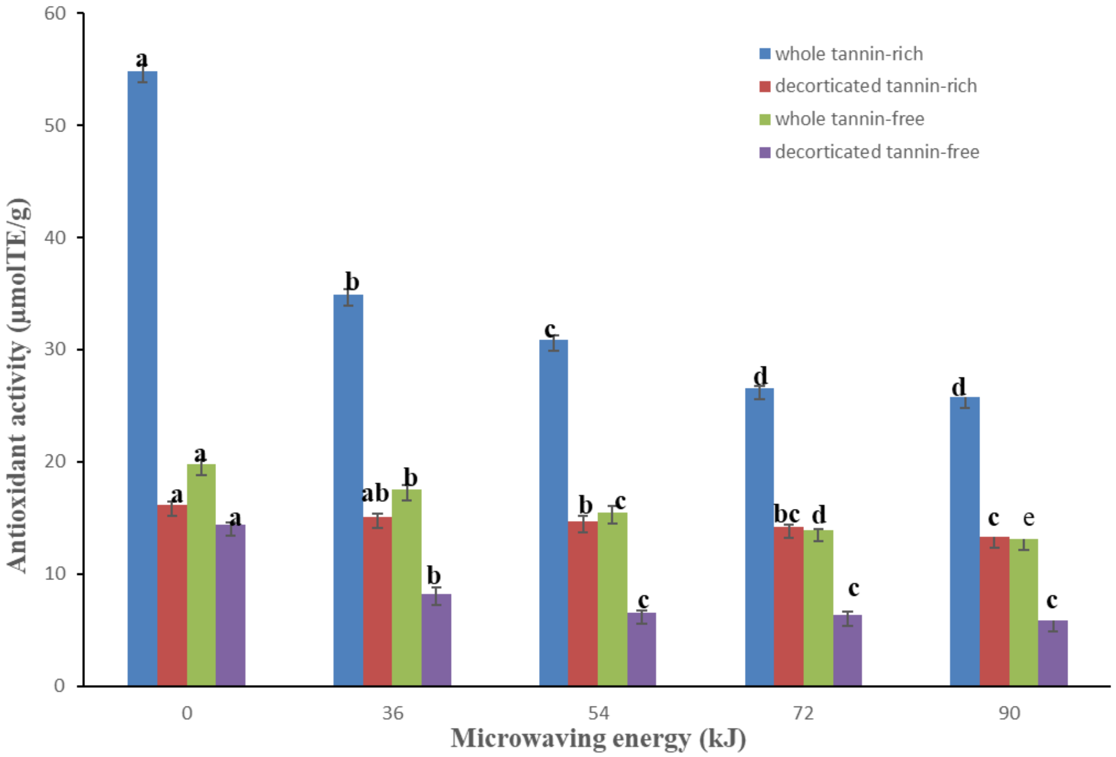


Values for the same colour bars with different letters, differ significantly ($p < 0.05$)

Figure 4.1. 1 Effect of microwave energy applied to tannin or non-tannin sorghum grains on the total phenolic content of whole and decorticated ground flours (unstored)

4.1.5.5 Antioxidant activity

The antioxidant activity (AOA) (expressed in µmol Trolox equivalent, db) of flours obtained from microwaved sorghum kernels in relation to the microwave energy input, is shown in Figure 4.1.2. The AOA of the samples decreased from 54.8 to 5.85 µmolTE/g, as the microwaving energy increased. This decreased further with decortication after the microwave treatment. Trolox equivalent (TE) values of free phenolic extracts were significantly ($p < 0.05$) higher for the untreated samples. Microwaved samples had significantly lower ($p < 0.05$) AOA (5.85-34.9 µmolTE/g) than the untreated samples (14.4-54.8 µmolTE/g). Highest AOA (54.8 µmolTE/g) was recorded in the flour from untreated tannin sorghum grain and lowest (5.85 µmolTE/g) from treated (90 kJ) and decorticated grain (Figure 4.1.2).



Values for the same colour bars with different letters, differ significantly ($p<0.05$)

Figure 4.1.2 Effect of microwave energy inputs to tannin or non-tannin sorghum kernels on the antioxidant activity of whole and decorticated grain flours (unstored)

4.1.5.6 Colour parameters of sorghum flour

The lightness (L*), redness (a*) and yellowness (b*colour values of flours from untreated (control) and microwaved sorghum kernels are presented in Table 4.1.4. It shows the differences in the colour of flours from sorghum grain types treated with varying microwaving energy levels and the flours from untreated sorghum kernels as controls. The L* values decreased while a* and b* values increased minimally with an increase in energy levels of microwaving sorghum kernels when compared to those of the controls in each treatment. The values of ΔE*, C*, H° and BI* for all these samples have been calculated using equations 1 to 4, the results are presented in Fig. 4.1.3. The total colour differences (ΔE*) of flour from untreated and microwaved sorghum kernels increased with increasing microwave energy input when compared to untreated kernels. The hue angle (H*) values of flours varied between 53.4° and 84.6° (Figure 4.1.3).

Table 4.1.4 The effects of microwave energy applied to tannin or non-tannin sorghum kernels on L*, a* and b* values of whole and decorticated grain flours (unstored)

Microwaving energy (kJ)	Sorghum type/processing	*L**	*a**	*b**
0	Tannin (wholegrain)	76.9(0.1)	5.5(0.1)	7.50(0.10)
36		76.3(0.3)	5.6(0.2)	7.55(0.13)
54		76.3(0.2)	5.6(0.1)	7.69(0.11)
72		76.2(0.3)	5.6(0.1)	7.78(0.18)
90		75.7(0.2)	5.7(0.2)	7.82(0.13)
0	Tannin (decorticated grain)	92.2(0.1)^{a}	0.7(0.1)^{c}	6.83(0.12)^{c}
36		92.1(0.3)^{ab}	0.7(0.2)^{c}	7.92(0.16)^{b}
54		91.9(0.1)^{ab}	0.8(0.1)^{bc}	8.20(0.23)^{ab}
72		90.5(0.3)^{b}	0.9(0.2)^{b}	8.54(0.25)^{ab}
90		86.7(0.3)^{c}	2.9(0.1)^{a}	8.78(0.14)^{a}
0	Non-tannin (wholegrain)	83.0(0.4)	3.6(0.2)	8.77(0.19)
36		82.6(0.4)	3.7(0.1)	8.86(0.11)
54		82.5(0.3)	3.8(0.2)	8.89(0.29)
72		82.1(0.1)	3.9(0.2)	8.98(0.13)
90		82.1(0.3)	3.9(0.1)	9.17(0.18)
0	Non-tannin (decorticated grain)	92.4(0.2)	0.7(0.1)	7.92(0.16)^{b}
36		92.1(0.3)	0.7(0.2)	8.20(0.13)^{ab}
54		92.0(0.1)	0.8(0.1)	8.49(0.13)^{ab}
72		91.6(0.3)	0.8(0.1)	8.54(0.15)^{ab}
90		91.6(0.2)	0.9(0.1)	8.77(0.14)^{a}

Results are expressed as a mean of three determinations ± standard deviation. For each sorghum type/processing, mean values in columns for different microwave energy levels with different superscripts differ significantly ($p < 0.05$).

L* indicates the lightness of the colour ranged between 0 (black) and 100 (white), a* indicates colour red (a*), b* indicates colour yellow (b*).

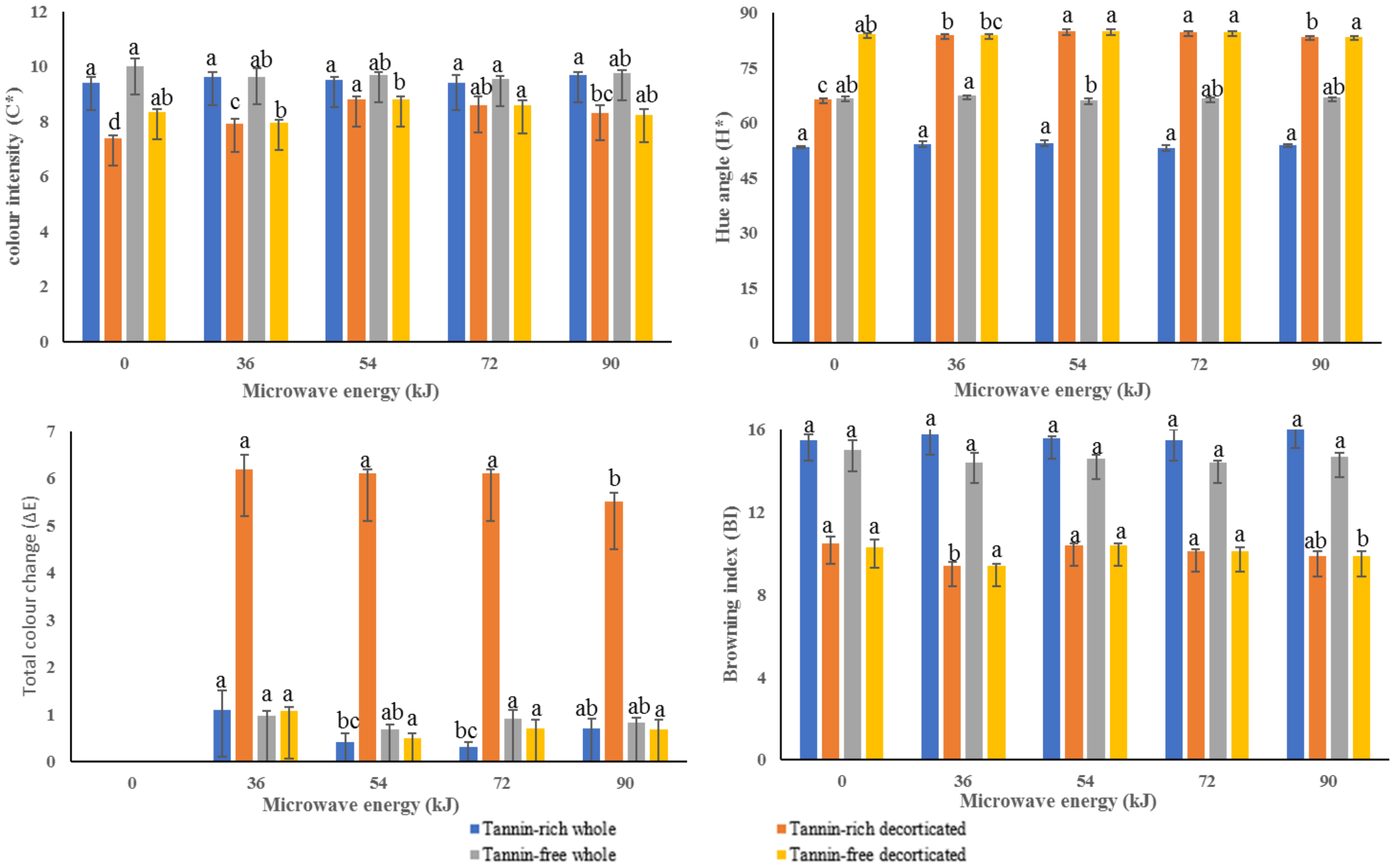


Figure 4.1.3 Effect microwave energy inputs to sorghum grain type (tannin and non-tannin) on colour intensity (a), hue angle (b), total colour change (c) and browning index (d) of whole and decorticated

In each subgraph, bars of the same colour that do not share a letter was significantly different ($p < 0.05$)

Table 4.1.5 Pearson's correlation (r) matrix of physicochemical properties of flours (unstored) from tannin and non-tannin sorghum grains treated at different microwave energy levels (kJ)

Variables	TPC	ABTS	FA	MC	H^o	*BI*
TPC	1.0000					
ABTS	0.8735*	1.0000				
FA	0.4544	0.7072*	1.0000			
MC	0.2411	0.2416	0.5256*	1.0000		
H∘	-0.4711	-0.7694*	-0.7789	-0.0829	1.0000	
BI	0.3662*	0.6700*	0.7642	0.2278	-0.9216	1.0000

*Significant at $p < 0.05$.

TPC = TPC; ABTS = AOA; FA = Fat acidity, MC = moisture content; H^o = Hue angle and BI = Browning index

4.1.5.7 Pasting properties

The pasting characteristics of the flour from untreated (control) and microwaved grains are presented in Figure 4(a-d). However, the viscograms of samples did not show normal clearly defined PV and hot paste viscosity. It was observed that the samples exhibit abnormally shaped pasting curves, such that some basic viscosity values such as breakdown and set back viscosities cannot be easily determined. There is no obvious sharp PV and hot paste viscosity (Fig 4.1.4) in the profiles of sorghum flour during pasting. Despite this, PV values for sorghum flour ranged between 805 and 1230 mPa.s, while FV ranged from 922 to 1786 mPa.s. Significant decreases ($p < 0.05$) in both PV and FV were noticed with increasing microwave energy input (Fig 4.1.4). Flour from decorticated grain exhibited PV and FV values of 1143 and 1786 mPa.s, after 12 and 22 min respectively, higher than the corresponding wholegrain flours (respective as 896 and 1364 mPa.s).

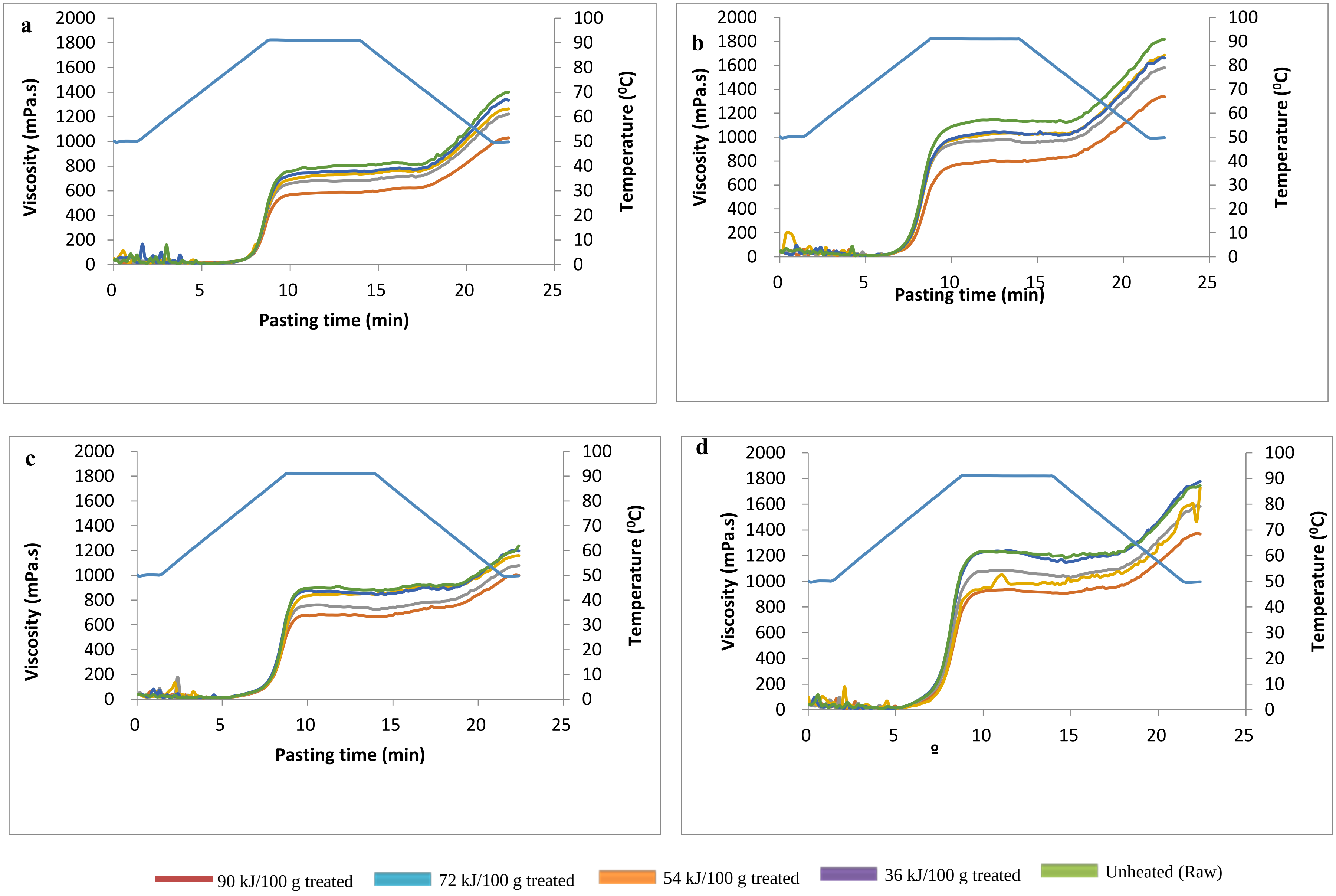


Figure 4.1.4 Pasting curves of flours from (a) whole grain non-tannin, (b) decorticated non-tannin, (c) whole tannin and (d) decorticated tannin sorghum grains treated at different levels of microwave energy (kJ)

4.1.5.8 Water absorption index and water solubility index of sorghum flour

The hydration properties of flour from unheated and microwave-heat treated kernels are reported in terms of water absorption index (WAI) and water solubility index (WSI) and shown in Tables 4.1.6. Microwaving tannin sorghum had impact ($p < 0.05$) on WAI of both whole and decorticated grain flours but not with non-tannin sorghum type ($p > 0.05$) both whole and decorticated grain flours. The effect of microwave heat treatments of sorghum grains on WSI of flours was only significant ($p < 0.05$) in flour of whole grain tannin.

Table 4.1.6 Effect of microwave energy level on water absorption and solubility indexes of whole and decorticated sorghum flour types

		Water absorption index		
Microwaving energy (kJ)	**Wholegrain tannin**	**Decorticated tannin**	**Wholegrain Non-tannin**	**Decorticated Non-tannin**
0	3.91(0.01)^{a}	2.68(0.08^{a}	3.66(0.05)	2.67(0.51)
36	3.78(0.05)^{ab}	2.49(0.05)^{b}	3.38(0.11)	2.44(0.23)
54	3.77(0.08)^{bc}	2.41(0.02)^{bc}	3.30(0.12)	2.23(0.16)
72	3.69(0.05)^{bc}	2.36(0.10)^{bc}	3.24(0.31)	2.09(0.03)
90	3.64(0.05)^{c}	2.27(0.07)^{c}	3.13(0.25)	2.06(0.06)
		Water solubility index		
0	0.032 (0.002)^{a}	0.025 (0.003)	0.025 (0.004)	0.027 (0.003)
36	0.031 (0.001)^{ab}	0.024 (0.002)	0.025 (0.003$^{)}$	0.026 (0.004)
54	0.029 (0.001)^{abc}	0.024 (0.002)	0.025 (0.002$^{)}$	0.024 (0.002)
72	0.028 (0.001)^{bc}	0.022 (0.002)	0.025 (0.002$^{)}$	0.022 (0.003)
90	0.026 (0.000)^{c}	0.022 (0.001)	0.026 (0.004)	0.021 (0.003)

Results are expressed as a mean of three determinations ± standard deviation. For each sorghum type/flour form, mean values in columns for different microwave energy levels with different superscripts differ significantly ($p < 0.05$).

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4.1.5.9 Microscopy

Figure 4.1.5 are micrographs of iodine-stained flours (wholegrain and decorticated) from microwave-heat treated and not microwave sorghum grains. Starch granules from unheated controls were smaller compared to the microwaved samples. The starch granules separately bind with the iodine. With increasing microwave energy (36 kJ/100 g, 54 kJ/100 g, 72 kJ/100 g and 90 kJ/100 g) in both wholegrain and decorticated flours, the starch granular size decreased. The native starch granules (0 kJ) presented distinct, characteristic Maltese crosses. Microwave heat treatment caused pre-gelatinization of the starch granules showing a loss of birefringence when viewed with a light microscope under polarized light. The extent of birefringence in flours from microwave-heated grains decreased with an increase in microwave energy inputs. More starch granules were gelatinized as the microwave energy inputs increased. Flours of decorticated samples show more loss of birefringence than wholegrain flours, indicating more pre-gelatinization of starch in the decorticated flours.

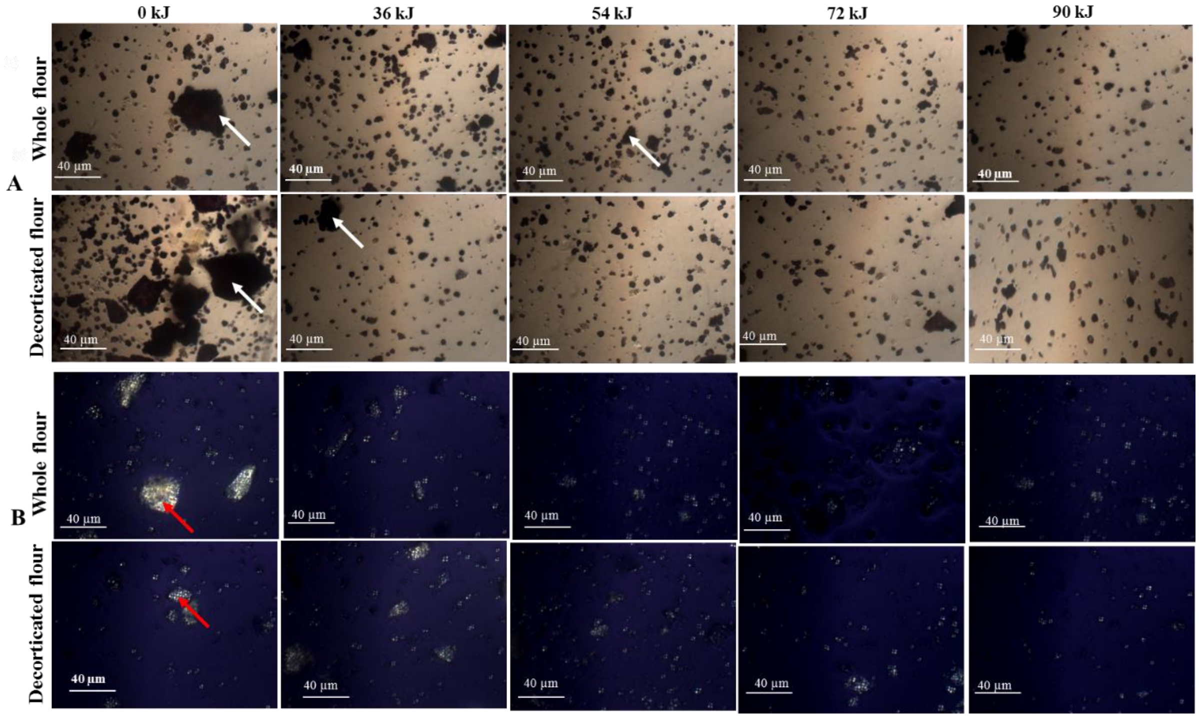

Figure 4.1.5 Photomicrographs of iodine-stained sorghum flours from microwave-heat treated (36 kJ/100 g, 54 kJ/100 g, 72 kJ/100 g and 90 kJ/100 g) and control (0 kJ) grains viewed under polarized light.

Bar = 40 µm. White arrows indicate iodine-stained starch granules and red arrows show ungelatinized starch granules with birefringence respectively.

A = iodine-stained flours (wholegrain and decorticated) from microwave-heat treated and not microwave sorghum grains viewed under non-polarized light. **B** = iodine-stained flours (wholegrain and decorticated) from microwave-heat treated and not microwave sorghum grains viewed under polarized light.

4.1.6 Discussion

Low moisture content (7-9 %) of flours of microwave-treated samples can be attributed to flash evaporation of moisture occurring during the heating process (Sumnu, Sahin, & Sevimli, 2005). In microwave treatment, heat generated by dipole molecular movements within the food matrix results in drastic reduction in moisture content of the samples. During microwaving of kernels, large amounts of interior heat probably created interior pressure and concentration gradients which increased the flow of liquid through the grains to the boundaries allowing for moisture loss. The pressure driving moisture migration during the heating process could have resulted in a high drying rate leading to lower moisture content (Dronachari & Yadev, 2015). In addition, microwaves being a volumetric heat process (from inside out) causing uniform heating throughout the sorghum kernels may have led to quick adsorption of energy by water molecules causing rapid evaporation of water resulting in a high drying rate for sorghum grain (Kubra, Kumar & Rao 2016). The moisture content of the flour is very critical to its stability, the lower the flour moisture, the better its storage stability. Nasir et al. (2003) suggested moisture contents ranging between 9 and 10 % are suitable for stable storage and longer shelf life of wheat flour because within that range fungi growth is impossible. The moisture loss after heating is desirable because microbial and enzymatic activities are reduced due to lower water activity, hence potentially extending the shelf life of flour (Akinola, Badejo, Osundahunsi, & Edema, 2017). However, the loss in weight can incur an economic loss.

The decrease in fat acidity possibly indicates that flour obtained from the heated kernels showed less lipase activity (Keying et al., 2009). Also, decrease in flour fat acidity may be attributed to the inactivation of lipase enzymes due to microwave heating. Lipase enzymes are associated with the degradation of triglycerides to free fatty acids (Meera et al., 2011).

The result agreed with the findings of Sharanagat et al. (2019) where L* values reduced (83.1-50.6) by nearly 40 % for microwave-roasted (600 W, 5-10 min) sorghum kernel flours. Decortication of the grains is probably responsible for the higher *L** values compared to the wholegrain flours because the testa layer was removed by decortication, increasing the lightness of decorticated flours. Awika, Rooney, and Waniska (2005) had reported increase lightness (*L** value) in the non-pigmented sorghum flour after decortication. The trend in colour changes because of microwaving was more apparent with the C* and H° values. Conversion of the L, a, b readings to the total colour difference (ΔE^*), hue angle (H^*), chroma (C^*) and browning index (BI) have been hypothesized to provide a more realistic assessment of likely perception of the food colour by the consumers (Pathare et al., 2013). The H° decreased only slightly with increasing microwave energy input, which may be an indication that the flours did not lose their original colour. The BI* shows the purity of brown colour and it has been reported as an important parameter in food processing particularly where enzymatic and non-enzymatic browning reactions take place (Demirhan & Özbek, 2015). Chandrasekaran et al. (2013) explained that the cold air surrounding the food product does not promote Maillard browning reaction.

Microwave heat treatment of sorghum kernels caused a reduction in TPC of flour. A similar decrease in TPC was reported by Zhang and Liu (2010) for microwave-heated buckwheat flour. Different mechanisms and explanations responsible for the reduction in TPC for microwave-heat treatment have been reported. It could be due to thermal degradation of heat-susceptible and or free phenolic compounds during microwaving (Chandrasekaran et al. (2013). The latter compounds could have possibly leached from the cell walls to form complexes with the macromolecules such as proteins in the endosperm and hence, their extractability decreased (Taylor & Duodu, 2015). In addition, oxidation of phenolics and depolymerization of high molecular weight phenolics such as condensed tannins were reported to cause a decrease in TPC (Taylor & Duodu, 2015). Similarly, during heating, the phenolic hydroxyl groups may have reacted, or formed insoluble complexes with food components (such as proteins) or even polymerized into condensed phenolics resulting in a decrease of assayable phenolic hydroxyl groups.

The antioxidant activity (AOA) determined as Trolox Equivalent (TE) values of free phenolic extracts were lower in flour from treated than raw grain. An indication that phenolic contents from the flour of raw sorghum grains were probably higher than those from treated grains. The AOA value (54 µmolTE/g) recorded in the present study for unheated tannin whole grain sorghum flour was lower than the range reported for sorghums (89 µmolTE/g – 240 µmolTE/g) by Awika, McDonough and Rooney, 2005). This may be ascribed to the effect of microwave energy inputs on the grains and/or removal of brans or pericarp (Taylor & Duodu, 2015). More so, the AOA of flour extracts from tannin whole and decorticated grains decreased with increasing exposure to microwave energy, indicating that the treatment, sorghum type and decortication/ dehulling may be critical factors affecting TE values (Figure 4.1.3). The implication of this finding is that a substantial amount of the phenols in sorghum kernels reside in the outer cover and that the antioxidant effect of the phenolics is lost due to decortication (Dlamini et al., 2007), rather than through the microwaving process. However, Sharma and Gujral (2011) found that a decrease in the TPC was inversely related to the total AOA during dry heating of barley. The positive correlation between TPC and AOA (Table 4.1.3) provides further evidence that the predominant contributor to AOA is the phenolic compounds (de Morais Cardoso et al., 2014). Awika et al. (2003) observed a similarly strong correlation ($r = 0.97$, $p < 0.05$) between AOA of sorghum grains and their phenolic content using the TE antioxidant activity and Folin-Ciocalteu methods, respectively.

Microwaving of sorghum kernels caused a decrease in the PV and final viscosity (FV) of flour during pasting. Reduction of PV may be associated with an increase of inter- and intramolecular hydrogen bonding due to association of starch chains during microwaving of sorghum kernels (Luo, He, Fu, Luo, & Gao, 2006). Elsewhere, it was reported that microwaving grains caused the breakdown of the starch granules into low-molecular-weight units (Mukisa et al., 2012). This action possibly weakened the starch granules due to the damage of the starch content. The reduction in the PV suggests that breakdown of the starch granular structure possibly decreases the water uptake and reduces the ability of starch in the flour to swell (Luo et al., 2006). In addition, partial gelatinization of the starch granules during microwaving, may affect the ability of starch granules to absorb water (Marston et al., 2016). However, the reduction in FV could be related to the formation of amylose-lipid complexes because amylose chains would not be any longer available for recrystallization (Gaying et al., 2016). The formation of amylose-lipid complexes could have inhibited swelling of starch granules and consequently reduce the FV due to less water uptake by the starch (Wokadala et al., 2012). The presence of other components such as fat and proteins could be associated with a lower viscosity in wholegrain flours, preventing possible ingress of water by the starch granules (Bolade et al., 2002). This could be because exposure of the hydrophobic site of denatured protein due to heating possibly cause the proteins to repel water from starch granules thereby resulting in low viscosity during pasting (Ogundele, Minnaar, & Emmambux, 2017). However, upon decortication of treated grains, the peak and final viscosities of flour during pasting were higher when compared to those of their respective wholegrain flours. This implies that the decortication process of sorghum grains prior to flour milling possibly improved the peak and final viscosities of the flour pastes. The FV obtained after stirring could be an indicator of the stability of the cooked paste in actual use. This may imply that samples (grains treated with 90 kJ/100g energy level) with lower FV values than the control could be less stable to retrogradation.

Lower WAI of flours was observed when microwaving energy was applied to kernels. The WAI is associated with the presence of hydrophilic groups and on the ability of the resultant gel formed from the macromolecules (Qu et al., 2017). It could be that microwaves create porous and ruptured starch microstructure with potential to efficiently hold moisture inside it (Singh & Adedeji, 2017). Also, most hydrophilic groups or gelling agent substances like pectin might have leaked owing to the microstructure breakage likely caused by the microwaves (Singh & Gujral, 2019). This effect can be due to the loose association between amylose and amylopectin in the raw sample starch granules and the weak binding forces that keep the structure of starch granules (Luo et al., 2006). Decrease in WSI of the flours from microwave-heated kernels may be attributed to the reduction in small fragments of amylopectin or amylose that may have leached out through opened starch granules of the flour (Wu et al., 2016). The WSI determines the number of free polysaccharides from the starch granules on the addition of excess water (Oikonomou & Krokida, 2011) which probably reflect the macromolecular breakdown of starch. Meera et al. (2011) studied the effects of heat treatment of sorghum grains on storage stability of flour and found that the decrease in WSI could be an indication that lesser amounts of water-soluble substances remained in the flour.

The reduction in birefringence of starch was likely due to microwave heating. After microwave heat treatment for 36 kJ/100 g, the Maltese cross of starch granules showed slight changes. This suggests that the radial arrangement of the chain axis of the starch granules is possibly influenced by the microwave energy. More of starch granules lost birefringence after microwaving for 90 kJ/100 g. This implies that the microwave energy vibrates the water molecules present in the crystalline regions of the starch granules thereby destroying the lamella arrangement of the amylopectin crystals.

4.1.7 Conclusion

Microwaving of sorghum grains at 900 W for different time periods did not change the lightness and colour intensity of the flours but led to reductions in the PV during pasting. However, moisture contents and fat acidity of the flour is reduced. High TPC and improvement in the AOA of flour from tannin sorghum grain was noted. Microwaving of sorghum grain before milling to flour could be recommended to prepare energy dense and low viscosity porridges suitable for weaning diets due to a reduction in the PV of the flour paste. Low moisture, reduction in the fat acidity and higher AOA due to microwave treatment of grains, have the potential to improve the stability of the flour during storage. The effects of using the two extremes of the microwave energy inputs for sorghum (non-tannin type) on the storage stability of flour should be evaluated in the next phase of the study. This can be based on sensory characteristics of the porridge prepared from stored flour over a time period.

4.2 Stabilization of wholegrain sorghum flour and consequent potential improvement of food product sensory quality by microwave treatment of the kernels

4.2.1 Abstract

Wholegrain sorghum flour (WGF) is sensitive to rancid off-flavour development during storage. Microwave treatment of whole grain kernels (WGK) at 36 kJ/100 g and 90 kJ/100 g using a pilot-scale commercial microwave oven was investigated as a flour stabilization technology. WGF from the microwaved and untreated WGK was then subjected to an accelerated storage test at 50 °C for 6 weeks. The effects of microwaving WGK on various quality parameters of the stored flour and the texture, colour and descriptive sensory characteristics of porridge prepared from flour were investigated. Both microwave energy levels resulted in a substantial reduction in the flour fat acidity (50.1-21.1 mgKOH/100g) and anisidine (80-35 *p*-anisidine units) value throughout storage; the higher level being more effective. Sensory indications of porridge rancidity were identified less intensely and much later during flour storage for microwave-treated samples. These data indicate that the microwave treatment partially inactivated the flour lipases and consequently retarded free fatty acid oxidation. The WGK microwave treatment had no substantial adverse effects on other flour and porridge attributes. Microwave treatment of WGK could thus be an effective, practical technology to stabilize WGF and thereby enhance its food product quality.

Keywords: microwave treatment, wholegrain, sorghum flour, storage stability, sensory attributes

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4.2.2 Introduction

Sorghum is a staple food grain for nearly 500 million people in sub-Saharan Africa and Asia (ICRISAT, 2018). Whole grain sorghum products (e.g., porridges, bread and cookies) are a source of bioactive compounds with promising potential for reducing the risk of diet-related diseases such as obesity and diabetes (de Morais et al., 2017). Trends show a renewed consumer interest in alternative 'ancient grains' including sorghum as alternatives to the common cereals such as wheat and maize in food products (Awika, 2017). However, despite the health-related benefits linked to wholegrain sorghum, there are some challenges of using wholegrain sorghum flour in food products. Notably, the flour deteriorates rapidly, limiting the shelf life of the flour (Meera et al., 2011). Generally, wholegrain flour is much higher in lipids and has higher lipase activity than refined flour (Doblado-Maldonado et al., 2012). The fat content in wholegrain sorghum is typically 3.2-3.9 g/100 g and the fat contain 88% unsaturated fatty acids (Chhikara et al., 2018). Hence, its fat is sensitive to deterioration by lipolysis and oxidative rancidity (Meera et al., 2011). Short shelf life and unpleasant sensory attributes are major factors limiting wholegrain flour utilization (Heiniö et al., 2016). Processing of whole grain kernels and storage of the flour often result in lipid deterioration, which is responsible for bitter taste and rancid flavours (McGorrin, 2019). Two interlinked processes are responsible: 1. FFA from triglycerides are released via lipolysis by the action of lipase enzymes (Meera et al., 2011); 2. Lipid oxidation, involving reaction of the unsaturated fatty acids with molecular oxygen, results in the production of volatile carbonyl compounds (Doblado-Maldonado et al., 2012). Since the first step in sorghum flour lipid degradation is generally the development of hydrolytic rancidity by lipase action, inactivation of lipase may be a potent strategy to prevent food product rejection.

Studies have demonstrated the effectiveness of various treatments to stabilize wholegrain cereal flours, including hot air (Nantanga et al., 2008), hydrothermal treatment (Yadav et al., 2012), and superheated steam (Hu, Wang, & Li, 2018). However, these treatments are of limited application due to their high energy requirements. It is therefore imperative to find technologies that can maintain or improve the shelf life and nutritional properties of whole-grain flour that are not energy intensive. With microwave technology, the heating mechanism involves the efficient absorption of energy from the microwave field, which results in rapid and volumetric heating of the water and/or fat in the food materials (Keying et al., 2009). Microwave technology has been investigated to inactivate lipase in oat and wheat kernels (Keying et al., 2009), in whole rice (Zhong et al., 2013), and wheat kernels (Qu et al., 2017). Microwave treatment also reduced the production of FFA during storage and consequently stabilized the flours against lipid oxidation. Conversely, microwave roasting (temperatures not stated) has been found to change the colour of sorghum wholegrain sorghum kernels from light brown to dark brown and reduce flour peak, paste and breakdown viscosity (Sharanagat et al., 2019). However, until now, the application of microwave treatment to sorghum kernels to stabilize the fat in the flour has not been studied.

Therefore, this study investigated microwave treatment of wholegrain sorghum kernels as a potential strategy for stabilization of sorghum flour, with the aim of improving flour storage stability and its products' sensory attributes. The whole grain flour was subjected to an accelerated storage test at elevated temperature and evaluated for indicators of lipolytic and oxidative rancidity during storage. Porridges prepared from the flours were used as a simple food vehicle to evaluate whether the flour had been stabilized without damaging its functionality.

4.2.3 Materials and methods

A process diagram of the study is given in Figure 4.2.1

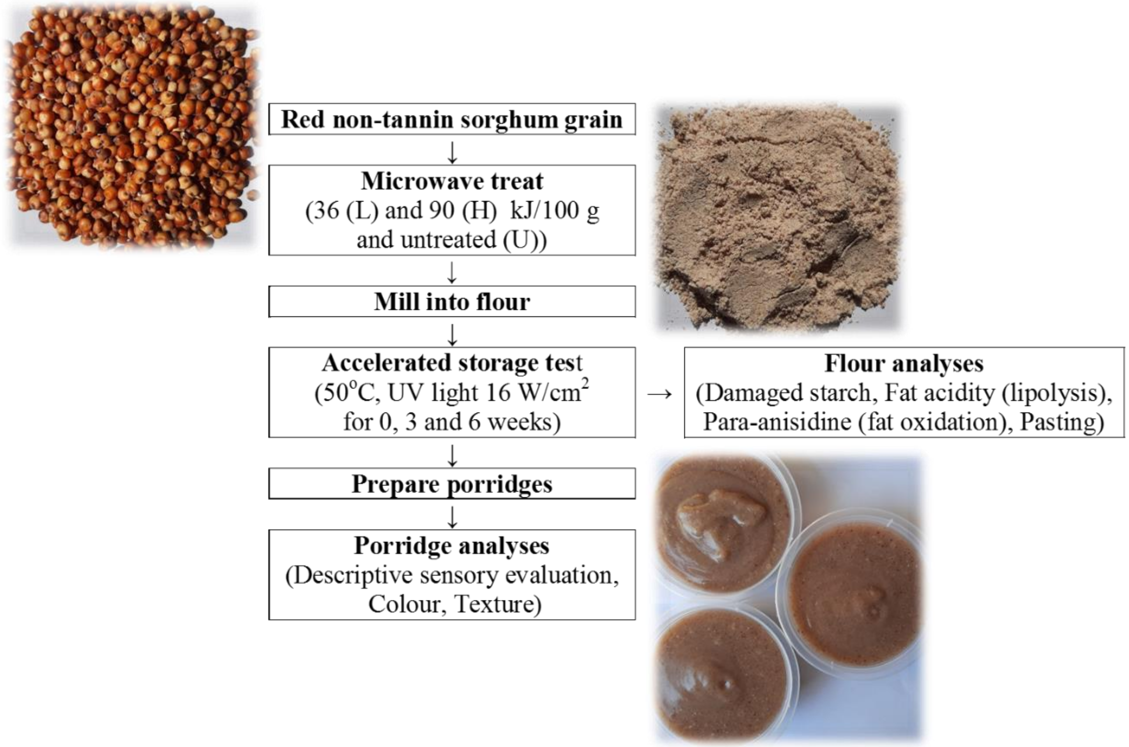

Figure 4.2.1 Process diagram for microwave treatment of the sorghum whole grain kernels, flour accelerated storage and analysis of the flours and their porridges

4.2.3.1 Materials

Red non-tannin sorghum grain (a blend of cultivars primarily PAN 8816) with a moisture content of 10.1±0.2 %, protein content of 10.3±0.1 % (N x 6.25) (dry basis) and fat content of 3.5±0.1 % (dry basis) was used.

4.2.3.2 Methods

4.2.3.2.1 Microwave treatment of wholegrain sorghum kernels, milling and flour storage

The kernels were conditioned to 14% moisture and microwave-treated in open containers at four energy levels from 36 kJ/100 g to 90 kJ/100 g sorghum, using a pilot-scale commercial microwave oven (Delphius Commercial and Industrial Technologies, Centurion, South Africa). All the microwave treatments substantially reduced stored flour fat acidity. Flours from the minimum (36 kJ/100 g) and maximum (90 kJ/100 g) treatments were selected for further evaluation and were designated as low (L) and high (H) microwave energy treatments. The untreated control was designated U. The temperatures of the L and H treated kernels, measured immediately after heating using a Fluke 62 mini non-contact infrared thermometer (Wantitall, Linbro Park, South Africa), were 54.6±2 ºC and 125±1 ºC, respectively. A laboratory hammer mill (Falling Number Laboratory Mill 3100, Perten Instruments, Hägersten, Sweden) fitted with a 500 µm mesh screen was used to mill the grains (500 g) to flour. Milled samples (250 g) were packaged in zip lock-type polyethylene bags and subjected to an accelerated storage test at 50ºC, (UV light-16 W/cm^2) for up to 6 weeks. At weekly intervals, flour samples were transferred to storage at –20 ºC until analyzed.

4.2.3.2.2 Porridge preparation

Soft porridges were prepared as described by Kayitesi, Duodu, Minnaar and de Kock, (2010). A slurry of 200 ml cold water (25±2 ºC) and 80 g flour was made in a plastic cup. The slurry was carefully and completely added to 600 ml boiling water in a stainless-steel saucepan, with continuous stirring using a plastic paddle to prevent lump formation. After which, the porridge was simmered at low gas heat for 20 min with stirring at 5 min intervals.

4.2.3.2.3 Training of the descriptive sensory panel

A descriptive sensory panel (2 males and 8 females), experienced in porridge sensory analysis, evaluated the samples. Ethical approval was granted by the Ethics Committee of the University of Pretoria (EC approval 180000119). The panel was trained for 10 h using the generic descriptive evaluation method (Lawless & Heymann, 2010). In the training, each panelist received porridges from flours stored for various periods and identified words used to describe the differences in sensory properties. From the training sessions, descriptors, definitions and scale anchors were developed for evaluation of the porridges (Table 4.2.1). The panel was also trained on the evaluation procedures and use of the data capture software, Compusense Cloud version 7.8.2 (Compusense, Guelph, Ontario, Canada).

4.2.3.2.4 Analyses

All parameters were determined at least at 0, 3- and 6-weeks flour storage.

4.2.3.2.4.1 Flour fat rancidity

Lipids were extracted from flour samples using petroleum ether (boiling point, 40-60 ºC). Fat acidity was analyzed by acid-base titration according to AACC Method 02-02A (AACC, 2000). Lipid oxidation was analyzed in terms of anisidine value according to ISO Standard method ISO 6885 (ISO, 2008).

4.2.3.2.4.2 Flour damaged starch content

Flour damaged starch content was measured using a SD-matic® instrument (Chopin Technologies, Villeneuve-la-Garenne Cedex, France), which measures iodine absorption amperometrically. Results were expressed in UCD (Unité Chop Dubois) units.

4.2.3.2.4.3 Flour pasting properties

The pasting properties were measured using an Anton Paar Physica MCR 301 rheometer (Ostfildern, Germany) as described in chapter 4.1 section 4.1.3.2.7

4.2.3.2.4.4 Instrument colour analysis of the porridge

The colour of porridge samples was measured using a tristimulus colorimeter (CR-400 Chroma Meter, Konica Minolta Sensing, Osaka, Japan) as described by Kayitesi et al. (2010). Colour was expressed in terms of lightness ($L*$), red/green ($a*$) and blue/yellow characteristics ($b*$) after standardization with a white tile supplied by the manufacturer. The difference in $L*$, $a*$ and $b*$ (Equations 1–3) values over the storage time compared to the baseline untreated control (U_0) were calculated:

$$\Delta L* = L* - L_{U0} \qquad (1)$$

$$\Delta a* = a* - a_{U0} \qquad (2)$$

$$\Delta b^* = b^* - b_{U0} \qquad (3)$$

Where L_{U0}, a_{U0}, b_{U0} are colour component values of the untreated control U at week 0. Total colour difference (ΔE) between the test porridges and the U_0 control was calculated as:

$$\Delta E = [(\Delta L^*)^2 + (\Delta a^*)^2 + (\Delta b^*)^2]^{1/2}$$

4.2.3.2.4.5 Instrumental texture analysis of the porridge

The texture parameters were measured using a texture analyser (EZL-Test EZL, Shimadzu, Kyoto, Japan) with a flat cylindrical Perspex probe (20 mm diameter). Porridge (15 ml) was filled into a sample tube (30 mm diameter), covered with aluminium foil and held at 50 ºC for 90 min. Test measurement of porridge started after removing the foil cover and scraping off the surface layer of the porridge. With the tube firmly placed centrally on the flat mantle position of the texture analyzer, the test cycle started immediately, and the force-time curve was recorded. The test parameters were pre-test speed of 2 mm/s; test speed at 2 mm/s; the post-test speed at 10 mm/s; sample penetration depth at 5 mm; trigger type was auto -0.01 N. Firmness and stickiness values were extrapolated from the curve. Porridge firmness, the maximum force obtained as the probe penetrated the porridge and porridge stickiness, the maximum force recorded as the probe withdrew from the porridge, was determined.

4.2.3.2.4.6 Descriptive sensory evaluation of the porridge

The porridges to be evaluated were kept warm in a bain-marie set at 50 ºC. Porridge samples (~ 40 g) were served in glass ramekins covered with aluminium foil. The porridge samples were kept warm on a table-top warmer at 50 ºC. Blind-coded samples were presented to panellists in a randomized order within a session. Porridge evaluation was conducted in sensory booths (University of Pretoria Sensory Evaluation Laboratory) equipped with desktop computers for direct data collection using Compusense Cloud. Panellists evaluated samples in duplicate (2 replicate sessions), during a 2 h session (three times a week) over two weeks. Within a session, seven samples were presented (one at a time), on a white tray, with a stainless teaspoon, and a serviette. Filtered water was provided to cleanse and refresh the mouth between each porridge sample evaluation. The panel evaluated 36 descriptors grouped under aroma, taste/flavour, texture and aftertaste attributes (Table 4.2.1). Short sniffs immediately after removing the aluminium cover on the ramekins, were employed to evaluate aroma. Then, a teaspoon full of the porridge was chewed in the mouth to evaluate flavour and texture. The aftertaste was evaluated after swallowing the porridge. A structured line scale with ten demarcated points was used to measure the intensity of each attribute. The minimum value was 0 (not intense) and the maximum value was 10 (very intense).

Table 4.2.1 Sensory descriptors and evaluation guidelines used by the trained descriptive sensory panel to evaluate sorghum porridges

Descriptors	Definition	Reference	Rating scale (0, 10)
Aroma			
Overall	The intensity of the overall aroma of the porridge	No reference	Not intense, Very intense
Earthy	The intensity of the aroma associated with damp soil	Damp soil = 10	Not earthy, Very earthy
Sweet	The intensity of sweet aromatic associated with the aroma of sweet-smelling honey or ripened fruit	Hullett's golden syrup = 10	Not sweet, Very sweet
Roasted nut	The intensity of the aroma of toasted peanuts	Roasted peanut = 10	Not nutty, Very nutty
Burnt	The intensity of the aroma of blackened burned sugar	Sugar caramel = 10	Not intense, Very intense
Sorghum	The intensity of the aroma of cooked sorghum	Cooked sorghum = 10	Not intense, Very intense
Wet cardboard	The intensity of the aroma of wet cardboard	Wet cardboard = 10	Not intense, Very intense
Starchy	The intensity of the aroma of under-cooked maize porridge	35 g/100 g ACE maize meal in boiling water = 10	Not starchy, Very starchy
Oily	The intensity of the aroma of cooking oil in the porridge	Fresh sunflower oil = 10	Not oily, Very oily
Painty	The intensity of an oxidized oil aroma similar to linseed oil or oil-based paint	Oxidized oil = 10	Not intense, very intense
Rancid	The intensity of the aroma of old used cooking oil	Overused sunflower oil = 10	Not rancid, Very rancid
Fermented	The intensity of the aroma of sorghum beer	Sorghum beer (*Umkhomboti*) = 10	Not intense, Very intense
Wheaty	The intensity of the aroma associated with milled wheat	Whole wheat grain = 10	Not intense, Very intense
Cooked maize meal porridge	The intensity of the aroma of cooked maize porridge	Cooked maize ACE porridge (12% solid) = 9	Not intense, Very intense
Fruity	The intensity of the aroma associated with fruit cocktail juice	Filtered water = 0 Fruit cocktail juice = 10	Not fruity, Very fruity
Spicy	The intensity of the aroma of nutmeg powder	Nutmeg spice powder = 10	Not spicy, Very spicy
Grassy	The intensity of the green slightly sweet aroma of fresh-cut grass	Fresh cut grass = 10	Not grassy, Very grassy
Appearance			
Brown colour	The degree to which the porridge appears brown	Chocolate milk = 10	Not brown, Very brown
Specks	The presence of visible particles in the porridge	Cooked sorghum porridge = 7	No speck, Many specks
Viscosity	The thickness of porridge when it is stirred with a spoon	Filtered water = 0 Hullett's golden syrup = 10	Not viscous, Very viscous
Glossy	The shine or gloss on the surface of the porridge	Egg white = 10	Not glossy, Very glossy
Sticky	How the spoon adheres to the porridge when stirring	10 g/100 g high-quality cassava flour in boiling water = 10	Not sticky, Very sticky
Taste and Flavour			
Bitter taste	The intensity of a bitter taste associated with caffeine or quinine	0.15% caffeine in water = 10	Not bitter, Very bitter
Sour taste	The intensity of a sour taste associated with citric acid	0.08% citric acid in water = 10	Not sour, Very sour

Sweet taste	The intensity of a sweet taste associate with sucrose	2 % sugar in water = 5	Not sweet, Very sweet
Starch flavour	The intensity of the flavour of under-cooked maize porridge	35 g/100 g ACE maize meal in boiling water = 10	Not starchy, Very starchy
Bland flavour	No aromatic or flavour perceived	No reference	Not bland, Very bland
Mouthfeel/ Texture			
Stickiness	Force required to remove porridge adhering to teeth and palate while eating	10g/100g high-quality cassava flour in boiling water = 10	Not sticky, Very sticky
Grainy	The degree of grittiness or graininess in the porridge as a result of small particles		Not grainy, Very grainy
Astringent	The puckering sensation on the tongue and other mouth surfaces	Strong black tea = 10	Not astringent, Very astringent
Aftertaste			
Bitter	The lingering of a bitter taste after swallowing the porridge	0.15% caffeine in water = 7	Not bitter, Very bitter
Oily	Perception of the presence of cooking oil in the porridge	Fresh sunflower oil = 10	Not oily, Very oily
Rancid	Perception of the presence of old cooking oil in the porridge	Overused sunflower oil = 10	Not rancid, Very rancid
Sour	The intensity of a sour taste associated with citric acid	0.08% citric acid in water = 10	Not sour, Very sour
Sweet	The intensity of sweet taste of which sucrose is typical	2 % sucrose in water = 5	Not sweet, Very sweet
Residual particles	The presence of particles left in the mouth after swallowing	Cooked sorghum porridge (Monati super mabele) = 7	Not intense, Very intense

4.2.4 Statistical analyses

All data were collected in triplicate, except for the sensory evaluation data which was in duplicate. Two-way analysis of variance based on $p < 0.05$ significant level was used to test the main effects and interaction effect of independent (microwaving treatments at 2 levels and storage periods at 7 levels) on dependent variables (sensory attributes, PV, colour parameters, firmness and stickiness of porridge). Fisher's least significant difference (LSD) test was used to separate means. Linear regression analysis was used to show the relationship between PV of flour pastes and storage period. Sensory attributes that described significant differences among porridges were analysed by principal component analysis. XLSTAT® software package (Addinsoft^{TM}, New York) was used for all analyses.

4.2.5 Results

4.2.5.1 Flour characteristics

4.2.5.1.1 Flour fat acidity

At baseline (week 0) prior to storage, the fat acidity of the flour of untreated (U) wholegrain sorghum kernels was significantly higher ($p < 0.05$), by nearly 50 % compared to flours of microwave-treated at 36 kJ/100 g (L) and 90 kJ/100 g (H) WGK (Fig. 4.2.1). The fat acidity of flour from U WGK also increased significantly more during the 6-week storage compared to the L and H flours. Similarly, the *p*AV of U flour was significantly higher at week 0 than the L and H treatment flours and increased more during the storage period (Figure 4.2.2).

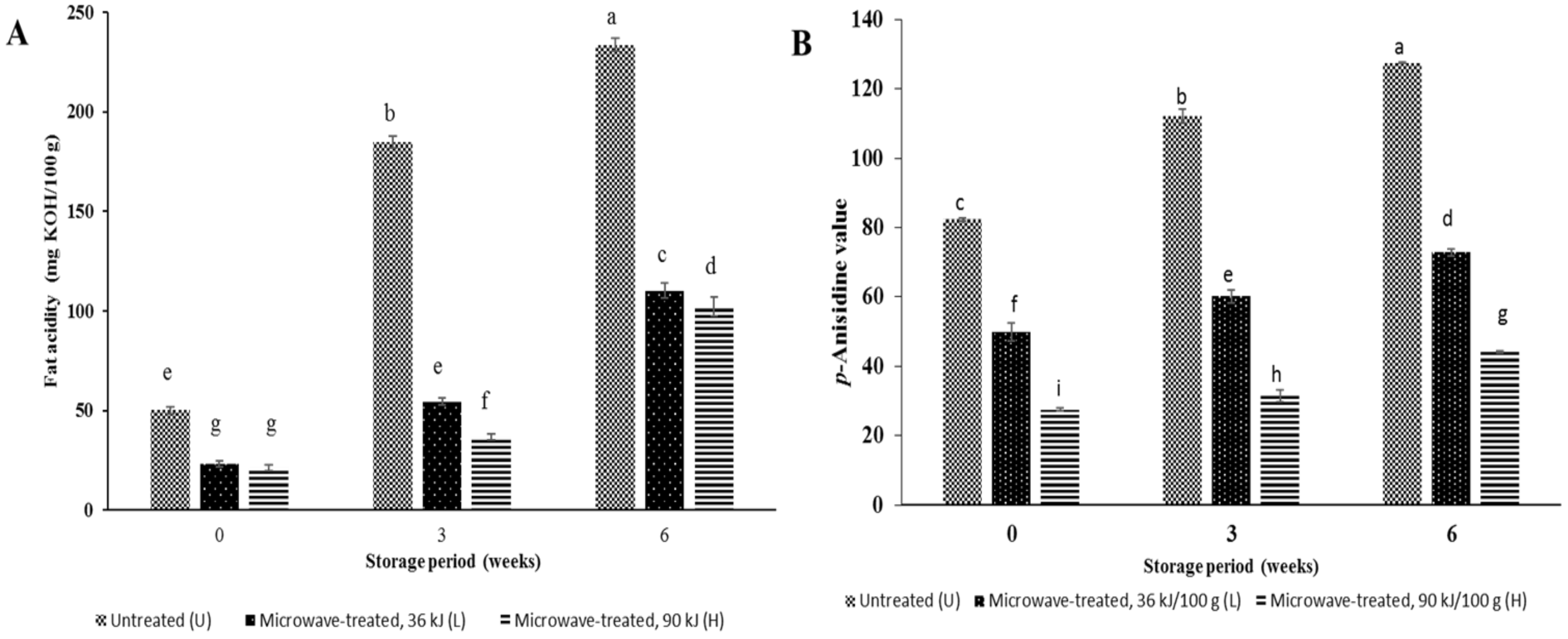

Figure 4.2.2 Effects of microwave heat treatments of wholegrain sorghum kernels on the (A) fat acidity and (B) *p*-anisidine values

Values with different letters are significantly different ($p < 0.05$).

4.2.5.1.2 Flour damaged starch content

Microwave treatment of WGK resulted in more damaged starch in the flours (Figure 4.2.3). At flour storage baseline, the damaged starch content of L and H was nearly twice that of untreated. However, damaged starch in the U had increased by 6 weeks storage but was still significantly lower than L and H.

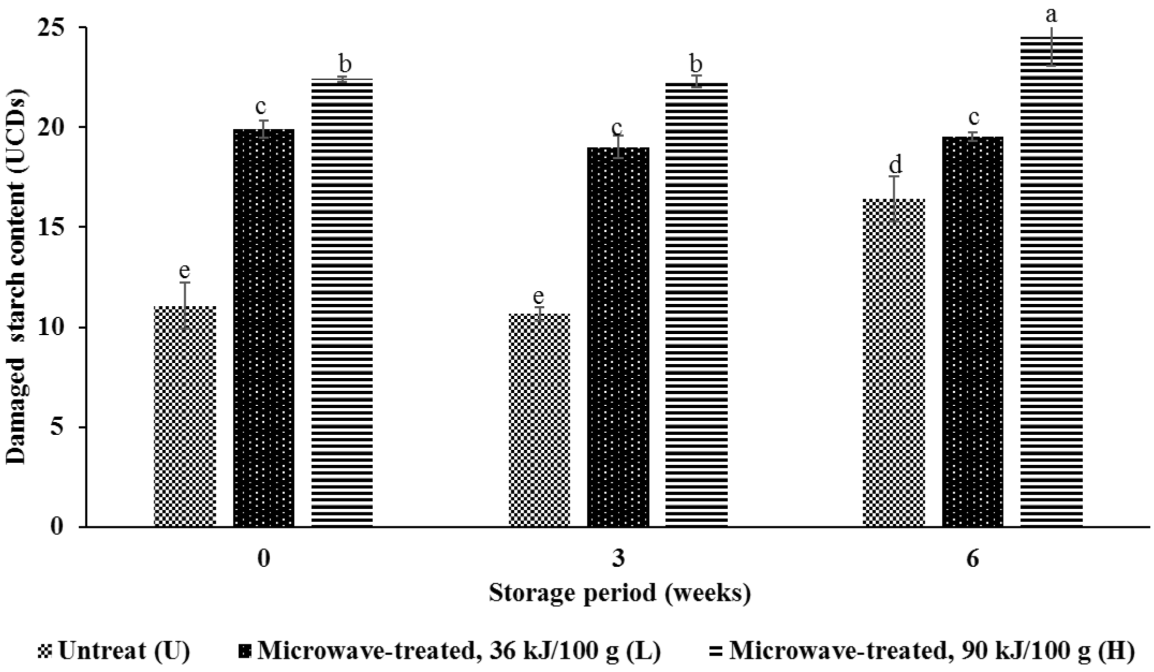

Figure 4.2.3 Effects of microwave treatments of wholegrain sorghum kernels on the damaged starch content of stored flours.

Values with different letters are significantly different ($p < 0.05$).

4.2.5.1.3 Flour paste viscosity

At storage baseline and throughout the storage period, the PV of flour pastes from U was significantly higher than those of L and H (Figure 4.2.4). With storage, the PV of all the flour pastes decreased but the PV of U remained the lowest.

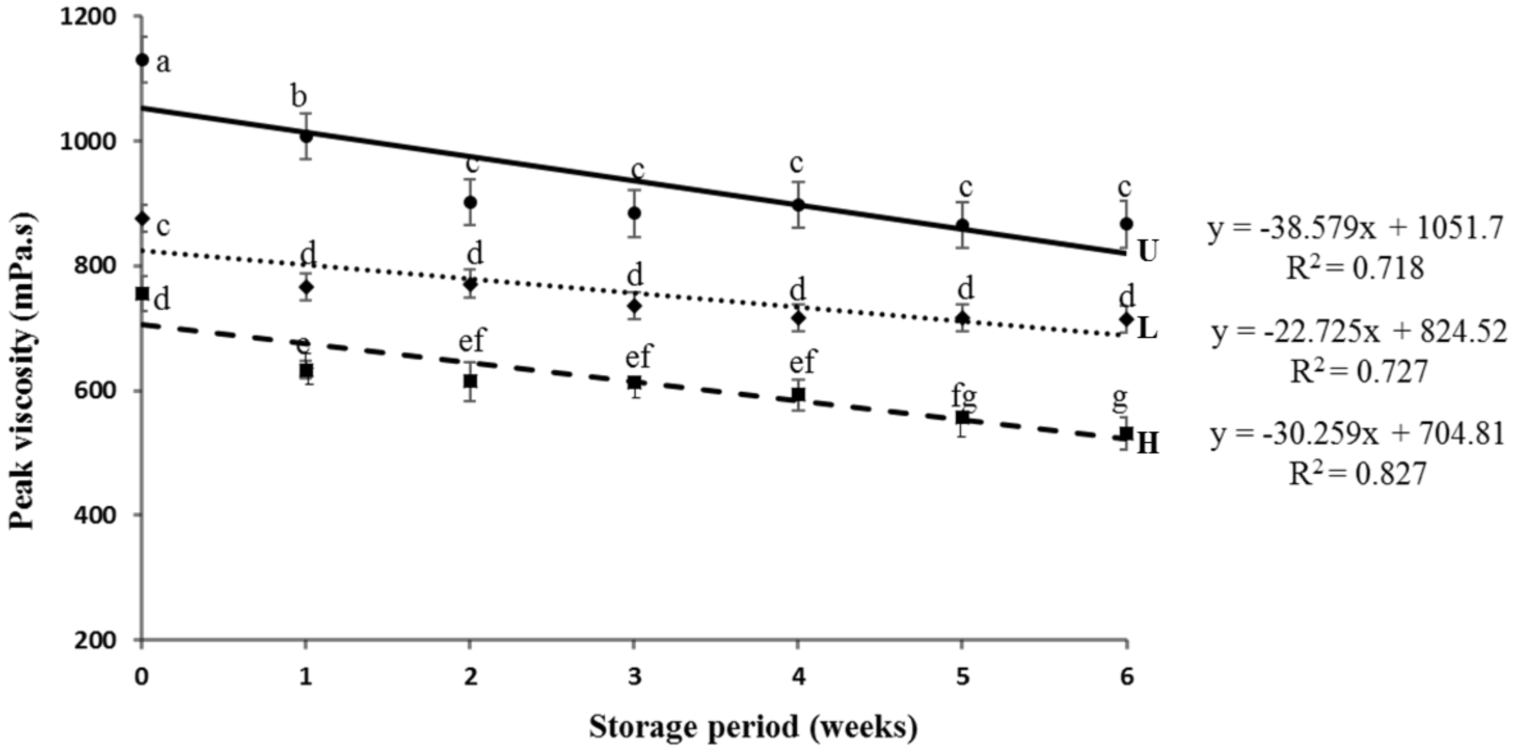

Figure 4.2.4 Effects of microwave heat treatments of wholegrain sorghum kernels on the Pasting viscosity (PV) of stored flours.

Values with different letters are significantly different ($p < 0.05$).

U = Untreated, L = Microwave treated, 36 kJ/100 g, H = Microwave treated, 90 kJ/100 g

4.2.5.2 Porridge characteristics

4.2.5.2.1 Instrumental colour analysis of the porridge

Microwave treatment of WGK affected the instrumental colour parameters of the porridges (Table 4.2.2). At flour storage baseline, lightness (L* value) of H porridge was slightly, but significantly lower ($p < 0.05$) than that of U and L porridges. Porridge L* values were also generally consistently lower for the H treatment over the storage period and its *b** values decreased with flour storage time. For the U and L treatments, porridge *a** and *b** values decreased substantially. Also, with the U treatment, porridges from flours stored for 3-4 weeks gave slightly elevated L* values. The total colour difference (ΔE*) between the test porridges and the U baseline control ranged between 0.45 and 2.36. This is because ΔE* values at baseline and during storage are < 3.0 for porridges of flour samples. The total colour differences between porridges form treated and untreated kernel flours probably showed that colour changes are neither obvious nor appreciative by the human eye (Baixauli et al., 2008). This suggests that microwave treatment and storage conditions have little pr no effect on ΔE* values of porridge.

Table 4.2.2 Effects of microwave treatments of non-tannin sorghum kernels and storage on colour parameters (L*, a*, b*, ΔE*) of porridges prepared from the sorghum flours

Treatment	Storage period (weeks)	Colour parameters			
		L*	***a****	***b****	**ΔE***
Untreated (U)	0	78.6(0.2)^{bcde}	4.6(0.1)^{a}	12.9(0.2)^{a}	0.0
	1	78.5(0.2)^{cde}	4.6(0.1)^{a}	12.9(0.3)^{a}	0.45
	2	78.5(0.3)^{cde}	4.3b(0.1)^{cdef}	11.4(0.2)^{defg}	1.31
	3	80.2(0.8)^{a}	4.2(0.1)^{defg}	10.8(0.2)^{hij}	1.94
	4	80.2(0.2)^{a}	4.5(0.1)^{abc}	11.1(0.3)^{fgh}	0.83
	5	79.1(0.6)^{bcd}	4.0(0.1)^{ghi}	10.3(0.2$^{)k}$	1.30
	6	79.3(0.9)^{bcd}	4.0(0.4)^{ghi}	11.7(0.9)^{de}	1.97
Microwaving, 36 kJ/100 g (L)	0	77.9(0.5)^{efgh}	4.6(0.2)^{a}	12.6(0.2)^{a}	0.00
	1	78.3(0.3)^{ef}	4.1(0.2)^{fhg}	10.9(0.2)^{hi}	1.85
	2	77.4 (0.4)^{hijk}	4.3(0.1)^{defg}	11.5(0.2)^{defg}	1.12
	3	79.1(0.9)^{bc}	4.3(0.1)^{defg}	11.0(0.3)^{gh}	1.89
	4	78.4(0.3)^{def}	4.1(0.1)^{gh}	10.4(0.4)^{jk}	1.31
	5	78.1(0.2)^{efg}	4.2(0.3)^{efg}	10.5(0.2)^{ijk}	0.68
	6	78.4(0.7)^{def}	3.8(0.1)^{i}	11.9(0.4)^{cd}	1.68
Microwaving, 90kJ/100 g (H)	0	77.2(0.5)^{ijk}	4.9 (0.2)^{a}	12.7(0.3)^{ab}	0.00
	1	77.1(0.5)^{jk}	4.4(0.2)^{bcde}	11.5(0.4)^{def}	1.36
	2	76.8(0.3)^{kl}	4.4(0.1)^{bcde}	12.3(0.3)^{bc}	1.07
	3	77.8(0.5)^{fghl}	4.4(0.2)^{abcde}	12.9(0.6)^{a}	1.42
	4	77.6(0.4)^{ghij}	4.2(0.2)^{efg}	11.3(0.2)^{efgh}	1.75
	5	76.1(1.1)^{l}	4.3(0.2)^{cdef}	12.6(0.9)^{ab}	2.36
	6	77.0(0.6)^{jk}	3.9(0.1)^{h}i	13.1(0.1)^{a}	1.69
	p-value	< 0.0001	< 0.0001	< 0.0001	< 0.0001

Values are the means of triplicate determinations. Standard deviations are in parentheses. Superscript with different letter(s) within the same column differ significantly ($p < 0.05$). *L** is lightness (0 = black, 100 = white); *a** is red; *b** is yellow. ΔE* is the total colour difference between the test porridges and the U baseline control

4.2.5.2. Instrumental texture analysis of the porridge

Firmness and stickiness of the porridges were not different at flour storage baseline (prior to storage, i.e., week 0). The severity of microwave treatment did not affect both the firmness and stickiness of the porridges of flour at week 0. With flour storage, porridge firmness decreased, while stickiness increased gradually with all three treatments (U, L and H) (Figure 4.2.5). Generally, the porridges from the L and H microwave treated flours were slightly more firm and stickier than the U controls.

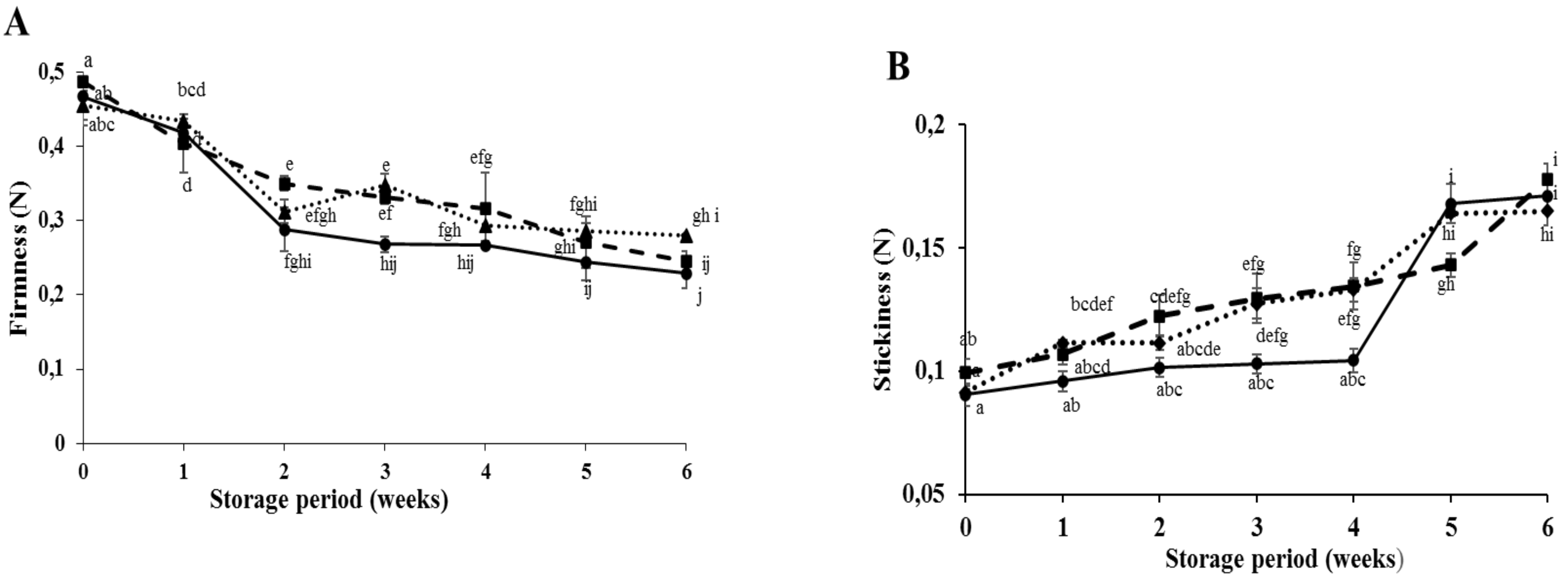

Figure 4.2.5 Effects of microwave treatments of wholegrain sorghum kernels on the (A) firmness and (B) stickiness of porridges from stored flours

Values with different letters are significantly different ($p < 0.05$)

Circles solid line = Untreated (U), Diamonds dotted line = Microwave treated 36 kJ/100 g (L), Squares dashed line = Microwaved treated 90 kJ/100 g (H).

4.2.5.2.3 Descriptive sensory evaluation of porridge

The 36-sorghum porridge sensory descriptors and their definitions and rating scales that were developed and used by the panellists (n = 10) comprised aroma, appearance, taste/flavour, mouthfeel/texture and aftertaste attributes (Table 4.2.1). With baseline stored flours, microwave treatments did not impact on any these attributes, other than significantly intensifying the bland flavour ($p < 0.05$) of the porridges (Table 4.2.3). Hence, no difference in the brown colour of porridges prepared from U, L and H flours was detected by the descriptive sensory panel (n = 10). This is in slight contrast to the instrumental L* value (lightness) of porridge prepared from U flour, which was slightly higher than that of H (Table 4.2.2).

Table 4.2.3 Descriptive sensory ratings of porridges from wholegrain sorghum flours at baseline storage (week 0) from untreated (U0) and microwave treated (L0) and (H0) kernels

	Sensory attributes	**Untreated (U_0)**	**Microwave treatment**		**p-values**
			36 kJ/100 g (L_0)	**90 kJ/100 g (H_0)**	
Aroma	Overall	6.7(2.4)	6.7(1.4)	6.6(2.4)	0.994
	Earthy	3.5(2.9)	3.6(2.0)	3.0(2.9)	0.734
	Sweet	3.1(3.0)	4.5(3.1)	2.3(2.5)	0.070
	Roasted	2.7(2.7)	3.8(2.9)	2.2(2.3)	0.191
	Burnt	1.5(2.1)	1.0(1.6)	0.9(1.4)	0.494
	Sorghum	5.3(2.5)	6.6(2.0)	5.8(2.9)	0.271
	Wet cardboardy	2.6(2.7)	2.1(2.5)	2.6(3.0)	0.771
	Starchy	4.6(3.0)	3.5(2.9)	2.9(3.0)	0.208
	Oily	2.3(1.9)	1.9(2.0)	1.3(2.1)	0.311
	Painty	2.3(2.6)	0.9(1.0)	1.6(2.2)	0.141
	Rancid	1.7(1.7)	1.6(2.0)	1.0(2.0)	0.412
	Fermented	2.9(2.2)	2.1(2.4)	1.4(2.0)	0.146
	Wheaty	3.3(3.3)	3.2(3.3)	2.8(2.6)	0.856
	Cooked maize meal porridge	2.2(3.7)	1.2(1.4)	1.7(1.5)	0.214
	Fruity	1.4(3.1)	2.8(3.0)	1.0(1.9)	0.070
	Spicy	1.0(1.4)	0.7(1.0)	0.5(0.9)	0.291
	Grassy	1.3(2.0)	1.8(2.2)	1.9(2.3)	0.699
Appearance	Brown colour	7.6(3.9)	7.4(2.4)	7.5(2.1)	0.976
	Specks	6.0(3.2)	6.5(2.7)	7.0(2.7)	0.600
	Viscosity	6.9(2.1)	7.9(1.8)	7.8(1.3)	0.161
	Glossy	7.8(1.7)	8.2(1.5)	8.2(1.7)	0.686
	Sticky	5.5(2.3)	5.3 (2.2)	5.5(2.6)	0.956
Taste/flavour	Bitter taste	2.3(2.2)	1.5(2.3)	1.8(2.6)	0.589
	Sour taste	1.6(2.0)	1.4(2.1)	1.6(2.5)	0.934
	Sweet taste	1.6(2.2)	1.4(1.9)	1.2(2.2)	0.846
	Starch flavour	4.8(3.0)	3.4(2.8)	3.7(3.1)	0.280
	Bland flavour	**4.7(2.9)^b**	**6.6(1.8)^a**	**6.4(2.1)^a**	**0.002**
Mouthfeel/texture	Stickiness	3.2(2.5)	2.4(2.2)	2.6(2.4)	0.555
	Grainy	4.8(2.7)	4.2(2.7)	4.0(3.2)	0.650
	Astringent	4.0(2.2)	3.2(2.1)	2.8(2.4)	0.239
Aftertaste	Bitter	1.5(1.3)	1.4(2.2)	1.9(2.6)	0.717
	Oily	1.3(1.9)	1.9(2.0)	1.3(1.8)	0.349
	Rancid	1.5(2.2)	1.2(2.2)	1.3(2.2)	0.905
	Sour	1.6(1.7)	1.0(1.8)	1.2(2.3)	0.725
	Sweet	0.9(2.0)	1.2(1.0)	0.9(1.7)	0.796
	Residual particles	3.5(2.8)	3.4(2.7)	2.8(3.3)	0.788

Values are the means of duplicate determinations. Standard deviations are in parentheses. The definition and rating scale (0 = Not intense/present; 10 = Very intense/present) of attributes are shown in Table 4.3.1. Attribute printed in bold indicates a significant difference among treatments ($p < 0.05$). Values within the same row followed by different letters differ significantly ($p < 0.05$).

Table 4.2.4 presents the significant changes ($p < 0.05$) in sensory attributes (oily, painty, rancid and fermented aromas, and bland flavour) of porridges from flours stored for 6 weeks. There were significant increases in the intensity of oily, painty, rancid and fermented aromas for porridge of U with flour storage time. There was no significant effect of flour storage time ($p \geq 0.05$) on these attributes with the H treatment and only a significant increase in painty aroma with the L treatment. Interestingly, the perception of differences in the porridges made from stored flours was detected as aroma by smelling yet not in the mouth during consumption.

Table 4.2.4 Effects of microwave treatments (L and H) of wholegrain sorghum kernels on sensory attributes* of porridges prepared from stored whole grain flours

Treatment	**Storage period (weeks)**	**Sensory attributes**				
		Oily aroma	**Painty aroma**	**Rancid aroma**	**Fermented aroma**	**Bland flavour**
Untreated (U)	0	2.3(1.8)^{ef}	2.3(2.6)^{cde}	1.7(1.1)^{cde}	2.9(2.0)^{de}	4.7(2.9)^{f}
	1	2.5(1.7)^{ef}	2.1(1.8)^{def}	1.2(2.6)^{def}	3.0(2.6)^{cd}	4.7(2.9)^{ef}
	2	3.4(2.0)^{de}	1.3(2.3)^{defg}	1.7(2.5)^{cde}	2.7(3.1)^{de}	6.1(2.8)^{abcdef}
	3	4.8(1.8)^{cd}	1.8(1.6)^{defg}	1.7(2.4)^{cde}	2.5(2.5)^{de}	5.5(3.1)^{bcdef}
	4	5.4(1.4)^{bc}	4.6(2.3)^{b}	4.3(2.4)^{b}	4.7(1.7)^{b}	6.3(2.5)^{abcde}
	5	6.9(1.4)^{b}	7.2(1.6)^{a}	6.2(1.8)^{a}	7.4(1.6)^{a}	6.3(2.1)^{abcde}
	6	8.5(1.1)^{a}	7.7(1.4)^{a}	7.3(1.1)^{a}	7.3(1.7)^{a}	5.4(2.6)^{cdef}
Microwaved, 36 kJ/100 g (L)	0	1.9(1.9)^{ef}	0.9(1.0)^{fg}	1.6(1.9)^{cdef}	2.1(2.6)^{de}	6.6(1.7)^{abc}
	1	2.8(2.9)^{ef}	1.9(2.9)^{defg}	1.0(1.3)^{ef}	1.7(0.9)^{de}	7.1(1.6)^{ab}
	2	1.9(1.9)^{ef}	0.8(1.0)^{g}	0.8(0.6)^{ef}	2.3(2.7)^{de}	5.3(2.6)^{cdef}
	3	2.4(3.1)^{ef}	1.8(2.7)^{defg}	1.4(2.9)^{def}	2.1(2.3)^{de}	5.9(2.6)^{bcdef}
	4	2.2(3.0)^{ef}	0.8(1.3)^{g}	0.3(0.5)^{f}	2.3(2.4)^{de}	5.0(2.6)^{def}
	5	3.2(2.7)^{e}	2.5(2.4)^{cd}	2.9(3.0)^{c}	2.8(2.3)^{de}	5.4(2.6)^{cdef}
	6	2.8(2.3)^{ef}	3.5(1.8)^{bc}	4.3(1.9)^{b}	4.5(1.9)^{bc}	6.0(2.4)^{abcdef}
Microwaved, 90 kJ/100 g (H)	0	1.3(2.0)^{f}	1.5(2.1)^{defg}	1.0(1.9)^{ef}	1.4(1.9)^{e}	6.4(2.0)^{abcd}
	1	2.5(2.6)^{ef}	1.5(2.0)^{defg}	1.7(2.8)^{cde}	2.9(2.9)^{de}	7.6(1.0)^{a}
	2	1.9(2.0)^{ef}	1.0(1.6)^{efg}	1.0(1.9)^{ef}	2.0(2.1)^{de}	5.9(2.4)^{bcdef}
	3	2.3(2.9)^{ef}	1.2(1.8)^{defg}	1.3(2.4)^{def}	2.1(3.0)^{de}	5.6(2.9)^{bcdef}
	4	2.1(2.8)^{ef}	1.5(2.6)^{defg}	1.5(2.4)^{def}	1.9(2.5)^{de}	6.4(2.4)^{abcd}
	5	2.0(2.7)^{ef}	0.9(2.1)^{fg}	1.1(2.4)^{def}	2.5(2.8)^{de}	5.2(2.8)^{cdef}
	6	2.6(2.7)^{ef}	1.0(1.3)^{efg}	2.4(2.1)^{cd}	1.9(2.5)^{de}	5.1(3.2)^{cdef}
	p-value	< 0.0001	< 0.0001	< 0.0001	< 0.0001	0.008

Values are the means of duplicate determinations. Standard deviations are in parentheses. Superscripts with a different letter (s) within the same column differ significantly ($p < 0.05$). The definition and rating scale (0 = Not intense/present; 10 = Very intense/present) of attributes are shown in Table 4.2.1.

*Note only sensory attributes that describe significant differences ($p < 0.05$) for the interaction effect (treatment x storage) among the porridge samples are presented.

Figure 4.2.6 shows Principal Component Analysis (PCA) plots of the first two principal components, with a score plot (A) for the porridges prepared from flours stored for six weeks and a loading plot (B) of the attributes. The plots provide a visual summary of the changes in the sensory properties of porridges from stored flours, with the inclusion of all attributes that were significant as either main or interaction effects. The PCA plot explained 65.3 % of the sensory variation among the porridges. PC1 (48.2% of the variation) clearly separates the L and H treatments that are on the left from the U treatment (U_2-U_6) on the right (A). These porridges on the right of the plot had more oily, painty, rancid and fermented aromas and were more bitter (B). These fat oxidation-indicating indices were significantly and very strongly positively correlated ($0.96< r >0.89$; $p < 0.05$) with each other and to some extent with bitter taste and aftertaste ($0.81<r >0.51$; $p < 0.05$). They were strongly ($-0.80< r >-0.64$; $p <0.05$) negatively correlated with viscosity and glossy appearance and generally weakly correlated ($r<-0.40$; $p < 0.05$) with sweet aroma and brown colour of the porridges. Porridges of L and H flours were darker in colour with sweeter aroma. The brown colour and sweet aroma were positively correlated ($r = 0.45$; $p < 0.05$). The score plot shows that the sensory properties of the porridges from U (U_0 to U_6) deteriorated with time of flour storage. PC2 adds an additional 17% to the explanation of the variation among the porridge samples. It separated the stickier porridges from baseline stored flour (H_0, L_0 and U_0) at the bottom of the plot, from the porridges from stored flours at the top, which were more grainy with residual particles

The changes in porridge sensory attributes with flour storage time were much more pronounced with U treatment than with the L, with the least changes with the H treatment. The shelf life of sorghum flour stored at 50 °C (UV light 16 W/cm^2 for 6 weeks) is therefore predicted as 3 weeks for the U control, 4 weeks for microwave-treated L and more than 6 weeks for H treatment.

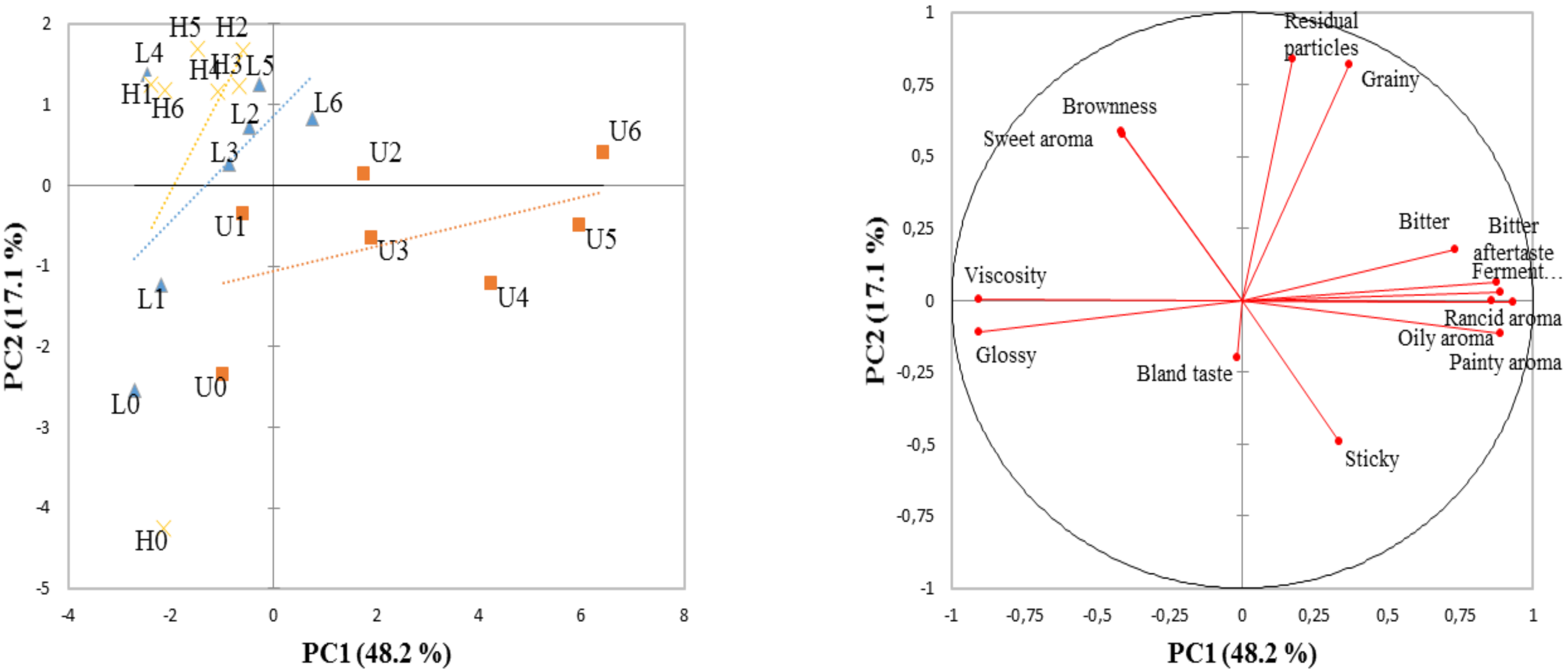

Figure 4.2.6 Principal component analysis (PCA) score (A) and loading (B) plots of the sensory attributes of porridges prepared from the flours of untreated and microwave treated wholegrain sorghum kernels stored for up to 6 weeks.

U = Untreated, L = Microwave treated, 36 kJ/100 g, H = Microwave treated, 90 kJ/100 g, 0 - 6 = Weeks of flour storage.

The dotted trend lines on the score plot show the rate of porridge attribute change with flour storage period.

4.2.6 Discussion

The much lower fat acidity of L and H flours over storage compared to U (Untreated/not microwaved) (Figure 4.2.2) shows that the microwave treatments largely inactivated the lipase in the WGK. However, microwave treatment of WGK at 90 kJ/100 g (H) was more effective at reducing fat acidity than at 36 kJ/100 g (L). This is probably due to more effective thermal inactivation of lipase and possibly lipoxygenase (Zhao, Xiong, Qiu, & Xu, 2007). However, the fat acidity of all flours increased with storage, which may have been because of incomplete inactivation of the lipase by the microwave treatments rather than thermal non-enzymic hydrolysis (Nantanga et al., 2008).

The flours from WGK microwave treatments had much lower pAVs over storage compared to the flours from U (Not microwaved) WGK (Figure 4.3.2). Moreover, intense oily, painty, rancid and fermented aromas were associated with the porridges of stored flour from U but not those from L and H treated flours, except for L week 6 storage (L_6) (Figure 4.2.6). Such unpleasant aromas are usually associated with oxidized foods and are due to the formation of volatile secondary products by unsaturated fatty acid oxidation (Duizer & Walker, 2016). The painty aroma could, for example, be attributed to the presence of pentanal, hexanal and heptanal (Steele, 2004). Nantanga et al. (2008) similarly observed an absence of unpleasant aroma in porridges made from flour from thermally treated pearl millet grains and attributed this to the inactivation of lipase prior to milling the grains.

Additionally, Maillard reaction products formed during heating presumably possess antioxidant properties, which may inhibit lipid oxidation (Martins, Jongen, & Van Boekel, 2001). The bland flavour of the L and H treatment porridges (Figure 4.2.6) could have been as a result of the wholegrain sorghum kernels microwave heat treatment releasing some of the characteristic flavours formed. Porridge with bland flavour could be positively appreciated, especially by consumers that dislike sorghum-type flavours.

The higher level of damaged starch in the flours of the L and H treated WGK (Figure 4.2.3) is attributable to thermal effects of microwave heating. Microwave treatment can disrupt the intermolecular forces between the starch and proteins and thereby increasing the content of damaged starch (Qu et al., 2017).

Firmness and stickiness are important sensory attributes of sorghum porridge from the consumer point of view (Aboubacar et al., 1999). It is probable that the significantly lower PV of the flour pastes from L and H treated WGK than from U (Figure 4.2.4), as was also found by Sharanagat et al. (2019) with microwave roasting sorghum WGK that heated grain flours displayed lower PV that the unheated. This was probably primarily a result of the thermal damage to the starch (Figure 4.2.3). Luo et al. (2006) attributed the reduction in the PV of thermally treated normal maize starch to the disruption of starch granular structure leading to a decrease in water uptake by starch and the possible reduction of the ability of starch to swell. Also, it has been proposed from work on pearl millet that a protective layer on the granular surface of starch could inhibit water absorption due to the hydrophobic nature of lipids (Sharma & Gujral, 2019), which may be an additional reason. A benefit of the reduction in porridge PV is that porridges of higher energy density with low viscosity could be achieved, thereby making the porridges more suitable for infant feeding (Moussa et al., 2011).

The generally somewhat higher firmness of the porridges of L and H treatments (Figure 4.3.4) was probably also a consequence of their flours' higher damaged starch content. However, the sensory panel did not detect any obvious difference in porridge texture in terms of viscosity between the treatments (Figure 4.2.6). It is possible that the more obvious aroma differences between the porridges attracted greater attention by the sensory panellists than the slight differences in texture.

Porridges from the microwave treated flours (L and H) were generally stickier than the porridges from U flour, as measured by instrumental texture analysis (Figure 4.3.4). The greater starch damage of the L and H flours (Figure 4.2.3) was probably responsible. However, no difference in porridge stickiness was detected by the descriptive sensory panel (Figure 4.2.6). As with porridge texture, this may have been masked by other effects on porridge sensory attributes.

The lower L* value of the porridges from the H treatment (Table 4.2.2) was presumably a result of non-enzymatic browning reactions such as Maillard reactions and caramelization, which can produce coloured compounds during the initial stages of wholegrain sorghum kernels processing (Purlis, 2010). With the U treatment, the increase in porridge L* value (Table 4.2.2) and in painty, oily and rancid aroma sensory attributes (Table 4.2.4) from flours that had been stored for 3-4 weeks was presumably a consequence of development of the secondary, carbonyl-type products of lipid oxidation.

4.2.7 Conclusions

Microwave pre-treatment of wholegrain sorghum kernels improved flour stability during storage yet affected the sensory properties of the porridge only slightly. The treatment retarded the development of rancidity through inactivation of lipase, more so at an energy level of 90 kJ/100 g than 36 kJ/100 g. As a consequence, porridges from treated grain flours were less rancid than those from untreated grain. The observed reduction in flour pasting PV from microwave treated wholegrain sorghum kernels suggests that the treatment has potential to produce less viscous porridges, which are more suitable for infant feeding. However, because of the slight changes in porridge sensory properties that resulted from microwave treatment of wholegrain sorghum kernels, the determination of consumer acceptability of the porridges is recommended. Additionally, the economic viability of the treatment needs to be assessed.

4.3 Effects of hot-air roasting of tannin and non-tannin sorghum grains on the stabilization and physicochemical and functional properties of their flours and improvement of food product sensory quality

4.3.1 Abstract

Despite the health benefits associated with wholegrain sorghum such as high fibre and antioxidants; some consumers find the taste of sorghum to be unappealing. Sorghum flours have a short shelf-life because of deterioration of lipids in flour due to lipolysis and oxidative rancidity. The effects of hot-air roasting of (150 °C for 10 min to 25 min) tannin and non-tannin WGK on stability and physicochemical and functional properties of their flours and porridge (of non-tannin wholegrain and decorticated flour) sensory quality, were studied. The fat acidity of tannin and non-tannin wholegrain sorghum flours decreased by nearly 25 % and 77% respectively by roasting the grains due to partial inactivation of lipase. The decrease in fat acidity was about 35 % and 39 % respectively for decorticated grain flours of tannin and non-tannin sorghum. There was a significant effect on the lightness (*L**) of flours from tannin sorghum grains when compared to other flour forms, as flours became darker. Roasting wholegrain tannin sorghum resulted in a substantial increase in antioxidant activity (AOA) of its flour but with the other flours there was no real effect of roasting. Decortication after roasting reduced the AOA of tannin sorghum flours further due to the partial removal of the bran. Peak and final viscosities of roasted tannin and non-tannin sorghum flour pastes were significantly reduced compared to those of untreated samples. There were no significant ($p > 0.05$) differences in WAI of both tannin and non-tannin, wholegrain and decorticated flours due to roasting. Whereas WSI of tannin, wholegrain and decorticated flours differed significantly ($p < 0.05$), those of non-tannin were not significantly affected ($p > 0.05$) by roasting. The fat acidity of flour from kernels roasted for longer (25 min) was substantially lower than those of shorter roasting duration. The lower fat acidity indicates greater stabilization of the flour against lipolysis and oxidative rancidity. With flour storage, porridges from unroasted non-tannin wholegrain flours had dominant painty, oily, rancid and fermented aromas while those prepared from decorticated flours displayed rancid and fermented aromas, brown colour with clearly visible specks and residual aftertaste. Roasting non-tannin sorghum kernels for 25 min and decorticating was most effective at reducing fat acidity (lipolysis) and *p*AV (oxidation). The treatment therefore has potential to improve the keeping quality of non-tannin sorghum grain flours and may improve sensory quality of products made from the flour.

Keywords Roasting, sorghum, Total phenolic content, antioxidant activity, rancidity, shelf-life

4.3.2 Introduction

The intake of gluten-free cereals such as wholegrain sorghum-based food products is increasing probably due to their inherent nutritional qualities and health-promoting benefits to the diet (Awika, 2017). Wholegrain sorghum has fat content ranging between 3.2 and 3.9 g/100 g, and the fat comprises some 88 % unsaturated fatty acids (Chhikara et al., 2018). Fats can have a positive impact on the sensorial and textural properties of food formulations, but they can as well impact negatively when hydrolyzed and oxidized (Osuna, Romero, & Bertola, 2018). Hence, due to its high contents of fat and unsaturated triglycerides, wholegrain sorghum flours are highly susceptible to lipolysis and lipid oxidation, which limits their storage stability (Meera et al., 2011). The lipid oxidation results in the loss of essential fatty acids, the emergence of unpleasant off-flavours and rancid taste, adverse colour changes, thereby decreasing the product sensory, nutritional and physical quality, leading to consumer rejection (Grosso et al., 2018). The development of unpleasant odours and off-flavours in such oxidized flour or flour-based food products increases progressively over storage time (Jiménez et al., 2020). This is due to the formation of primary (hydroperoxides) and secondary oxidation products such as aldehydes, ketones and alcohols (Wang et al., 2014). Rancidity in sorghum flour is a problem (Meera et al., 2011), and how to prevent these chemical changes of lipids in flour and flour products remain a major research and development challenge,

Microwaving non-tannin WGK with 90 kJ/100 g can effectively be applied to stabilize the whole flour without affecting the sensory qualities of the porridge of the flours (Chapter 4.2). Similarly, research has shown the effectiveness of hot-air roasting of pearl millet before milling to flours in order to stabilize the flour (Nantanga et al., 2008). The process of roasting sorghum was found to be a simple process for developing different convenience foods (Ranganathan et al., 2013). This is because grain roasting employs dry heat for short durations of time and can enhance cereal grain and their food products characteristics (Sharma et al., 2011). It was shown that roasting oat kernels at up to 160 ^{o}C is a processing technology with potential to produce oat products (flakes) characterized by improved sensory quality (Schlörmann et al., 2019). The authors found that the improvement in sensory properties and other quality characteristics of oat products due to roasting involved some structural and chemical alterations, notably by the formation of Maillard reaction products. Maillard reaction products are responsible for much of the typical flavour and taste associated with roasted foods (Ranganathan et al., 2013). Some of these reaction products can enhance colour development and inhibit the activity of lipolytic enzymes, and extend flour shelf-life (Ntso, Njintang, & Mbofung, 2017). WGF is more vulnerable to lipid deterioration than decorticated (refined) flour due to its higher levels of lipid-degrading enzymes (lipase and lipoxygenase) and lipids which are concentrated in the pericarp and germ (Meera et al., 2011). Decortication of the grain before milling to flour is likely to reduce rancidity and improve the keeping qualities of the flour because it removes a substantial part of the germ and pericarp (Awika, 2017). Sorghum is a rich source of phenolic compounds with proven antioxidant properties (de Morais Cardoso et al., 2017). There have been efforts to identify possible natural and safer antioxidants of plant origin (Gülçin et al., 2012) and ways of incorporating these compounds into food systems such as porridges (Apea-Bah et al., 2014) for human benefits. The phenolics in sorghum could impart antioxidant properties to the flour and may extend its shelf-life. Increases in TPC, AOA redness, and yellowness for roasted sorghum flour with a decrease lightness have been reported (Ranganatha et al., 2013; Sharanagat et al., 2019).

Relatively little is known about the effects of roasting sorghum grain types on the stability of their flours. Therefore, this study evaluated the effects of the extent of roasting tannin and non-tannin sorghum grains on flour (non-tannin) stability and their products' sensory attributes.

4.3.3 Material and methods

A process diagram of the study in presented in Figure 4.3.1.

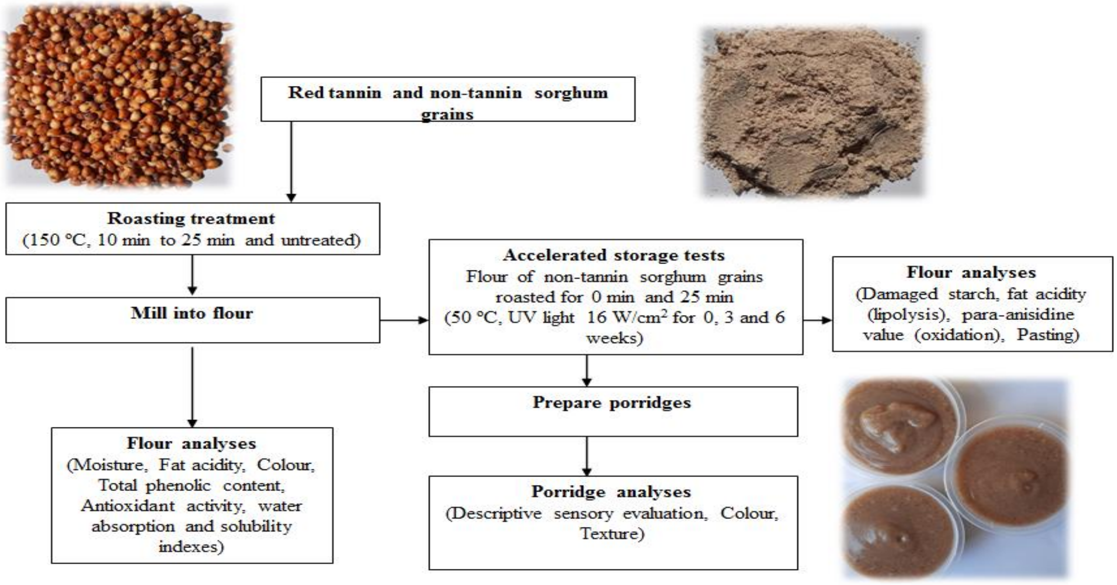

Figure 4.3.1 Process diagram for roasting treatments of tannin and non-tannin sorghum grain kernels, flour (non-tannin) stability testing and sensory quality of their porridges

4.3.3.1 Materials

Red tannin (54.1 mg CE/g, a blend of sorghum cultivars PAN 8616 and PAN 8625) and non-tannin sorghum grains (a blend of cultivars but primarily PAN 8816) was used.

4.3.3.2 Methods

4.3.3.2.1 Roasting of tannin and non-tannin sorghum grains

About 5 kg of each sorghum type was divided into five equal parts. Four parts were conditioned to 14% moisture and roasted at 150 °C (at constant temperature throughout the roasting period) in a preheated convection continuous tumble roaster (Roastech, Bloemfontein, South Africa). Speed sets of 380, 340, 290 and 240 rpm were selected, resulting in heating times of 10, 15, 20 and 25 min, respectively reaching a temperature of 150±2 °C. Temperatures of roasted kernels were measured instantly after roasting with a non-contact infrared thermometer (Fluke 62 Mini, Wantitall, Linbro Park, South Africa). Untreated (U) sorghum grains served as controls. Roasted grains were spread on aluminium trays to cool for 10 min at room temperature (20-22 °C), packaged in zip-lock bags and stored at -20 °C.

4.3.3.2.2 Grain milling

As described in research chapter 4.1 section 4.1.3.2.2

4.3.3.2.3 Flour storage

Flours from the minimum (10 min) and maximum (25 min) roasting (non-tannin sorghum, type mainly consumed as food unlike tannin type) treatments were selected for accelerated storage (50 ºC, UV light 16 W/cm^2 for 6 weeks) similar to the experiment as described in research chapter 4.2 section 4.2.2.2.1.

4.3.3.2.4 Porridge preparation

As described in research chapter 4.2 section 4.2.2.2.2.

4.3.3.2.5 Training of the descriptive sensory panel

As described in research chapter 4.2 section 4.2.2.2.3.

4.3.4 Analyses

4.3.4.1 Determination of moisture content

As described in research chapter 4.1 section 4.1.3.3.1.

4.3.4.2 Extraction of phenolic compounds

As described in research chapter 4.1.3.2.4.1.

4.3.4.3 Determination of the total phenolic content

The TPCs of sorghum flour extracts (from tannin and non-tannin types) were determined by using Folin-Ciocalteu assay described in research chapter 4.1 section 4.1.3.3.2.2.

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4.3.4.4 Determination of the antioxidant activity

Antioxidant activity (AOA) of sorghum flour extract (from tannin and non-tannin types) was determined using ABTS* [(2, 2-azinobis (3-ethlybenzothiazoline-6-sulfonic acid)] assay described by Awika et al. (2003) described in research chapter 4.1 section 4.1.3.3.2.3.

4.3.4.5 Flour colour measurement

The colour of tannin and non-tannin sorghum grain flours was measured using a tristimulus colorimeter (CR-400 Chroma Meter, Konica Minolta Sensing, Osaka, Japan) described in research chapter 4.1 section 4.1.3.3.3.

4.3.4.6 Flour pasting property

Flour (from tannin and non-tannin sorghum types) pasting properties were measured using the rheometer as described in research chapter 4.1 section 4.1.3.3.4.

4.3.4.7 Flour water absorption and solubility indexes

As described in research chapter 4.1 section 4.1.3.3.5.

4.3.4.8 Flour fat rancidity

Lipid hydrolysis and lipid oxidation of non-tannin sorghum flours (stored) were analyzed in terms of fat acidity (FA) and *p*-anisidine (*p*AV), with procedures described in research chapter 4.2 section 4.2.2.2.4.1.

4.3.4.9 Flour damaged starch content

As described in research chapter 4.2 section 4.2.2.2.4.2.

4.3.5 Porridge

4.3.5.1 Instrumental colour analysis of the porridge

The colour of porridge made from non-tannin sorghum flours was measured using a tristimulus colorimeter (CR-400 Chroma Meter, Konica Minolta Sensing, Osaka, Japan) as described in research chapter 4.2 section 4.2.2.2.4.4.

4.3.5.2 Instrumental pasting properties of porridge

The pasting properties of non-tannin sorghum flour pastes were measured using an Anton Paar Physica MCR 301 rheometer. Here only the PV and FV are reported because it can be related to the ease of swallowing of porridge. Detailed procedures are described in research chapter 4.2 section 4.2.3.2.3.

4.3.5.3 Instrumental texture analysis of the porridge

The texture parameters of porridges made from non-tannin sorghum grain flours were measured in terms of firmness and stickiness using a texture analyzer. Procedures were described in research chapter 4.2 section 4.2.2.2.4.5.

4.3.54 Descriptive sensory evaluation of porridge

As described in research chapter 4.2 section 4.2.2.2.4.6

4.3.5 Statistical analyses

As described in research chapter 4.1 section 4.1.4 for the physicochemical and functional properties of unstored flours from treated tannin and non-tannin grains. For stored flours (non-tannin type only), two-way analysis of variance (ANOVA) was used to test the main effects and interaction effect of independent (roasting at 150 ºC for 10 min and 25 min, and storage periods from 0 week to 6 weeks) on the dependent variables (sensory attributes, pasting profiles, colour parameters, porridge firmness and stickiness). Fisher’s least significant difference (LSD) test was used to separate means. Linear regression analysis was used to identify relationships between PV of the flour pastes and storage period. Sensory attributes that described significant differences among porridges were analysed by principal component analysis (PCA). The XLSTAT® software package (Addinsoft^{TM}, New York) was used for all analyses.

4.3.6 Results

4.3.6.1 Raw material characterization

Sorghum type had a significant ($p \leq 0.001$) effect on all the flour parameters except for water solubility index (WSI) (Table 4.1.2). Decortication significantly affected ($p < 0.05$) all the flour parameters except WSI. The interaction of sorghum type and decortication was significant ($p < 0.05$) for the colour attributes (yellowness, chroma and browning index values).

4.3.6.1.1 Effects of sorghum type and decortication on moisture and fat acidity of unroasted and roasted tannin and non-tannin sorghum flours (unstored)

The moisture content of flours (unstored) obtained from untreated (U) sorghum grains was in the range of 7-10 % (Table 4.3.1). The moisture content of flour (unstored) from roasted sorghum was lower ($p < 0.05$) compared to U flour. The moisture content of tannin and non-tannin U flours did not differ. Roasting tannin and non-tannin wholegrain sorghum had negligible effect on fat acidity of flour from whole and decorticated grains. The level of FA in the flours from the roasted tannin and non-tannin kernels was significantly ($p < 0.05$) lower than those of U controls. Decortication after roasting the kernels led to a further reduction in fat acidity. FA values were in the range 14.7-19.6 mg KOH/g for wholegrain tannin, 10.6-16.3 mg KOH/g for decorticated grain tannin, 11.5-50.1 mg KOH/g for wholegrain non-tannin and 10.0-16.4 mg KOH/g for decorticated non-tannin sorghum, respectively.

Table 4.3.1 The effects of roasting time applied to tannin and non-tannin wholegrain sorghum kernels on the moisture content and fat acidity of their wholegrain and decorticated grain flours (unstored)

Roasting time (min)	Sorghum type and flour form	Moisture (g/100 g)	Fat acidity$^{\$}$ (mg KOH/g)
0	Tannin (wholegrain)	9.43 (0.01)^{a}	**19.6 (0.0)^{a}**
10		4.64 (0.07)^{b}	15.3 (0.2)^{b}
15		4.03 (0.01)^{b}	15.1 (0.0)^{b}
20		3.79 (0.08)^{c}	15.1 (0.0)^{b}
25		2.78 (0.03)^{d}	14.7 (0.1)^{b}
0	Tannin (decorticated)	7.35 (0.11)^{a}	**16.3 (0.2)^{a}**
10		4.52 (0.07)^{b}	13.4 (0.1)^{b}
15		4.00 (0.05)^{b}	12.5 (0.1)^{c}
20		3.64 (0.04)^{c}	11.2 (0.1)^{d}
25		2.62 (0.01)^{d}	10.6 (0.1)^{e}
0	Non-tannin (wholegrain)	10.07 (0.43)^{a}	**50.1 (1.6)^{a}**
10		5.66 (0.13)^{b}	13.0 (0.3)^{b}
15		4.78 (0.05)^{c}	12.2 (0.6)^{c}
20		4.60 (0.17)^{c}	11.7 (0.6)^{c}
25		3.46 (0.03)^{d}	11.5 (0.3)^{c}
0	Non-tannin (decorticated)	9.82 (0.04)^{a}	**16.4 (0.1)^{a}**
10		5.43 (0.02)^{b}	12.7 (0.1)^{b}
15		4.62 (0.03)^{c}	12.1 (0.0)^{c}
20		4.51 (0.01)^{cd}	11.1 (0.1)^{d}
25		3.27 (0.01)^{e}	10.0 (0.1)^{e}

Values for each dependent variable for each sorghum type and flour (unstored) form followed by different superscripts indicate significant differences between means ($p < 0.05$). Results are expressed as the mean of triplicate determinations ± standard deviation. $^{\$}$ expressed on a dry weight basis. Flour fat acidity of the respective grains/treated samples prior to heat treatments (roasting at 150 °C, 10 min – 25 min) are printed bold.

4.3.6.1.2 Effect of sorghum type and decortication on the total phenolic and antioxidant activity of their flours

The total phenolic content (TPC) of the flour (unstored) obtained from U and roasted sorghum grains at the different roasting times (10 min to 25 min) exhibited considerable variations (Table 4.3.2). Generally, the TPC of flours was reduced by roasting the sorghum grain with the exception of wholegrain sorghum kernels (WGK) tannin sorghum samples. There were no significant ($p > 0.05$) differences in TPC of flours from sorghum grain due to roasting in all the samples except for that of decorticated tannin sorghum. Generally, the TPC of flours was increased by roasting the sorghum grain samples compared to the U samples. With decortication of sorghum grains after roasting, TPC of flours decreased. There was a substantial increase in antioxidant activity (AOA) of tannin WGF due to roasting (Table 4.3.2). However, AOA of tannin sorghum flour decreased drastically after decortication of the grains. The highest AOA (244.0 µmol TE/g) was recorded due to 25 min roasting of tannin sorghum, while the lowest activity in decorticated flour (14.4 µmol TE/g) was recorded due to 10 min of roasting of non-tannin sorghum grains.

Table 4.3.2 The effects of roasting time applied to tannin and non-tannin wholegrain sorghum kernels on the TPC and AOA of their wholegrain and decorticated grain flours

Roasting time (min)	Sorghum type and flour form	TPC^{+} (mg CE/g)	AOA^{+} (µmol TE/g)
0	Tannin (wholegrain)	19.4 (0.1)^{ab}	56.3 (0.1)^{e}
10		19.5 (0.1)^{ab}	195.0 (4.7)^{d}
15		19.9 (0.1)^{b}	214.0 (3.7)^{c}
20		20.1 (0.2)^{a}	225.0 (3.2)^{b}
25		20.7 (0.1)^{a}	244.0 (2.0)^{a}
0	Tannin (decorticated)	6.1 (0.2)^{a}	16.1 (0.5)^{e}
10		3.6 (0.1)^{b}	17.5 (0.6)^{d}
15		2.9 (0.4)^{bc}	18.6 (0.6)^{c}
20		2.8 (0.1)^{bc}	24.7 (0.3)^{b}
25		2.8 (0.2)^{c}	35.5 (0.5)^{a}
0	Non-tannin (wholegrain)	5.8 (0.5)^{a}	18.6 (0.3)^{c}
10		4.1 (0.1)^{b}	25.3 (1.2)^{b}
15		3.9 (0.1)^{b}	28.5 (2.4)^{ab}
20		3.8 (0.1)^{b}	29.7 (3.4)^{a}
25		3.7 (0.1)^{b}	31.9 (2.4)^{a}
0	Non-tannin (decorticated)	4.2 (0.1)^{a}	14.4 (0.2)^{d}
10		0.6 (0.1)^{b}	14.7 (0.1)^{d}
15		0.5 (0.1)^{b}	16.7 (0.1)^{c}
20		0.4 (0.1)^{b}	17.3 (0.1)^{b}
25		0.3 (0.0)^{b}	18.6(0.1)^{a}

Values for each dependent variable for each sorghum type and flour form followed by different superscripts indicate significant differences between means ($p < 0.05$). Results are expressed as the means of triplicate determinations ± standard deviation.

$^{+}$calculate dry weight basis. CE = catechin equivalent, TE = Trolox equivalent

4.3.6.1.3 Effect of sorghum type and decortication on flour colour

Roasting did not affect *L** values of tannin WGF. With decortication, the flours of tannin sorghum became lighter. The non-tannin wholegrain sorghum flour (WGF) was lighter than tannin sorghum flours but darker than the decorticated non-tannin sorghum flours which were the lightest overall. Conversely, other colour parameters redness/greenness, yellowness, chroma, browning index and total colour difference were generally not affected ($p \geq 0.05$) by roasting of sorghum grains (Table 4.3.3).

Table 4.3.3 Effects of roasting time applied to wholegrain sorghum (tannin and non-tannin) on the colour properties (L*, a*, b*, C*, H*, ΔE* and BI*) of their wholegrain and decorticated grain flours

Roasting time (min)	Sorghum type and flour form	Colour properties						
		*L**	a*	b*	C*	H*	ΔE*	BI*
0	Tannin (whole grain)	76.3 (0.3)	5.61 (0.01)^{b}	7.55 (0.13)^{b}	9.50 (0.03)	53.7(0.4)	Not applicable	15.5 (0.1)
10		76.3 (0.6)	5.76 (0.17)^{b}	7.66 (0.14)^{a}	9.67 (0.06)	53.3(0.6)	0.33 (0.05)^{ab}	16.0 (0.1)
15		76.4 (0.6)	5.78 (0.10)^{b}	7.74 (0.17)^{a}	10.1 (0.03)	53.3(0.3)	0.67 (0.06)^{b}	16.0 (0.1)
20		76.6 (0.4)	5.97 (0.16)^{b}	7.77 (0.13)^{a}	10.1 (0.01)	52.7(0.4)	1.66 (0.07)^{a}	16.7 (0.3)
25		76.7 (0.3)	6.07 (0.11)^{a}	7.94 (0.20)^{a}	10.3 (0.04)^{a}	52.3(0.1)	1.66 (0.10)^{a}	16.3 (0.2)
0	Tannin (decorticated)	86.7 (0.5)^{b}	2.97 (0.11)	6.78 (0.12)	7.33 (0.05)^{a}	66.3(0.6)^{b}	Not applicable	10.3 (0.5)^{a}
10		88.4 (0.3)^{a}	2.31 (0.03)	6.68 (0.16)	7.26 (0.02)^{a}	72.0(0.1)^{ab}	1.67 (0.06)^{b}	9.7 (0.1)^{ab}
15		88.5 (0.3)^{a}	2.17 (0.05)	6.67 (0.15)	7.13 (0.1)^{a}	72.6(0.5)^{ab}	2.00 (0.01)^{ab}	9.5 (0.2)^{b}
20		88.7 (0.4)^{a}	2.12 (0.05)	6.64 (0.01)	7.02 (0.01)^{a}	72.8(0.3)^{ab}	2.33 (0.05)^{ab}	9.3 (0.1)^{ab}
25		88.9 (0.1)^{a}	2.11 (0.01)	6.62 (0.17)	6.71 (0.04)^{b}	76.0(0.1)^{a}	2.67 (0.06)^{a}	9.1 (0.1)^{b}
0	Non-tannin (whole grain)	82.6 (0.6)^{a}	3.63 (0.02)^{c}	8.80 (0.0.2)^{b}	9.97 (0.29)^{a}	66.8(0.4)^{b}	Not applicable	15.1 (0.5)^{a}
10		82.5 (0.4)^{ab}	3.74 (0.08)^{bc}	8.98 (0.09)^{ab}	9.87 (0.08)^{a}	66.9(0.3)^{ab}	0.79 (0.06)	14.9 (0.1)^{a}
15		81.9 (0.3)^{ab}	3.82 (0.03)^{ab}	8.99 (0.07)^{ab}	9.76 (0.08)^{ab}	67.2(0.1)^{ab}	0.83 (0.04)	14.8 (0.2)^{a}
20		81.8 (0.3)^{bc}	3.83 (0.04)^{ab}	9.10 (0.09)^{a}	9.74 (0.06)^{ab}	67.4(0.5)^{ab}	0.87 (0.04)	14.6 (0.2)^{ab}
25		81.7 (0.2)^{c}	3.93 (0.12)^{a}	9.17 (0.28)^{a}	9.52 (0.02)^{b}	67.6(0.1)^{a}	0.96 (0.17)	14.2 (0.1)^{b}
0	Non-tannin (decorticated)	91.6 (0.3)^{c}	0.14 (0.06)^{a}	8.64 (0.31)^{a}	9.70 (0.33)^{a}	84.3(0.3)^{c}	Not applicable	10.3 (0.1)^{a}
10		92.8 (0.1)^{a}	0.15 (0.02)^{a}	8.61 (0.33)^{a}	9.57 (0.30)^{a}	87.5(0.3)^{b}	1.15 (0.02)^{a}	9.7 (0.1)^{ab}
15		92.5 (0.2)^{ab}	0.27 (0.07)^{ab}	8.55 (0.27)^{a}	9.50 (0.22)^{a}	88.2(0.5)^{ab}	1.17 (0.06)^{a}	9.7 (0.3)^{ab}
20		92.2 (0.3)^{ab}	0.34 (0.04)^{b}	8.30 (0.11)^{ab}	9.41 (0.25)^{a}	88.9(0.3)^{a}	1.20 (0.05)^{a}	9.3 (0.2)^{b}
25		92.5 (0.3)^{ab}	0.87 (0.08)^{c}	7.87 (0.28)^{b}	8.89 (0.01)^{b}	89.1(0.4)^{a}	1.52 (0.03)^{a}	9.0 (0.1)^{b}

Values for each dependent variable for each sorghum type and flour form followed by different superscripts indicate significant differences between means ($p < 0.05$). Results are expressed as the mean ± standard deviation.

*L** = lightness, a* = redness, b* = yellowness, C* = colour intensity, H* = hue angle, ΔE* = total colour change and BI* = browning index

4.3.6.1.4 Effects of sorghum type and decortication on pasting profiles of flours

Roasting wholegrain sorghum kernel caused decreases in the pasting profiles (peal viscosity, final viscosity, breakdown viscosity, and set back viscosity) of tannin and non-tannin sorghum flours (Fig 4.3.2). The decrease in the pasting profiles is significantly ($p < 0.05$) lesser in the decorticated grain flour than those of wholegrain flour during pasting. With decortication, both the peak and final viscosities of flours of tannin and non-tannin sorghum grains increased (Fig 4.3.2).

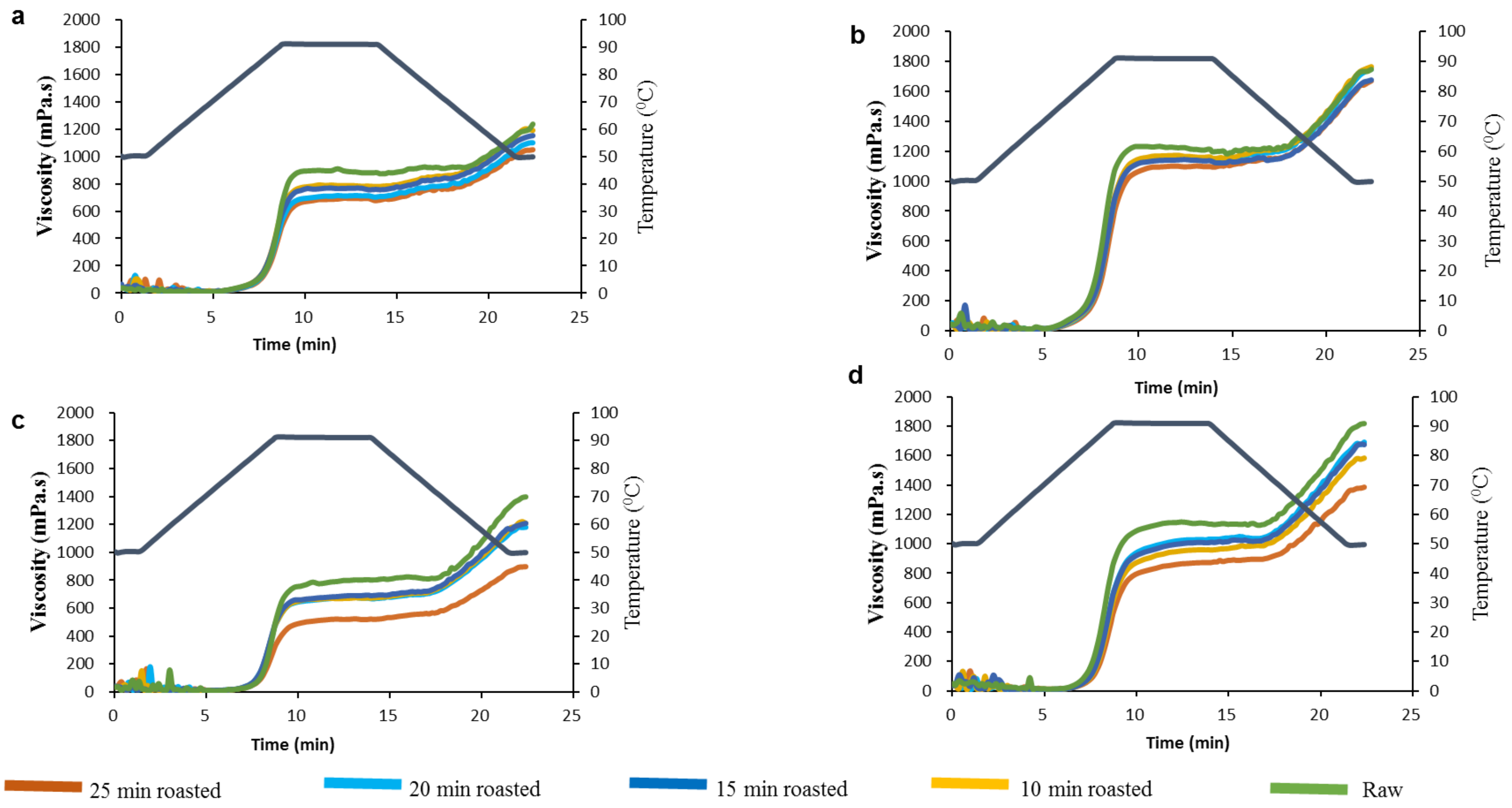

Figure 4.3.2 Effects of roasting time applied to wholegrain sorghum (tannin and non-tannin) on the pasting (viscosity) profiles of their wholegrain and decorticated grain flours.

a = wholegrain tannin, b = decorticated grain tannin, c = wholegrain non-tannin, and d = decorticated non-tannin sorghum

4.3.6.1.5 Effects of sorghum type and decortication on water absorption and solubility indexes

Roasting significantly ($p < 0.05$) progressively increased the WAI and reduced the WSI of all the flour types (Table 4.3.4). There were no significant ($p < 0.05$) differences in WAI of whole and decorticated grain flours due to roasting of non-tannin sorghum. Whereas WSI differed ($p < 0.05$) between whole and decorticated grains flours from roasted tannin sorghum, those of non-tannin sorghum were not ($p > 0.05$) different. Wholegrain flours from tannin sorghum roasted for 25 min exhibited the highest WAI (4.10), while the highest WSI (0.153 and 0.133) were observed in decorticated grain flours from tannin sorghum roasted for 20 min and 25 min, respectively. WSI is an indication of the degradation of molecular components; such as the amount of soluble polysaccharide of starch released after roasting sorghum grains (Oikonomou & Krokida, 2011). Therefore, an increase in the WSI values in decorticated grain flours can be ascribed to the rupture of the structural poly saccharides by roasting treatments

Table 4.3.4 The effects (dry basis) of roasting time applied to sorghum grains (tannin and non-tannin) on the WAI and WSI of wholegrain and decorticated grain flours

Roasting time (min)	Sorghum type and flour form	WAI	WSI
0	Tannin (wholegrain)	2.62 (0.04)^{b}	0.033 (0.002)^{a}
10		3.01 (0.05)^{b}	0.026 (0.001)^{b}
15		3.07 (0.04)^{b}	0.020 (0.003)^{c}
20		3.21 (0.05)^{b}	0.018 (0.002)^{cd}
25		4.10 (0.01)^{a}	0.015 (0.001)^{d}
0	Tannin (decorticated)	2.24 (0.04)^{a}	0.025 (0.003)^{a}
10		2.28 (0.03)^{b}	0.025 (0.002)^{a}
15		2.31 (0.04)^{b}	0.017 (0.001)^{b}
20		2.38 (0.05)^{b}	0.153 (0.003)^{bc}
25		2.68 (0.03)^{a}	0.133 (0.002)^{c}
0	Non-tannin (wholegrain)	2.43 (0.11)	0.025 (0.004)^{a}
10		2.45 (0.12)	0.024 (0.002)^{ab}
15		2.54 (0.03)	0.023 (0.002)^{ab}
20		2.57 (0.02)	0.022 (0.003)^{ab}
25		3.66 (0.05)	0.022 (0.001)^{b}
0	Non-tannin (decorticated)	2.29 (0.02)	0.027 (0.003)
10		2.37 (0.03)	0.024 (0.002)
15		2.41 (0.03)	0.023 (0.001)
20		2.45 (0.04)	0.023 (0.002)
25		2.67 (0.05)	0.023 (0.001)

Values for each dependent variable for each sorghum type and flour form followed by different superscripts indicate significant differences between means ($p < 0.05$). Results are expressed as the mean triplicate determinations ± standard deviation

4.3.6.1.6 Physicochemical characteristics of flour

Figure 4.3.3 shows the sensory characteristics of porridge using Principal Component Analysis (PCA) plots of the first-two principal components, with a score plot (A) for the samples from different sorghum type and processing and a loading plot (B) of the flour parameters (Fig 4.3.3). The plots indicate a visual summary of the changes in flour samples due to different treatments, with the inclusion of all flour parameters that showed significant differences as main or interaction effects. The PCA plots explained nearly 76% of the treatment variation among the samples.
PC1 (53 % of the variation) clearly separates wholegrain flour, that is on the right, from those of decorticated grains on the left-hand side. PC1 also separate the samples into three groups (due to forming cluster-like patterns while others are at distant) from right to left WT (wholegrain tannin), WN (wholegrain non-tannin) and then DT (decorticated tannin) and DN (decorticated non-tannin). Those on the left have higher *L**-values and lower BI (browning index), TPC (total phenolic content), WAI (water absorption index), FFA (fat acidity) and ABTS (antioxidant activity). PC2 separates the controls (unroasted) flours of all treatments with a higher moisture content (mc) at the top of the plot from the roasted samples further down.

The PC2 adds 22.5% to the variation and it primarily separates the roasted from the unroasted sorghum grain flours. Separation of the roasted samples along PC2 is according to the extent of roasting time. The longer the roasting time the lower the mc, and the higher the ABTS. The PCA plot revealed that wholegrain flours from roasted tannin sorghum (WT_0 - WT_{25}) were associated with higher concentration of total phenols (TPC), antioxidant activity (ABTS), FFA, browning index (BI) and WAI. The TPC, browning index and AOA were positively correlated with each other and were associated with roasted whole grain tannin sorghum flours (WT). Flours of decorticated non-tannin sorghum (DN) were lighter in colour (higher L-value) than those of wholegrain flours.

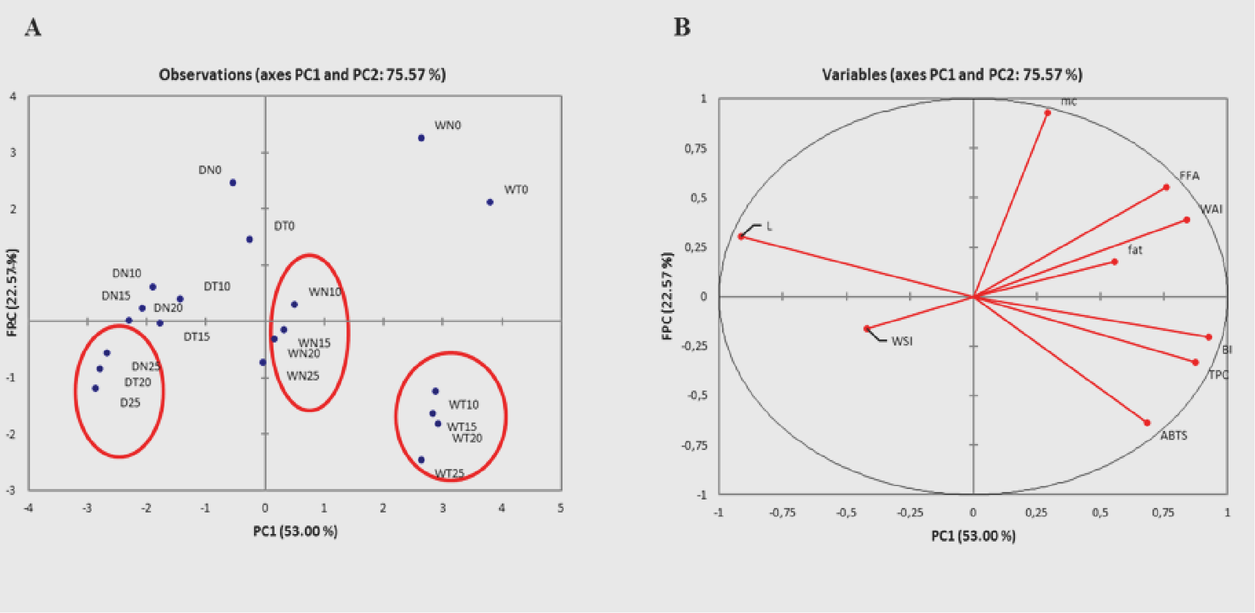

Figure 4.3.3 Principal component analysis (PCA) of unroasted and roasted (10, 15, 20, 25 min) tannin and non-tannin sorghum grains and the physicochemical properties of their wholegrain and decorticated flours (unstored)

A. Treatment Roasting time and Decortication: Unroasted tannin wholegrain (WT_0 minutes), untreated tannin decorticated grain (DT_0), tannin roasted wholegrain (WT_{10}, WT_{15}, WT_{20}, WT_{25}), roasted tannin decorticated grain (DT_{10}, DT_{15}, DT_{20}, DT_{25}); unroasted non-tannin wholegrain (WN_0), unroasted non-tannin decorticated grain (DN_0), roasted non-tannin whole grain (WN_{10}, WN_{15}, WN_{20}, WN_{25}) and roasted non-tannin decorticated grain (DN_{10}, DN_{15}, DN_{20}, DN_{25}).

B. PCA Loading: Moisture content (mc), fat acidity (FA), water absorption index (WAI)), browning index (BI), total phenolic content (TPC), antioxidant activity (ABTS), water solubility index and lightness (L*).

Red ring indicating clusters.

4.3.6.2 Properties of stored flour of non-tannin sorghum and sensory quality of food product

4.3.6.2.1 Effect of roasting non-tannin sorghum on flour (stored) fat rancidity

Fat rancidity of stored flour was measured in terms of fat acidity (lipolysis) and para-anisidine value (oxidation). The amount of FFA can be considered a lipid quality index for foods because studies had shown that FFA oxidize more quickly than their respective methyl esters (Zou et al., 2018). Roasting of non-tannin sorghum kernels had substantial effect on the fat acidity of flours from whole and decorticated grains. Reduction in the fat acidity values of roasted (l = roasted for 10 min and h = roasted for 25 min) whole and decorticated grain flours during storage compared to those of U (unroasted sample) shows that the roasting treatments largely inactivated the lipase in the flours (Table 4.3.5). During storage, the fat acidity of whole flours from l and h was generally much lower ($p < 0.05$) than that of U flours. Generally, the fat acidity of all flour forms, irrespective of the heat treatment, increased with storage (Table 4.3.5).

Table 4.3.5 Effects of roasting non-tannin sorghum grains on fat acidity (mg KOH/100 g, dry basis) values of flours stored as whole and decorticated.

Flour type/ Roasting time (min)		**Storage period (weeks)**			**p-value**
		0	**3**	**6**	
Whole	0	**50.1 (1.6)**^{cA}	184. 7 (3.1)^{bA}	233.6 (3.4)^{aA}	< 0.0001
	10	**48.9 (3.1)**^{cA}	174.6 (4.7)^{bA}	190.1 (5.7)^{aB}	< 0.0001
	25	**34.4 (1.3)**^{cB}	107.9 (3.5)^{bB}	173.5 (3.6) ^{cC}	< 0.0001
	p-value	0.0330	0.0003	0.0005	
Decorticated	0	**9.9 (0.6)**^{cA}	16.5 (1.5)^{bA}	20.9 (1.3)^{aA}	0.013
	10	**5.5 (0.2)**^{aAB}	7.7 (0.3)^{aB}	9.9 (0.5)^{aB}	0.142
	25	**3.3 (0.1)**^{bB}	5.5 (0.4)^{bB}	11.5 (0.3)^{aB}	0.018
	p-value	0.0515	0.0312	0.0049	

Values are means of triplicate determinations. Means for a flour type with $^{a,\ b\ \text{and}\ c}$ superscripts are significantly ($p < 0.05$) different row wise, and means with $^{A,\ B\ \text{and}\ C}$ superscripts are significantly ($p < 0.05$) different column wise. Flour fat acidity of the respective grains/treated samples at day 0 (baseline) prior to heat treatments (roasting at 150℃ for 10 min and 25 min) are printed bold

The *p*AV of flours from roasted non-tannin WGK was significantly lower than that of U at week 0 (Fig 4.3.4A). Similarly, at week 0 the *p*AV of flour from decorticated grain was lower than those of WGF (Figure 4.3.4B). The *p*AVs of all the samples increase during the storage period. The *p*AV of all WGF increased by more than two-fold and for decorticated grain flours nearly two-fold (Fig 4.3.4).

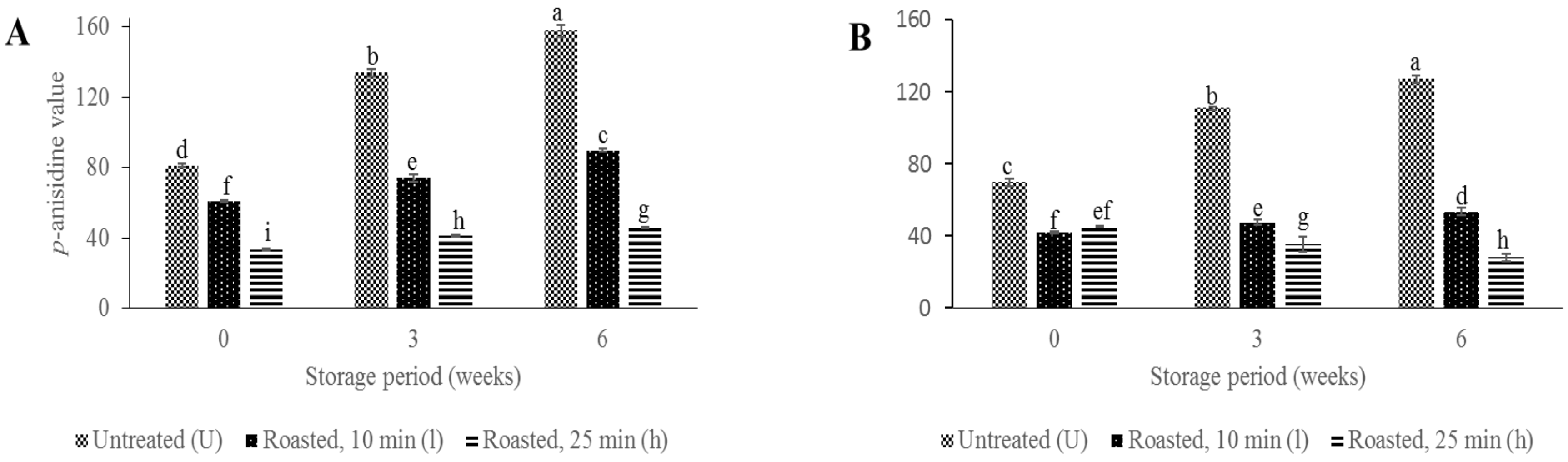

Figure 4.3.4 Effects of roasting non-tannin whole grain sorghum kernels on the *p*AV of flours stored as (A) wholegrain and (B) decorticated.

Values with different letters are significantly different ($p < 0.05$).

4.3.6.2.2 Effect of roasting non-tannin wholegrain sorghum on flour (stored) damaged starch content

Roasting of non-tannin WGK led to a slight increase in the flour damaged starch content (Fig 4.3.5). The decortication process had an impact on flour of U non-tannin kernels which led to some damage in starch content. That is, the process caused a greater damage to starch in the flour of the unroasted non-tannin kernels, hence higher damage starch content.

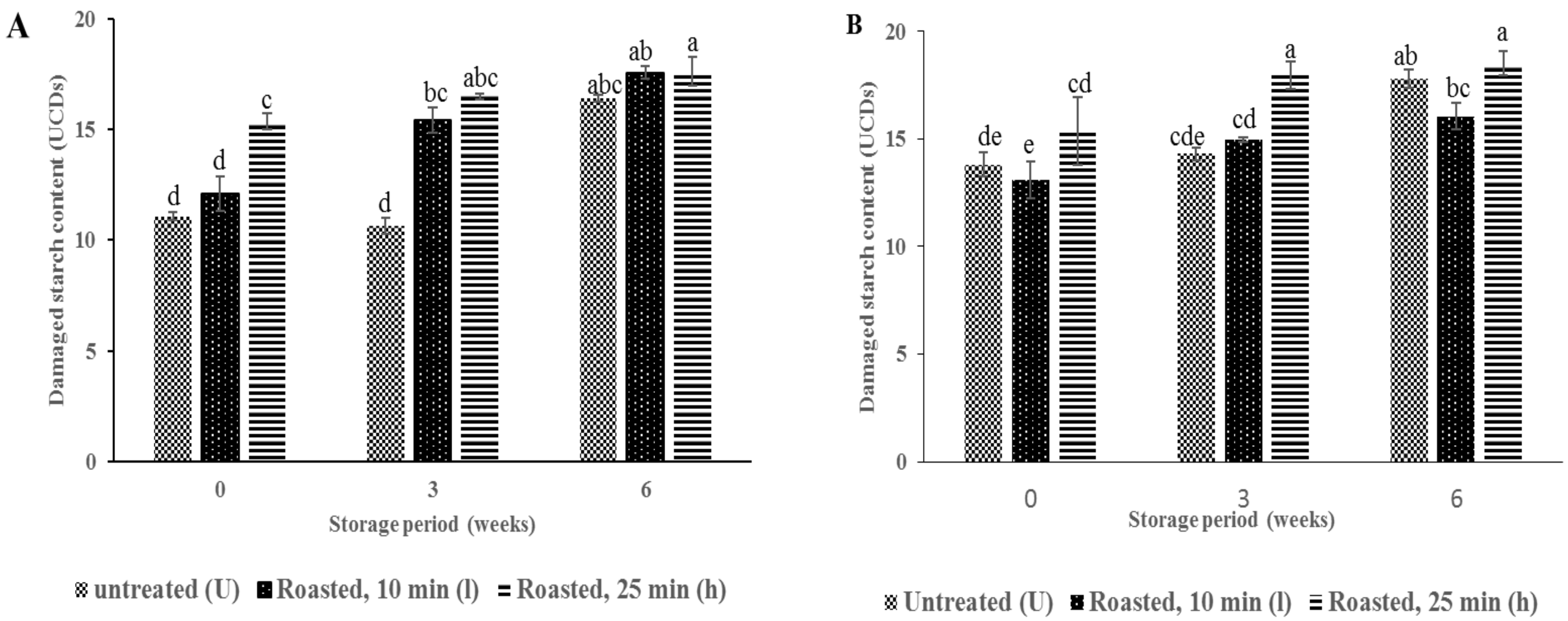

Figure 4.3.5 Effects of roasting non-tannin wholegrain sorghum kernels on damaged starch contents of flours stored as whole (A) and decorticated (B).

Bars with the same shape outline but with different letter(s) differ significantly ($p < 0.05$) for each figure.

4.3.6.2.3 Effect of roasting non-tannin whole grain sorghum on flour (stored) paste viscosity

Roasting non-tannin WGK affected flour paste viscosity of WGF and decorticated grain flour. There was reduction in both peak viscosity (PV) and final viscosity (FV) values of flour pastes from roasted whole and decorticated grain flours compared to their U samples. The PV and FV values of flour pastes from roasted sorghum kernel exhibited a continuous decrease related to an increase in the roasting time. Storage period of flours had a significant effect on the paste viscosity. There were decreases in both PV and FV of flour pastes with flour storage (Figure4.3.6).

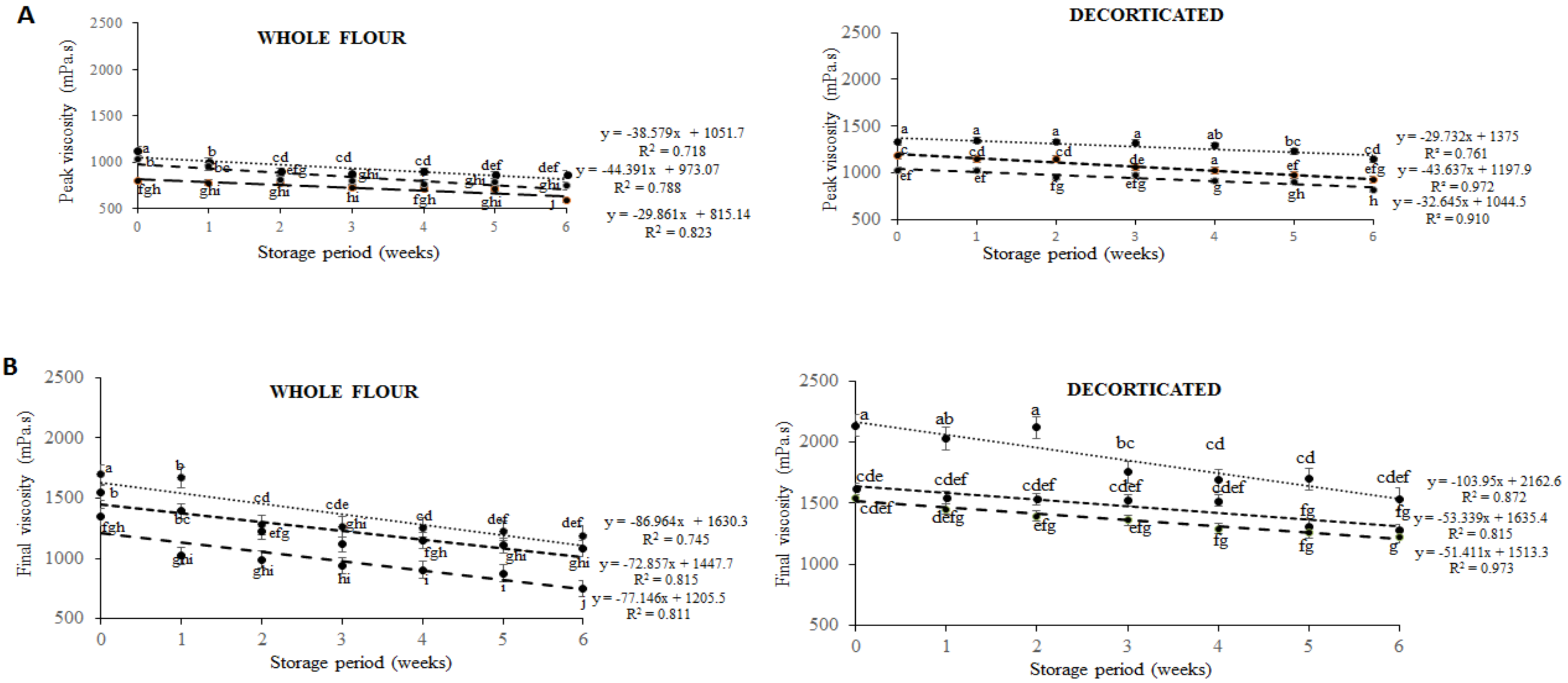

Figure 4.3.6 Effect of roasting of non-tannin wholegrain sorghum kernels on peak viscosity (A) and final viscosity (B) of flour paste from whole and decorticated stored flour.

Value per subgraph with different letter(s) differ significantly ($p < 0.05$).

Circles solid line = Untreated (U), Diamonds dotted line = Roasted, 10 min (l), Squares dashed line = Roasted, 25 min (h).

4.3.6.2.4 Effect of roasting non-tannin sorghum on porridge colour instrumental analysis

There were negligible effects of either roasting non-tannin whole grain sorghum flours or storage on whole flour L* values (Table 4.3.6). Roasting of non-tannin sorghum grains had a negligible effect on its flour a* values (redness/greenness) and b* values (yellowness/blueness) but there was a reduction in redness and yellowness with flour storage. These effects are captured in total colour difference (ΔE*). The ΔE* values of porridge samples ranged between 0.0 and 3.3. With value of ΔE* < 1, colour differences of porridges are not obvious for the human eye, but when ΔE* is 3.3, it implied that the colour differences are obvious for the human eye (Table 4.3.6).

Table 4.3.6 Effects of roasting wholegrain sorghum kernel on L*, a*, b* and ΔE* colour values of porridges prepared from flour stored as a whole

Treatment	**Storage period (weeks)**	**Colour parameters**			
		L*	**a***	**b***	**ΔE***
Unroasted (U)	0	78.6(1.2)	4.63(0.2)b	12.9(0.2)a	0.0
	1	78.5(1.3)	4.62(0.2)b	12.9(0.3)a	0.0
	2	78.5(1.4)	4.32(0.1)cd	11.4(0.3)cde	1.4
	3	80.2(1.8)	4.22(0.1)def	10.8(0.3)f	2.6
	4	802(1.2)	4.48(0.1)bc	11.1(0.3)ef	2.3
	5	79.0(1.7)	4.04(0.1)fg	10.3(0.2)g	2.6
	6	79.3(1.6)	4.02(0.1)fg	11.7(0.2)cd	1.5
Roasted, 10 min (l)	0	78.3(1.3)	4.58(0.1)b	12.3(0.2)b	0.6
	1	78.1(1.1)	4.66(0.1)b	11.8(0.1)c	1.2
	2	78.0(1.5)	4.51(1.1)bc	11.8(0.1)c	1.2
	3	76.7(1.7)	4.92(0.3)a	11.7(0.7)cd	2.1
	4	79.3(1.9)	4.50(0.2)bc	11.7(0.6)cd	1.4
	5	79.0(1.5)	3.97(0.1)g	10.8(0.5)f	2.1
	6	81.0(1.2)	3.64(0.1)h	10.8(0.1)f	3.3
Roasted, 25 min (h)	0	78.4±1.3	4.48(0.1)bc	12.6(0.2ab	0.3
	1	78.9±12	4.31(0.2)cde	11.4(1.1)cde	1.5
	2	79.1±1.3	4.10(0.1)fg	11.3(0.1)de	1.7
	3	79.3±1.2	4.15(0.1)defg	11.1(0.4)ef	1.9
	4	79.4±1.2	4.11(0.1)efg	10.3(0.2)g	2.7
	5	78.6±1.3	4.13(0.1)defg	10.3(0.3)g	2.6
	6	79.8±1.0	4.11(0.1)efg	11.8(1.0)cd	1.2
	p-value	0.433	< 0.0001	< 0.0001	

Values are the means of triplicate determinations. Values with different superscripts within the same column differ significantly ($p < 0.05$). p - value = level of significance. *L** is lightness (0 = black, 100 = white); *a** is red; *b** is yellow; ΔE* is the total colour difference between control and actual sample.

Similarly, roasting and storage of non-tannin sorghum had negligible effects on the L* values of porridges of the decorticated grain flours. There was minimal effect of roasting non-tannin sorghum grains on a* value (ranging from green to red) of porridge but there was a little increase in redness with flour storage. Also, there was little effect of roasting on porridge b* value (ranging from blue to yellow) with flour storage. With decortication, porridges of flour from roasted non-tannin sorghum stored for 6 weeks appeared lighter than those from WGF (Table 4.3.7). The ΔE* of porridge samples ranged between 0.0 and 5.6. Thus, ΔE* is 5.6 for porridges of h flour were perhaps detectable by the human eye because ΔE* > 3 for porridge of flour stored for 5 weeks.

Table 4.3.7 Effects of roasting non-tannin wholegrain sorghum kernel on L*, a*, b* and ΔE* colour values of porridges prepared from flour stored as decorticated

Treatment	Storage period (weeks)	Colour parameters			
		L*	**a***	**b***	**ΔE***
Unroasted (U)	0	$88.1(1.2)^{abcd}$	$1.33(0.1)^{f}$	$11.8(0.2)^{ab}$	0.0
	1	$88.2(1.1)^{ab}$	$1.31(0.2)^{f}$	$11.8(0.6)^{ab}$	0.1
	2	$87.6(1.2)^{bcdef}$	$1.61(0.1)^{de}$	$10.9(0.3)^{bcdef}$	1.1
	3	$87.2(1.1)^{efg}$	$1.48(0.3)^{ef}$	$10.9(0.8)^{bcdef}$	1.3
	4	$87.6(1.7)^{bcdef}$	$1.63(0.2)^{cde}$	$9.9(0.5)^{ef}$	2.0
	5	$87.7(1.3)^{abcdef}$	$1.82(0.1)^{abc}$	$9.8(0.5)^{f}$	2.1
	6	$88.4(1.5)^{ab}$	$1.54(0.4)^{def}$	$13.3(0.8)^{a}$	1.5
Roasted, 10 min (l)	0	$88.0(1.4)^{abcde}$	$1.49(0.1)^{ef}$	$11.0(0.4)^{bcdef}$	0.8
	1	$87.7(1.9)^{bcdef}$	$1.33(0.2)^{f}$	$11.7(0.5)^{abc}$	0.5
	2	$87.3(1.4)^{cdefg}$	$1.66(0.1)^{cde}$	$11.4(0.3)^{bcd}$	1.0
	3	$87.3(1.1)^{cdefg}$	$1.77(0.1)^{bcd}$	$11.2(0.5)^{bcde}$	1.1
	4	$86.6(2.9)^{g}$	$1.64(0.1)^{cde}$	$10.8(0.7)^{bcdef}$	1.8
	5	$86.9(1.3)^{fg}$	$2.00(0.1)^{a}$	$10.4(0.3)^{cdef}$	1.9
	6	$88.0(1.5)^{abcde}$	$1.50(0.1)^{ef}$	$11.8(0.3)^{ab}$	0.1
Roasted, 25 min (h)	0	$87.8(1.5)^{abcde}$	$1.53(0.2)^{ef}$	$10.7(0.5)^{bcdef}$	1.1
	1	$88.2(1.2)^{abc}$	$1.59(0.1)^{de}$	$11.1(0.3)^{bcdef}$	0.7
	2	$88.2(1.6)^{abc}$	$1.51(0.2)^{ef}$	$10.4(0.2)^{cdef}$	1.4
	3	$87.5(1.5)^{bcdefg}$	$1.76(0.1)^{bcd}$	$10.3(0.6)^{def}$	1.7
	4	$88.6(1.3)^{a}$	$1.61(0.3)^{de}$	$10.0(0.5)^{ef}$	1.8
	5	$87.0(1.1)^{efg}$	$1.91(0.2)^{ab}$	$6.3(0.1)^{g}$	5.6
	6	$88.3(1.1)^{ab}$	$1.76(0.1)^{bcd}$	$10.7(0.1)^{bcdef}$	1.1
	p-value	0.010	<. 0.0001	< 0.0001	

Values are the means of triplicate determinations. Values with different superscripts within the same column differ significantly ($p < 0.05$). p-value = level of significance. *L** is lightness (0 = black, 100 = white); *a** is green/red; *b** is blue/yellow; ΔE* is the total colour difference between control (U_0) and actual sample.

4.3.6.2.5 Effect of roasting non-tannin sorghum grains on porridge texture instrumental analysis

Roasting of non-tannin WGK affected the firmness of porridges. There was a significant increase in firmness of WGF porridges while that of decorticated decreased significantly ($p < 0.05$) when compared to their respective controls. With flour storage, porridge firmness decreased gradually in porridge prepared from both whole and decorticated grain flours (Fig 4.3.7).

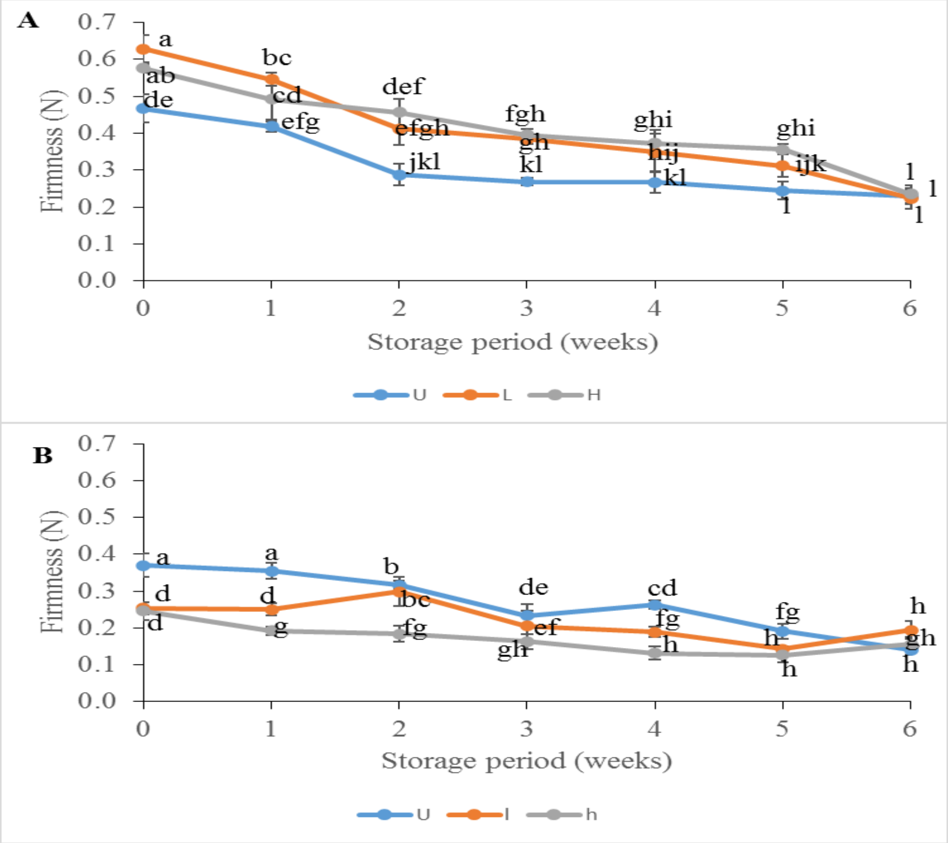

Figure 4.3.7 Effects of roasting non-tannin whole grain sorghum kernels on the firmness of porridges from flours stored as whole (A) and decorticated (B).

Values with different letter(s) differ significantly ($p < 0.05$).

U = Unroasted/untreated, l = roasted for 10 min, h = roasted for 25 min

Figure 4.3.8 showed that roasting non-tannin sorghum grain had no significant ($p > 0.05$) on the stickiness of porridges of whole and decorticated grain flour. However, with flour storage porridges of whole flour were slightly stickier than those of decorticated grain flours (Figure 4.3.7).

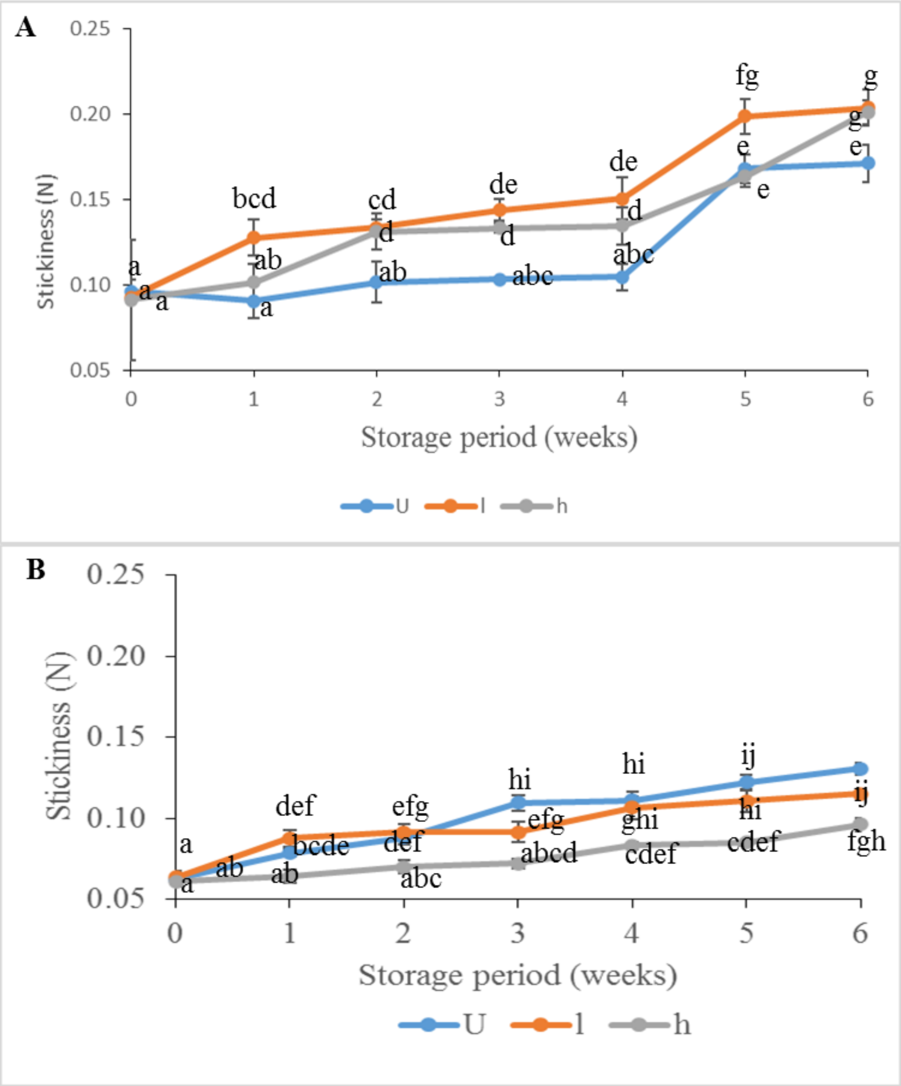

Figure 4.3.8 Effects of roasting non-tannin wholegrain sorghum kernels on stickiness of porridges from flours stored as whole (A) and decorticated (B).

Values with different letter(s) differ significantly ($p < 0.05$).

U = Unroasted/untreated, l = roasted for 10 min, h = roasted for 25 min

4.3.6.2.6 Descriptive sensory evaluation of porridge

At baseline, porridges based on the extent of roasting treatments (0, 10 and 25 min) applied to WGK significantly ($p < 0.05$) differ in ten sensory attributes (in bold characters). Roasting non-tannin WGK affected the aroma, appearance, mouthfeel/texture, taste and flavour of porridges prepared from WGF (Table 4.3.8). For instance, roasting reduced painty aroma, starch flavour and grainy texture of WGF porridge (Table 4.3.8).

Table 4.3.8 Descriptive sensory ratings of porridges from non-tannin whole sorghum flours at baseline (week 0) for unroasted (U0) and roasted kernels (l0 and h0)

	Sensory attribute	**Treatment**			**p-value**
		Unroasted (U$_0$)	**Roasted, 10 min (l$_0$)**	**Roasted, 25 min (h$_0$)**	
Aroma	Overall	6.7 (2.4)	6.2 (2.2)	7.3 (1.3)	0.211
	Earthy	3.4 (2.9)	3.3 (2.8)	3.1 (2.7)	0.916
	Sweet	3.1(3.0)	2.8 (2.6)	3.3 (2.6)	0.857
	Roasted	2.7 (2.7)	2.9 (2.8)	3.2 (2.7)	0.814
	Burnt	1.5 (2.1)	1.0 (2.1)	0.8 (1.2)	0.500
	Sorghum	5.2 (2.5)	4.6 (3.4)	5.6 (2.7)	0.541
	Wet Cardboard	2.6 (2.7)	2.8 (3.2)	3.1 (3.1)	0.869
	Starchy	4.5 (3.0)	4.6 (3.2)	3.7 (2.70	0.574
	Oily	2.3 (1.8)	1.8 (2.3)	1.6 (1.9)	0.615
	Painty	**2.2 (2.6)^a**	**0.6 (0.8)^b**	**0.9 (1.5)^b**	**0.018**
	Rancid	1.7 (1.1)	0.8 (1.4)	1.1 (2.3)	0.284
	Fermented	2.8 (2.0)	2.3 (2.4)	2.6 (2.4)	0.807
	Wheaty	3.3 (3.1)	3.3 (3.3)	3.5 (2.6)	0.967
	Cooked maize meal porridge	2.1 (2.0)	3.1 (2.8)	1.4 (1.7)	0.076
	Fruity	1.4 (2.2)	1.5 (2.2)	1.2 (1.8)	0.888
	Spicy	1.0 (1.2)	1.5 (2.2)	0.6 (1.0)	0.178
	Grassy aroma	**1.3 (2.0)^b**	**4.6 (3.1)^a**	**2.5 (2.3)^b**	**0.001**
Appearance	**Brown colour**	**7.6 (1.5)^a**	**3.9 (4.3)^b**	**8.2 (1.8)^a**	**<0.0001**
	Specks	6.0 (2.8)	7.8 (1.7)	6.5 (2.9)	0.090
	Viscosity	**6.8 (2.3)^b**	**5.6 (2.4)^b**	**7.7 (2.0)^a**	**0.019**
	Glossy	**7.8 (1.5)^a**	**3.3 (2.1)^b**	**8.1 (1.7)^a**	**< 0.0001**
	Sticky	**5.4 (2.1)^a**	**1.1 (1.8)^b**	**4.9 (2.1)^a**	**< 0.0001**
Taste/flavour	**Bitter taste**	**2.3 (2.2)^b**	**5.6 (3.2)^a**	**5.9 (2.2)^b**	**< 0.0001**
	Sour taste	1.6 (2.0)	0.9 (1.5)	0.9 (1.4)	0.369
	Sweet taste	**1.5 (2.2)^b**	**3.7 (2.7)^a**	**3.9 (1.4)^b**	**0.000**
	Starch flavour	**4.8 (3.0)^a**	**1.5 (2.4)^b**	**4.0 (2.8)^a**	**0.002**
	Bland flavour	4.6 (2.9)	6.3 (2.2)	6.1 (2.3)	0.089
Mouthfeel/texture	Stickiness	3.1 (2.5)	1.6 (1.7)	2.5 (1.9)	0.080
	Grainy	**4.8 (2.5)^a**	**0.3 (0.7)^c**	**3.3 (2.9)^b**	**< 0.0001**
	Astringent	4.0 (2.2)	4.1 (1.9)	2.8 (2.4)	0.152
Aftertaste	Bitter aftertaste	1.4 (1.6)	1.1 (1.9)	1.3 (1.9)	0.858
	Oily aftertaste	1.2 (1.3)	1.0 (1.5)	1.9 (2.1)	0.278
	Rancid aftertaste	1.5 (1.9)	1.8 (2.2)	0.8 (1.5)	0.254
	Sour aftertaste	1.5 (2.2)	2.6 (3.0)	1.4 (2.2)	0.237
	Sweet aftertaste	0.9 (1.7)	2.3 (3.1)	1.2 (1.6)	0.128
	Residual particles	3.4 (2.8)	3.1 (3.4)	3.3 (3.0)	0.948

Values are the means of duplicate determinations. Standard deviations are in parentheses. Values within the same row followed by different letters differ significantly ($p < 0.05$). p - value = level of significance.

Attributes printed in bold indicate significant ($p < 0.05$) differences in rows between treatments from descriptive sensory panels (n = 10) in two replicate sessions.

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The porridges of decorticated grain flours based on the extent of roasting treatments (0, 10 and 25 min) applied to WGK significantly ($p < 0.05$) differed in only five sensory attributes (in bold character), notably are rancid and fermented aroma, brown colour, visible specks and residual particles (Table 4.3.9). Similarly, roasting reduced rancid and fermented aromas, residual particles with the decorticated grain flour porridges (Table 4.3.9). Roasting duration (l = roasted for 10 min and h = roasted for 25 min) affected porridge sensory attributes. Porridges of decorticated grain flours tasted less rancid with fermented aroma but appeared darker with more specks.

Table 4.3.9 Descriptive sensory ratings of porridges of flours from non-tannin decorticated grain at baseline (week 0) for unroasted (U) and roasted kernels (l and h)

		Treatment			
	Sensory attribute	**Unroasted (U_0)**	**Roasted, 10 min (l_0)**	**Roasted, 25 min (h_0)**	**p-value**
Aroma	Overall	7.6 (1.7)	6.2 (2.2)	6.7 (1.8)	0.067
	Earthy	3.8 (3.3)	3.2 (2.7)	3.4 (2.6)	0.799
	Sweet	2.8 (2.9)	2.8 (2.5)	2.2 (2.5)	0.752
	Roasted	2.2 (3.0)	2.6 (2.5)	2.6 (2.4)	0.837
	Burnt	1.7 (2.8)	0.7 (1.5)	1.2 (1.6)	0.317
	Sorghum	3.9 (3.4)	4.5 (3.3)	3.2 (3.2)	0.452
	Wet cardboard	3.8 (3.5)	2.6 (2.9)	2.9 (3.1)	0.462
	Starchy	6.5 (1.6)	4.5 (3.1)	5.1 (3.4)	0.073
	Oily	2.0 (2.4)	1.7 (2.1)	1.7 (2.1)	0.880
	Painty	1.5 (2.5)	0.8 (1.4)	0.4 (0.6)	0.134
	Rancid	**2.5 (2.6)^a**	**0.8 (1.4)^b**	**0.6 (1.2)^b**	**0.005**
	Fermented	**4.1 (2.4)^a**	**2.2 (2.3)^b**	**1.6 (1.6)b**	**0.002**
	Wheaty	4.1 (3.7)	3.0 (3.1)	2.6 (2.9)	0.347
	Cooked maize meal porridge	4.2 (3.5)	2.8 (2.8)	4.2 (3.5)	0.337
	Fruity	1.3 (2.2)	1.3 (2.1)	0.7 (1.1)	0.518
	Spicy	0.5 (0.7)	0.4 (0.5)	0.6 (1.2)	0.795
	Grassy	0.5 (0.7)	1.8 (2.2)	1.3 (2.5)	0.138
Appearance	**Brown colour**	**3.5 (3.9)^a**	**3.4 (4.2)^a**	**0.4 (0.5)^b**	**0.001**
	Specks	**3.8 (3.1)^a**	**3.6 (3.0)^a**	**1.8 (2.2)^b**	**0.009**
	Viscosity	7.8 (1.7)	7.9 (1.7)	7.6 (2.2)	0.838
	Glossy	8.2 (1.9)	8.3 (1.3)	8.8 (1.1)	0.467
	Sticky	5.5 (3.0)	5.5 (2.3)	5.3 (2.4)	0.962
Taste/flavour	Bitter taste	1.7 (2.0)	1.7 (2.5)	2.4 (2.5)	0.632
	Sour taste	1.1 (1.9)	1.4 (1.9)	2.1 (2.7)	0.356
	Sweet taste	1.1 (1.7)	1.0 (1.7)	1.8 (2.0)	0.307
	Starch flavour	5.7 (2.4)	5.5 (3.1)	6.4 (1.9)	0.477
	Bland flavour	6.0 (3.2)	5.8 (2.2)	5.7 (2.6)	0.952
Mouthfeel/texture	Stickiness	3.5 (3.0)	2.7 (2.5)	2.5 (1.9)	0.398

Aftertaste	Grainy	3.7 (3.0)	2.9 (2.5)	2.7 (3.0)	0.509
	Astringent	3.7 (2.5)	3.2 (1.9)	2.7 (3.0)	0.337
	Bitter	1.4 (2.0)	1.3 (2.3)	1.6 (2.5)	0.891
	Oily	1.3 (1.9)	1.7 (1.7)	1.7 (1.7)	0.786
	Rancid	0.6 (1.3)	0.2 (0.5)	0.2 (0.3)	0.150
	Sour	1.1 (1.9)	1.1 (1.9)	1.2 (2.0)	0.987
	Sweet	1.1 (1.6)	0.9 (1.4)	1.3 (2.5)	0.827
	Residual	**4.7 (3.1)^{a}**	**3.2 (2.7)^{ab}**	**2.3 (2.7)^{b}**	**0.035**

Values are the means of duplicate determinations. Standard deviations are in parentheses. Values within the same row followed by different letters differ significantly ($p < 0.05$). p-value = level of significance.
Attributes printed in bold indicate significant ($p < 0.05$) differences in rows between treatments among treatments from descriptive sensory panels (n = 10) in two replicate sessions.

Only the sensory attributes that described significant ($p < 0.05$) differences among the porridges prepared from stored flours are presented in Tables 4.3.10. These sensory attributes prevailing in porridge samples from non-tannin WGF are oily, painty, rancid and fermented aromas, brown colour, glossy appearance, sticky texture, bitter and sweet tastes and grainy mouthfeel. The large standard deviations (SD) for some of the sensory attributes (SD value range from 0.7-3.2) indicated widespread differences in perceptions of the panellists, probably contributing to the lack of more differences noticed among the porridges. Despite the wide range in SD, the data are still useable because they were generated by trained panellists. With flour storage, increase in the intensities of oily, painty, rancid and fermented aromas were mostly obvious for porridge of U WGF (Table 4.3.11). Other sensory attributes not printed bold (Table 4.3.8 and 4.3.9) are not significantly ($p > 0.05$) different with the treatments and storage. However, increasing trends were observed in some of the attributes of porridge such as brown specks and bland flavour (Table 4.3.8), glossiness, bitter taste and starch flavour (Table 4.3.9).

Table 4.3.10 Effects of roasting non-tannin whole grain sorghum kernels on sensory attributes* of porridges prepared from stored whole flour

	Storage period (week)	Oily aroma	Painty aroma	Rancid aroma	Fermented aroma	Brown colour	Glossy	Sticky	Bitter taste	Sweet taste	Grainy
Unroasted (U)	0	2.3 (1.8)^{def}	2.2 (2.6)^{c}	1.7 (1.1)^{cd}	2.8 (2.0)^{c}	7.6 (1.5)^{ab}	7.8 (1.5)^{ab}	5.4 (2.1)abc	2.3(2.2)bcd	1.5(2.2)b	4.8(2.5)bcde
	1	2.4 (1.7)^{def}	2.0 (1.8)^{cde}	1.2 (1.8)^{cde}	3.0 (2.6)^{c}	7.9 (2.9)^{ab}	8.2 (1.5)^{a}	3.2 (2.4)e	3.7(2.8)bcd	1.1(1.7)b	4.7(3.2)cde
	2	3.3 (2.0)^{d}	1.2 (2.3)^{cdefg}	1.7 (2.5)^{cd}	2.7 (3.2)^{cd}	7.0 (1.9)^{b}	5.7 (2.7)^{def}	5.7 (2.7)abc	2.9(3.1)bcd	1.0(1.8)b	6.4(2.7)abc
	3	4.7 (1.8)^{c}	1.8 (1.6)^{cdef}	1.7 (2.4)^{cd}	2.4 (2.5)^{cd}	7.3 (2.3)^{ab}	5.8 (2.8)^{def}	5.2 (2.9)abcd	3.2(3.9)bcd	1.2(2.0)b	5.5(3.1)abcd
	4	5.4 (1.4)^{c}	4.6 (2.3)^{b}	4.2 (2.4)^{b}	4.6 (1.7)^{b}	7.7 (1.8)^{ab}	5.3 (3.1)^{ef}	4.9 (3.2)abcd	4.0(3.9)abc	0.8(1.6)b	5.6(3.0)abcd
	5	6.9 (1.4)^{b}	7.2 (1.6)^{a}	6.2 (1.8)^{a}	7.4 (1.6)^{a}	7.2 (1.9)^{ab}	5.3 (2.2)^{ef}	5.1 (2.5)^{abcd}	2.9(3.3)bcd	0.8(2.0)b	6.5(2.9)a
	6	8.4 (1.1)^{a}	7.6 (1.4)^{a}	7.3 (1.1)^{a}	7.3 (1.7)^{a}	7.8 (1.7)^{a}b	5.2 (2.5$^{)f}$	4.8 (2.4)^{abcd}	4.2(3.8)ab	0.9(1.6)b	6.1(2.4)abcd
Roasted-10 min (l)	0	1.9 (2.2)^{ef}	0.8 (1.4)^{fg}	0.8 (1.4)^{cde}	2.3 (2.3)^{cd}	4.1 (4.2)^{c}	3.5 (2.1)^{g}	1.2 (1.8)^{f}	5.7(3.2)a	3.8(2.7)a	0.3(0.7)f
	1	1.5 (1.7)^{f}	0.6 (1.1)^{fg}	0.1 (0.2)e	1.3 (1.3)^{d}	8.0 (1.6)^{ab}	6.8 (1.7)^{abcde}	5.4 (2.3)^{abcd}	2.3(2.3)bcd	0.8(1.2)b	6.4(2.6)ab
	2	1.4 (1.8)^{f}	1.2 (2.2)^{cdefg}	0.9 (2.1)^{cde}	2.7 (2.6)^{cd}	7.7 (1.8)^{ab}	6.3 (2.9)^{cdef}	4.9 (2.6)^{abcd}	2.0(2.8)cd	0.9(1.6)b	6.4(2.6)abc
	3	2.2 (3.1)^{def}	1.4 (2.4)^{cdefg}	1.1 (3.0)^{cde}	2.2 (2.6)^{cd}	7.8 (2.0)^{ab}	6.2 (2.5)^{cdef}	4.6 (3.0)^{abcde}	3.5(3.4)bcd	1.0(1.4)b	6.0(2.4)abcd
	4	1.4 (1.8)^{f}	0.6 (1.1)^{fg}	0.5 (1.2)^{de}	2.3 (2.6)^{cd}	8.2 (1.7)^{ab}	5.9 (2.6)^{def}	4.5 (2.9)^{bcde}	2.7(3.0)bcd	0.8(2.0)b	6.5(2.6)a
	5	2.3 (2.8)^{def}	0.5 (1.1)^{g}	0.9 (1.8)^{cde}	2.1 (2.3)^{cd}	8.2 (1.6)^{ab}	5.6 (2.3)^{ef}	4.8 (2.8)^{abcd}	2.5(3.2)bcd	0.6(1.6)b	6.0(2.8)abcd
	6	2.9 (3.3)^{de}	1.3 (2.4)^{cdefg}	1.8 (3.1)^{c}	1.6 (2.4)^{cd}	8.4 (1.4)^{a}	5.9 (2.7)^{def}	4.3 (2.7)^{cde}	3.0(3.5)bcd	0.9(1.4)b	6.0(2.0)abcd
Roasted-25 min	0	1.6 (1.9)^{ef}	0.9 (1.5)^{efg}	1.1 (2.3)^{cde}	2.6 (2.4)^{cd}	8.2 (1.8)^{ab}	8.1 (1.7)^{ab}	4.9 (2.1)^{abcd}	1.9(2.2)d	0.9(1.4)b	3.3(2.9)e
	1	2.1 (1.7)^{def}	0.9 (1.2)^{defg}	1.2 (1.7)^{cde}	2.9 (2.3)^{c}	7.6 (1.7)^{ab}	7.5 (1.8)^{abc}	5.9 (2.5)^{ab}	2.4(2.7)bcd	0.7(1.1)b	4.6(3.0)de
	2	1.6 (2.0)^{ef}	0.7 (1.1)^{fg}	0.5 (0.7)^{de}	2.1 (2.3)^{cd}	7.1 (2.2)^{ab}	6.6 (2.1)^{bcdef}	5.0 (2.1)^{abcd}	2.6(3.2)bcd	1.7(2.5)b	6.0(2.8)abcd
	3	1.7 (2.5)^{ef}	2.1 (3.3)^{cd}	1.3 (2.4)^{cde}	2.2 (2.9)^{cd}	7.7 (1.9)^{ab}	5.7 (3.0)^{def}	6.2 (2.7)^{a}	2.0(2.8)d	1.1(1.6)b	6.0(2.9)abcd
	4	1.6 (2.0)^{ef}	1.0 (1.7)^{cdefg}	0.8 (2.0)^{cde}	1.8 (2.5)^{cd}	7.6 (2.3)^{ab}	7.2 (2.1)^{abcd}	3.8 (2.8)^{de}	3.6(3.5)bcd	1.5(2.3)b	5.9(2.8)abcd
	5	2.0 (2.5)^{def}	0.8 (1.3)^{fg}	1.3 (2.5)^{cde}	1.9 (2.5)^{cd}	7.8 (1.9$^{)ab}$	6.2 (2.3)^{cdef}	4.4 (2.4)^{bcde}	2.2(3.0)cd	0.8(1.8)b	6.5(2.8)a
	6	2.0 (2.5)^{def}	0.9 (2.2)^{efg}	1.8 (2.7)^{c}	1.7 (2.2)^{cd}	8.1 (1.6)^{ab}	5.9 (2.8)^{def}	5.0 (2.7)^{abcd}	3.4(3.4)bcd	0.8(1.6)b	5.9(2.8)abcd
	p-value	< 0.0001	< 0.0001	< 0.0001	< 0.0001	< 0.0001	< 0 .0001	< 0.0001	0.030	0.003	0.001

*Note: only sensory attributes that describe significant differences ($p<0.05$) in columns between treatments among the porridge samples are presented. p-value = level of significance. Values are the means of duplicate determinations. Values within the same column followed by different letters differ significantly ($p < 0.05$) from panellists ($n = 10$) in two replicate sessions. Standard deviations are in parentheses. p = level of significance.

Porridge samples made with decorticated kernel flours stored over time displayed significant ($p < 0.05$) differences are presented in Table 4.3.11. Three (3) sensory attributes that described significance in this respect are rancid aroma, brown colour and stickiness (Table 4.3.11). There was a dramatic reduction in brown colour after 1-week of flour storage with the U and l decorticated kernel flour porridges. Darker brown appearance and stickiness of porridge were not obviously increasing due to flour storage (Table 4.3.11). Rancidity was clearly noticed in porridges made from U roasted kernels 'flour, and it increased during the storage, whereas porridges made from l and h roasted kernels' flour were evaluated less rancid.

Table 4.3.11 Effects of roasting non-tannin of wholegrain sorghum kernel on sensory attributes* of porridges prepared from flour stored as decorticated

Treatment	Storage period (weeks)	Rancid aroma	Brown colour	Stickiness
Unroasted	0	2.5 (2.6)^{cde}	3.6 (3.9)^{a}	3.6 (3.0)^{ab}
	1	2.9 (3.9)^{bcd}	0.1 (0.2)^{b}	5.4 (3.0)^{a}
	2	1.8 (2.6)^{def}	0.1 (1.2)^{b}	2.9 (2.5)^{bcd}
	3	1.6 (3.1)^{defg}	0.7 (2.2)^{b}	1.5 (2.1)^{cd}
	4	3.3 (2.2)^{bc}	0.2 (0.2)^{b}	3.0 (2.6)^{bc}
	5	3.9 (2.1)^{b}	0.2 (0.3)^{b}	3.5 (3.1)^{b}
	6	6.0 (1.3)^{a}	0.6 (2.2)^{b}	3.0 (2.4)^{bc}
Roasted-10 min	0	0.8 (1.4)^{fg}	0.4 (0.5)^{b}	2.7 (2.5)^{bcd}
	1	0.5 (0.7)^{fg}	0.3 (0.3)^{b}	1.3 (1.4)^{d}
	2	0.8 (1.5)^{fg}	0.2 (0.3)^{b}	2.6 (2.5)^{bc}
	3	0.8 (2.1)^{fg}	0.3 (0.4)^{b}	2.6 (2.1)^{bcd}
	4	0.7 (1.9)^{fg}	0.4 (0.4)^{b}	2.8 (1.1)^{bcd}
	5	1.3 (1.8)^{efg}	0.5 (1.0)^{b}	3.1 (3.0)^{b}
	6	1.0 (1.7)^{fg}	0.3 (0.3)^{b}	2.9 (2.7)^{bcd}
Roasted-25 min	0	0.6 (1.2)^{fg}	4.3 (4.2)^{a}	2.5 (1.9)^{bcd}
	1	0.2 (0.4)^{g}	0.2 (0.3)^{b}	2.1 (2.4)^{bcd}
	2	1.0 (1.7)^{fg}	0.2 (0.2)^{b}	2.2 (2.2)^{bcd}
	3	1.2 (2.4)^{efg}	0.3 (0.6)^{b}	2.2 (2.7)^{bcd}
	4	1.2 (2.4)^{efg}	0.2 (0.3)^{b}	2.5 (3.0)^{bcd}
	5	1.4 (2.9)^{efg}	0.3 (0.5)^{b}	2.4 (2.8)^{bcd}
	6	1.5 (2.8)^{efg}	0.2 (0.3)^{b}	2.7 (2.7)^{bcd}
	p-value	0.002	< 0.0001	0.019

Values are the means of duplicate determinations. Standard deviations are in parentheses Values within the same column followed by different letters differ significantly ($p < 0.05$). p-value = level of significance.

*Note: only sensory attributes as determined by panellist ($n = 10$) in two replicate sessions that describe significant differences ($p<0.05$) in columns between treatments among the porridge samples are presented.

A multivariate data analysis model was used to summarize the variation in the descriptive sensory attributes of sorghum porridge samples (Figures 4.3.9 and 4.3.10). Figure 4.3.9 shows principal component analysis (PCA) plot of sensory attributes of porridge samples prepared from the WGF of U, l and h flours stored for up to 6 weeks. The first two PCs described near 75 % of the total variation. It gives a very good view of the relationship between 11 attributes that were significant ($p < 0.05$) due to treatment x storage interaction effects. PC1 explained nearly 45 % of the total variation and shows porridges of U non-tannin WGF on the right-hand side of the plot was to a greater extent separated completely from those of roasted (l and h) on the left-hand side. The porridge from the stored flours prepared from U flours were associated with fermented, painty, oily and rancid aroma, and furthermore, the porridge was darker, sticky and grainy. Porridge on the left-hand side of the plot included mostly l and h WGF and partly those of U at early period of flour storage (U_0 = unroasted at week 0 and U_1= unroasted at week 1). Porridges from all the flours (both unstored and stored) prepared from l and h WGK were associated with a glossy appearance. The second principal component (PC2) added 30 % to the explanation of variation and separated completely l_0 on the upper side of the plot from the others. Only porridge from the 10 min roasting treatment which had not been stored (0 week) was associated with a sweet taste.

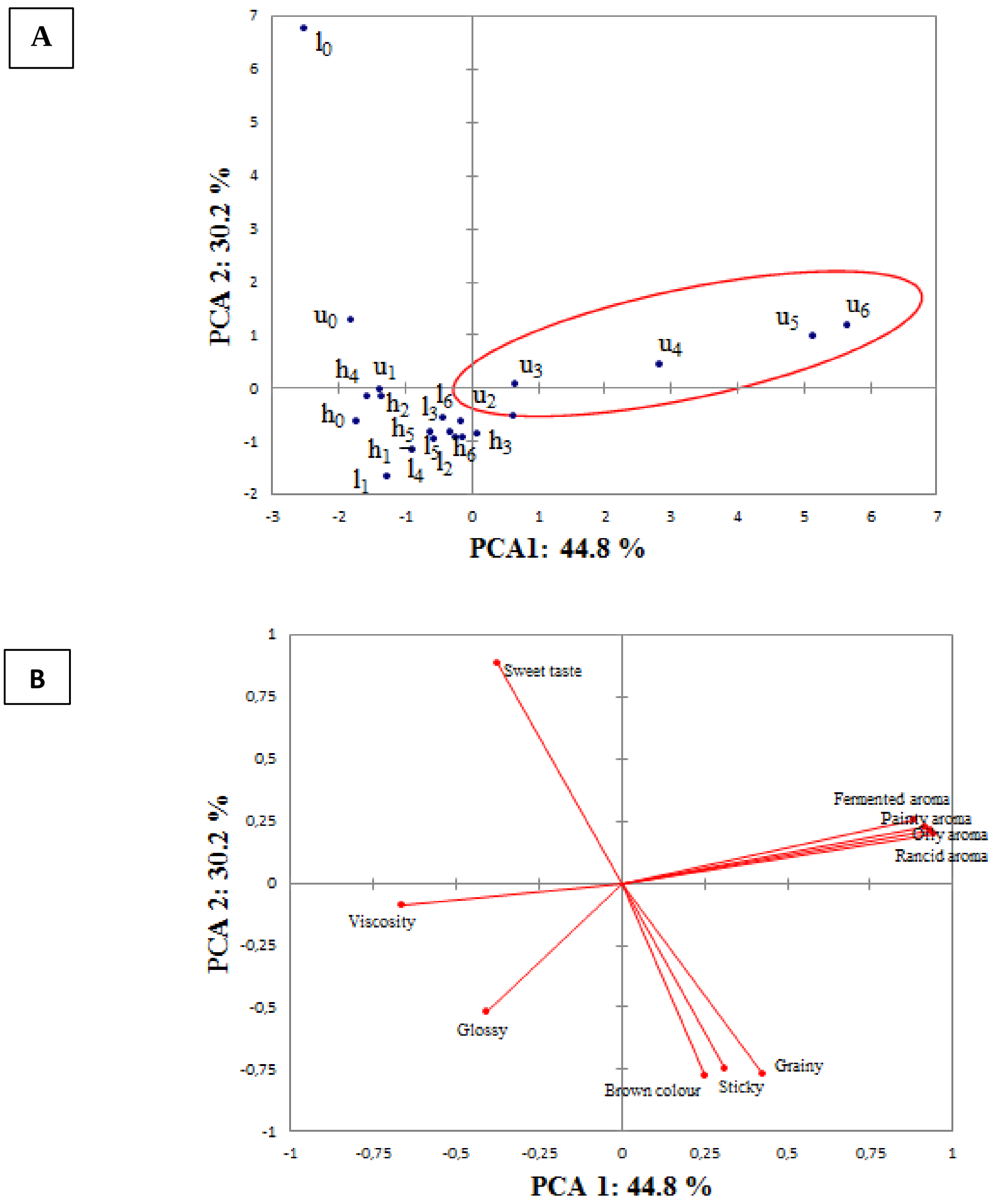


Figure 4.3.9 Principal component analysis (PCA) plot of the sensory attributes of porridges prepared from whole flour of unroasted and roasted non-tannin sorghum kernels stored for up to 6 weeks.

A: Sample treatments and storage**:** U (Unroasted control)**,** l (roasted for 10 min) and h (roasted for 25 min). 0-6 (storage period (weeks) of sorghum kernel flours)

B: PCA loading projections of sensory attributes**:** fermented, painty, oily and rancid aromas, grainy, sticky, brown colour, glossy, viscosity and sweet taste.

Red ring on the score plot shows the rate of porridge attribute change with untreated grain flour of over storage period

A PCA summary of the changes in sensory properties of porridge from decorticated kernel stored flours (Figure 4.3.10). PC1 explained 44.8 % of the sensory variation among the porridge samples. It showed demarcation towards the right side only with porridge samples characterized mainly by intense brown colour, stickiness and rancid aroma. However, for the decorticated kernel flour, only three sensory attributes notably, brown colour, stickiness and rancid aroma showed significant ($p < 0.05$) difference due to the treatment and storage interaction effects. Stickiness and rancid aroma were positively correlated with each other and were completely separated from the brown colour.

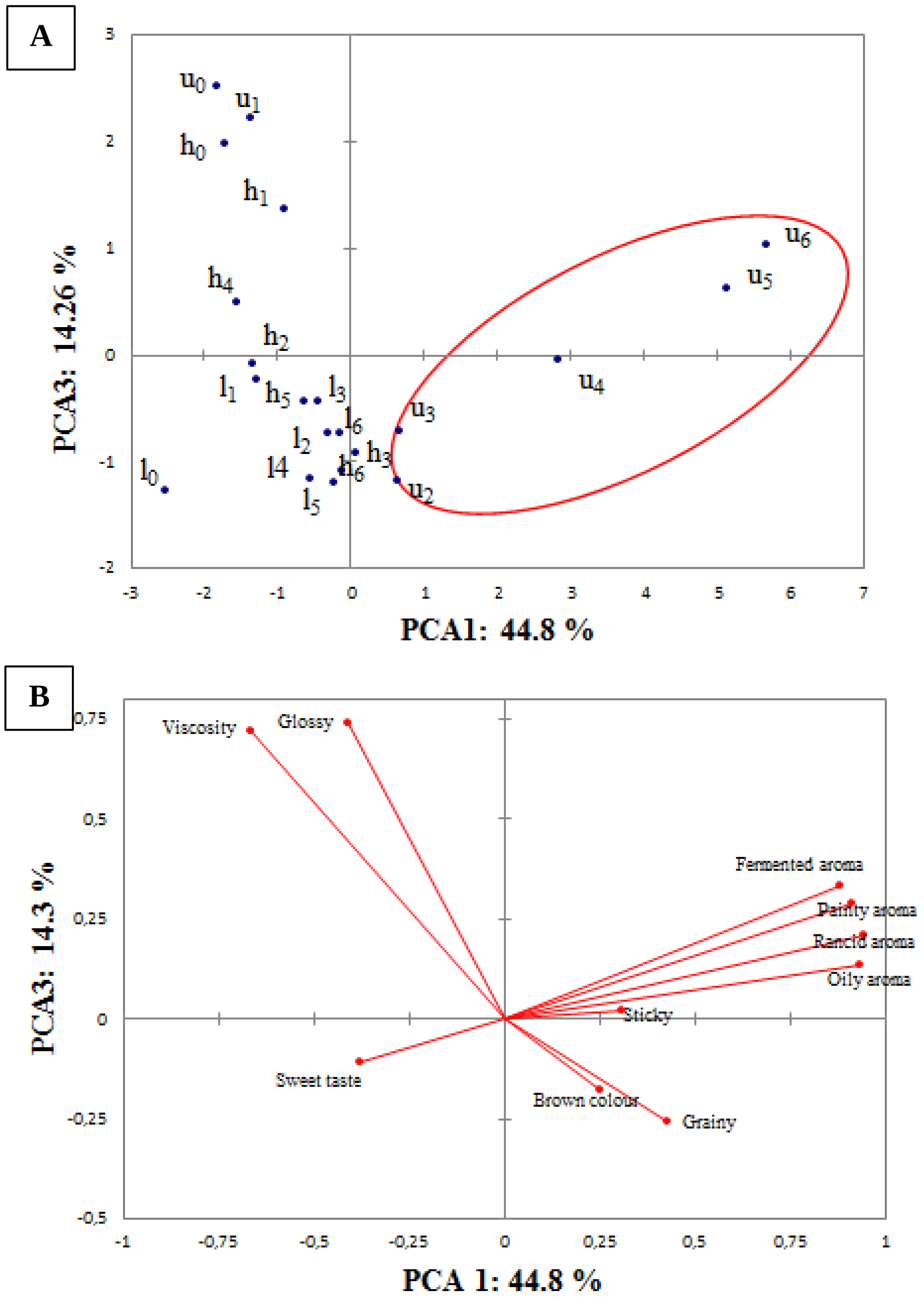


Figure 4.3.10 Principal component analysis (PCA) plot of the sensory attributes of porridges prepared from the decorticated kernel flour of unroasted and roasted non-tannin sorghum kernels stored for up to 6 weeks.

A: Sample treatments and storage**:** U (Unroasted control)**,** l (roasted for 10 min) and h (roasted for 25 min). 0-6 (storage period (weeks) of sorghum kernel flours)

B: PCA loading projections of sensory attributes**:** rancid aromas, stickiness and brown colour.

Red ring on the score plot shows the rate of porridge attribute change with untreated grain flour over storage period

4.3.7 Discussions

4.3.7.1 Properties of flours of roasted tannin and non-tannin sorghum grain

Roasting could have converted grain moisture into vapour and hence allowing for moisture loss which could be attributed to water evaporation (Jogihalli et al., 2017). During the hot-air roasting of sorghum grains part of the bound water could have been converted to free water that evaporated at elevated temperature of roasting. Though very low moisture content in flours may improve the shelf stability but during storage the flour may rapidly pick-up mixture and return to the 10 % moisture content. A 10% flour moisture content is totally microbiological safe moisture content. The moisture contents of flours from the pearl millet grains that were subjected to the different thermal treatments increased significantly during storage (Nantanga et al., 2008).

Fat acidity of flours decreased upon roasting sorghum kernels. The decrease in fat acidity may be attributed to inactivation of lipase enzymes and consequently lesser fat degradation by lipolysis (Goyal et al., 2017). The decrease in fat acidity of flours upon roasting sorghum grains concurs with the explanation of Nantanga et al. (2008) that thermal treatment millet grains significantly reduce fat acidity generation in flour due to inactivation of lipase enzymes. Similarly, in our previous study using microwave treatment of non-tannin wholegrain sorghum kernels to stabilize the whole flour, we found that the treatment partially inactivated the flour lipases and consequently slowed free fatty acid oxidation (Chapter 4.2).

Roasting process of tannin wholegrain sorghum caused an increase in TPC of the flour, whereas roasting led to a reduction in TPC of other flours (Table 4.3.2). The trends show that TPC for roasted sorghum (tannin decorticated and non-tannin) was in the order-10 min > 15 min > 20 min >25 min. Thus, increase in phenolic contents of tannin wholegrain sorghum flour due to roasting suggested an increase in in vitro antioxidant activities and free radical scavenging capacities (Zhu et al., 2019). An increase in TPC from 2.64 to 4.67 mg GAE/100 g upon microwave roasting has been reported for red sorghum by Sharanagat et al. (2019). Roasting of wholegrain tannin sorghum may cause the release of more bound phenolics through the disruption of cellular constituents (Wani et al., 2016) to simple phenolics and thus enhance increasing levels of measurable phenols (Duodu, 2014). This relationship agrees with several previous studies on the positive correlations between TPC and in vitro antioxidant activities measured by ABTS assay (Awika et al., 2004). Roasting can induce Maillard reaction with the ultimate production of many compounds such as melanoidins, which have AOA (Topuz & Pischetsrieder, 2009) and react with Folin-Ciocalteu reagent (Wani et al., 2016).

However, TPC is generally reduced due to roasting for other flour forms. Decortication of tannin sorghum grain caused a substantial decrease in TPC. This is because phenolic compounds generally are not evenly distributed across the sorghum grain; they are concentrated in greater amounts mainly in the bran (Chandrasekara & Shahidi, 2010) and the content of phenolics is reduced with decortication. Further, these components were having less contamination with endosperm, because during the early stages of decortication, minimal disruption of sorghum kernels occur (Buitimea-Cantua, Torres-Chavez, Ledesma-Osuna, Ramırez-Wong, Robles-Sanchez, & Serna-Saldıvar2013). As the decortication of sorghum kernels was prolonged, the exposure and endosperm rupture increased too. This possibly diluted the concentration of phenols present in the kernel flours (Awika et al., 2005). Like present study, a study on the effect of decortication yield of millet by Bora et al. (2019) also show a decrease in TPC due to decortication on millet grains, however the authors concluded that mixed results are imminent depending on the variety of millet selected.

There were no significant differences in L* (lightness) values of flours from roasted grains compared to those of unroasted (control) samples. Except for flour from wholegrain tannin-free, the a* and b* values of others flour from roasted grains were not statistically different. However, there was a decrease in *L** values and an increase in a* and b* values of flour due to the roasting of sorghum grains but the colour differences were not visible to confirm the instrumental or colorimeter values. The decrease in a* and b* values observed in the flours (decorticated, tannin and non-tannin) could be due to the removal of the bran by decortication (Awika, 2017). Similar reduction in a* and b* values have been reported for sorghum (Meera et al., 2011) after heat treatments of the kernels. The changes in total colour differences (ΔE*) of flours could be an indication of the overall colour deviation from the standard white during roasting of the sorghum grain.

Reduction in pasting viscosity of flour during pasting could be due to non-swelling of starch granules in sorghum flour (Ranganathan et al., 2013). Increased roasting time might have resulted in case hardening which could reduce water uptake required by flour for swelling of the starch granules, thus less swelling and pasting characteristics are adversely affected (Ranganathan et al., 2013). Further, the presence of amylose and native lipids in sorghum grains might have formed amylose-lipid complexes (Wokadala et al., 2012). The formation of a lipid layer on the granular surface could inhibit water uptake due to the hydrophobic nature of the complexes and prevent swelling (Sharma & Gujral, 2019). There is an increase in the setback values recorded in flours from roasted tannin grains when compared to the unroasted samples.

The WAI is an index of gelatinization that measures the amount of water absorbed by starch, protein and other molecules while WSI of the product will depend on the protein and starch from the sorghum flour and their interaction with water (Qu et al., 2017). Increasing roasting time of sorghum significantly ($p < 0.05$) increases WAI and reduces WSI of their flour (Table 4.3.4). The increase in WAI could be attributed to an increase in the level of starch damage during the roasting process of the grains (Wani et al., 2016). The extent of damaged starch in flour samples may be partly attributed to the milling rather than roasting. This may be as a result of bursting of the starch granules due to the elevated temperature of roasting (Gujral et al., 2011). Similarly increase in the contents of the damaged starch have been reported in oat flour (Mariotti et al., 2006) and wheat flour (Qu et al., 2017). Also, the formation of permeable structure in starch granules absorbed water by capillary action could be another reason for the increase in WAI (Sharma et al., 2011) The hydrophilic parts of major components like proteins and carbohydrates in the flour could aid water absorption of flours and thus increase WAI of flour (Lawal et al., 2011). The WSI of flours is majorly attributed to the availability of water-soluble molecules including sugars, amylose and albumin in the flour (Wani et al., 2015). The decrease in WSI possibly suggests that few water-soluble substances are remaining treatment (Meera et al., 2011) in flours after roasting the grains. Decreased WSI of roasted grain flours could be ascribed to the decreased depolymerization of starch chains that may result in the less water uptake by starch granules (Wu et al., 2002).

4.3.7.2 Properties of stored flours and sensory characteristics of porridges

Lower fat acidities of WGF from l and h over storage compared to that of unroasted non-tannin whole grain sorghum kernels (Table 4.3.5) shows that l and h treatments largely inactivated the lipase enzymes in the WGK. Roasting of non-tannin WGK for 25 min (h) was highly effective at reducing fat acidity than for 10 min (l). This could be that more effective thermal inactivation of lipase and possibly lipoxygenase (Zhao et al., 2007) occurred with longer thermal treatment than shorter time. However, the fat acidities of all flour forms increased with storage, which may be ascribed to incomplete inactivation of the lipase enzymes by roasting treatments and not necessarily thermal non-enzymic hydrolysis (Nantanga et al., 2008). The increase in fat acidity of flour during storage could be due to degradation of fat caused by lipolysis and lipid oxidation (Zhou et al., 2002). During lipolysis, ester bond linking glycerol with fatty acids breaks either by heat or by the action of lipase enzymes, while lipid oxidation takes place by action of lipoxygenase enzyme which attacks the double bond in fatty acids of cereal grains or by autoxidation of unsaturated fatty acids (Wang et al., 2017). Higher fat acidity content in whole flours suggests an increase of de-esterified fatty acids, possibly due to hydrolysis of triglycerides by lipase (Nantanga et al., 2008). This result agrees with the report of (Zou et al., 2018), in which roasting led to a decrease in the fat acidity content of wheat germ compared to those from the unroasted samples.

Lower fat acidity in the decorticated grain flours compared to whole flours suggests that decorticating of whole kernels could reduce further the fat acidity because of the total or partial removal of the bran and germs from the kernels during operation. The decortication process reduces the number of triglycerides in sorghum grain flour (Abdelraham et al., 1983), making fewer lipids available for possible hydrolysis to FFA (Zou et al., 2018).

The whole and decorticated grain flours from the roasted kernels had much lower *p*AVs over storage compared to the flours from unroasted (Figure 4.3.4). The *p*AV indicates products of secondary oxidation that are associated with unpleasant aromas/off-flavours in oxidized foods (Viscid et al., 2004). The flours from the roasted non-tannin wholegrain sorghum kernels had much lower *p*AVs over storage compared to the flours from unroasted grain flours (Figure 4.3.4A). However, intense oily, painty, rancid and fermented aromas which are unpleasant, were associated with the porridges of stored whole flours from unroasted non-tannin whole grains but not those from the roasted grain flours (Figure 4.3.9). Such unpleasant aromas are commonly associated with aged or oxidized foods and are due to the formation of volatile secondary products by unsaturated fatty acid oxidation (Duizer & Walker, 2016). The painty aroma could, for instance, be attributed to the presence of pentanal, hexanal and heptanal (Steele, 2004, pp. 129–131). Similarly, observation related to the absence of unpleasant aroma in porridges prepared from flour of thermally-treated pearl millet grains, the unpleasant aroma was attributed to the inactivation of lipase before milling the grains (Nantanga et al., 2008).

The significantly lower peak and final viscosities of the flour pastes from roasted non-tannin whole grain flours compared to those of unroasted (Figure 4.3.6), as was also reported by Ranganathan et al. (2013) with roasting whole grain sorghum, was probably due to the thermal damage to the starch (Figure 4.3.5). Also, roasting of whole sorghum kernels has resulted in a case hardening situation during which the hydration ability of the roasted kernels is reduced thereby resulting in less swelling of the starch granules and consequently reduced peak and final viscosities (Ranganathan et al., 2013). Furthermore, the of formation of amylose-lipids complexes between amylose components of starch and native lipids embedded in the grains, these complexes can inhibit swelling of starch granules because the amylose component of starch made the structure rigid and firm against the possible breakdown of starch preventing the swelling (De Pilli et al., 2008). Lipids component of the complexes may inhibit hydration of starch granules from swelling, because the lipids may have covered the starch granule surface with a film layer, increasing hydrophobicity (Sharma & Gujral ,2019). The film layer potentially reduces the ability of starch granules to hydrate, thus resulting in reduced PV. In Addition, the high temperature of roasting could lead to partial gelatinization of the starch with a subsequent reduction of PV (Gujral et al., 2011). After roasting of grains, the loosely packed starch granules gelatinized partially and damaged due to heat, then imbibe water and swell rapidly resulting in less PV (Mariotti et al., 2006). Decorticated grain flours displayed higher peak and final viscosities than those of whole flours (Figure 4.3.6). The decrease in viscosity of flour pastes could be attributed to the presence of pre-gelatinized starch in the roasted grain flour (Gujral et al., 2011) as decorticated grain flours contain. The much lower viscosities due to roasting recorded in the present study in non-tannin sorghum grain flours may not affect their potential to improve the flour stability.

The much higher firmness of the porridges of the roasted non-tannin whole grain flours (Figure 4.3.7A) was probably an outcome of their flours' higher damaged starch content. Roasting of whole grain sorghum had no significant effect on the porridge stickiness (Figure 4.3.8). With storage, porridges of whole and decorticated grain flours became stickier. Increased porridge stickiness could be ascribed to further starch damage during storage at elevated temperature. Whereas the sensory panels detected an obvious difference in porridge texture in terms of viscosity between the treatments of whole grains (Figure 4.3.9) but could identify such in the porridge of decorticated grain flours (Figure 4.3.10). Nevertheless, no difference in porridge stickiness was detected by the descriptive sensory panel (Figures 4.3.9 and 4.3.10), as was also found in chapter

4.2 with microwave roasting of wholegrain sorghum kernels, was possibly primarily due to thermal damage to the starch. Porridges from the roasted grain flours (l and h) were generally stickier than the porridges from unroasted grain flour, as measured by instrumental texture analysis (Figure 4.3.8). The greater starch damage of the roasted grain flours was probably responsible. However, no difference in porridge stickiness was detected by the descriptive sensory panel (Figures 4.3.9 and 4.3.10). As with porridge texture, inability of the descriptive sensory panel to detect stickiness of porridge may have been masked by other sensory attributes such as the unpleasant aromas (Chapter 4.2),

Darker brown colour of porridge of whole flour from the roasted non-tannin whole grains can be attributed partly to the formation of non-enzymatic brown pigments associated with Maillard reaction products. Maillard reaction occurs between free amino acids of proteins and the carbonyl group of reducing sugars at such elevated temperatures ranging between 140 ºC and 150 ºC, leading to the development of brown colour (Sharma & Gujral, 2011).

4.3.8 Conclusions

Roasting of whole grain sorghum kernels improves flour stability during storage and still affects the sensory properties of the porridge only to a small extent. Roasting of non-tannin sorghum kernels retards the development of rancidity through inactivation of lipase, more so at 25 min than 10 min roasting periods. The significant decreases in fat acidity and *p*AVs with treatments enhancing stability of whole and decorticated grain flours. As a result, porridges from roasted grain flours were less rancid than those from untreated grain. The much reduction in flour pasting PV from roasted non-tannin sorghum kernels suggests that the treatment has the potential to produce less viscous porridges, which are more suitable for infant feeding. However, consumer acceptability of the porridges may be necessary because of the slight changes in porridge sensory properties due to the treatment. Roasting grains at 150 ºC for 25 min and decorticating the grains are worthwhile processing technologies to improve the keeping quality of sorghum flours due to reduction in fat acidity and *p*AV.

5. GENERAL DISCUSSION

This chapter is divided into two sections. Section one discusses the methodologies used focusing on the basic principles and highlights the strengths and weaknesses (that is advantages and limitations) of the treatments (microwaving and roasting) and the major sample preparations and methods of analyses used in this study, namely, lipid extraction, determination of fat acidity, *p*-AV, extraction of the phenolic compounds, TPC, antioxidant capacity and descriptive sensory evaluation. Section two discusses the main findings of this research with emphasis on the influence of dry heat (microwaving and roasting) treatment of sorghum (tannin and non-tannin types) grain on the physicochemical properties, storage stability of flour (non-tannin type only) and the sensory characteristics of porridge from the stored flour.

5.1 METHODOLOGIES

5.1.1 Selection of raw materials

Sorghum *(Sorghum bicolor* (L.) Moench) is the second most important cereal food, after maize, for millions of people living in the semi-arid and sub-tropical regions of Africa (ICRISAT, 2018). The high cost of maize due to its high patronage for both domestic and large-scale utilization and effect of change in climate on its yield could be some of the factors responsible for renewing consumers' interest for sorghum-based foods. Sorghum is a climate-smart crop and plays a critical role as a source of energy and dietary protein to the food insecure people of sub-Saharan Africa cannot be overemphasized (Taylor, 2003). For this study, red non-tannin and tannin sorghum was selected as shown in the experimental design (Figure 5.1).

Tannins are known for their anti-nutritional effect but have been reported to provide benefits to human health (Chhikara et al., 2018). Despite these health benefits tannin sorghum grains are not widely consumed in most parts of Africa. The inclusion of tannin sorghum in the present study may therefore be a weakness as the raw material used to not reflect consumers' choice for consumption. Another weakness in the selection of the raw material for this study was that it only considered commercial red non-tannin sorghum grain for studying the stabilization of their flours and did not also include tan-plant sorghum which is commonly consumed in semi-arid and sub-tropical regions of Africa.

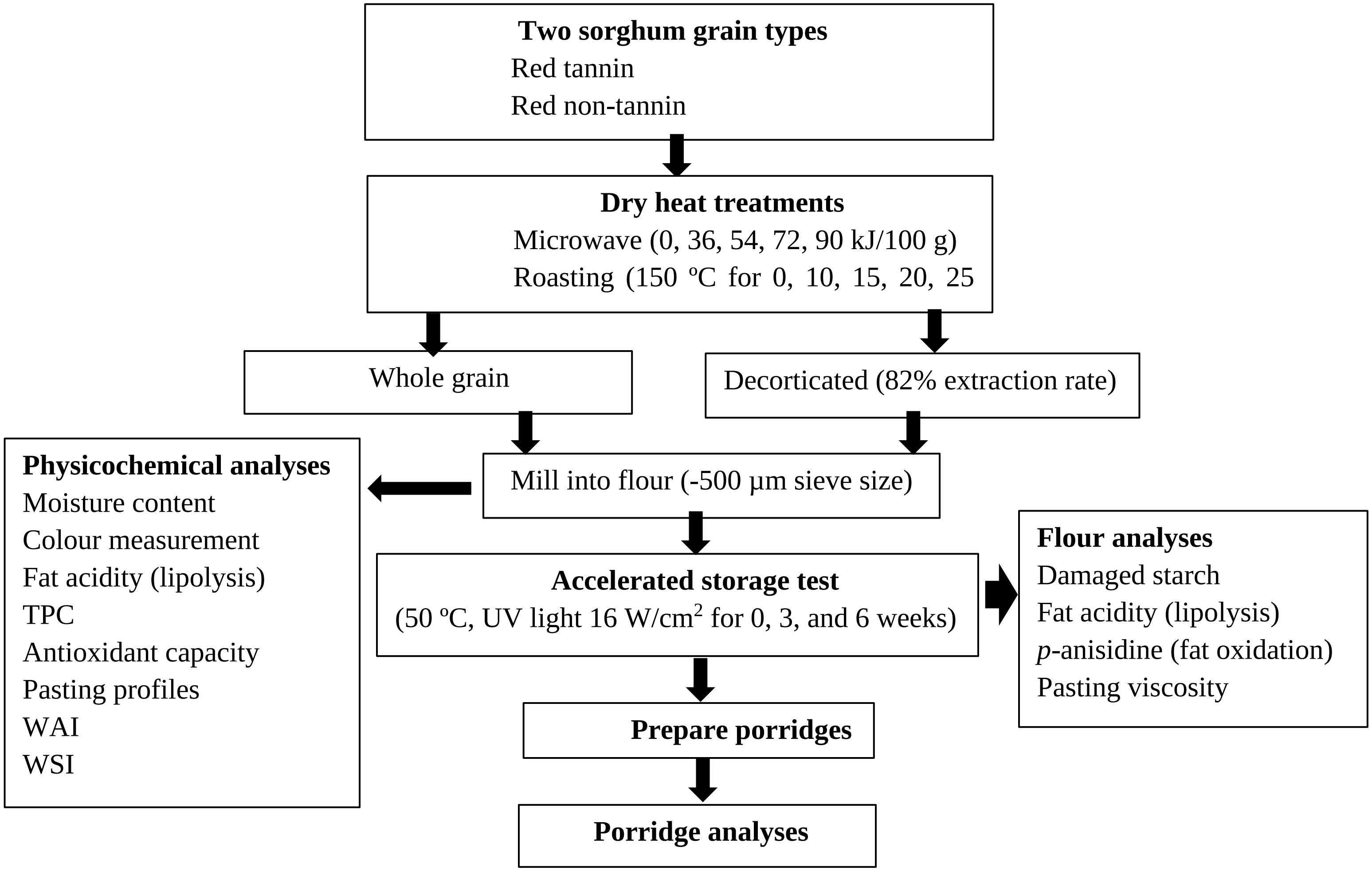


Figure 5.1 Experimental design of the research study showing sorghum types, heat treatment methods, processing, flour storage conditions and analyses on flours and porridges.

5.1.2 Dry heat treatment of wholegrain sorghum kernels

For this study, a microwave frequency of 2450 MHz corresponding to an energy of 1.02 x 10-5 eV was applied to pre-conditioned (14 % moisture content) sorghum kernels (100 g/batch). The microwave processing parameters were selected based on a combination of results from preliminary trials and some information from previous research studies (Keying et al., 2009; Yadav et al., 2012). The aim was to set treatment parameters that could produce kernels which are gently heat-treated.

The principle of microwave heating is based on direct internal heating of food materials due to oscillation of bipolar water molecules it can be assumed that the heating of each grain will be rapid and uniform (Chandrasekaran et al., 2013). This type of heating is referred to as volumetric heating of food material, using microwaves (dielectric) heating which depends on the electrical properties of the food (Chandrasekaran et al., 2013). With the application of an electric field, the bipolar molecules behave like microscopic magnets and tend to align themselves with the field (Yadav et al., 2012). As the electrical field rotates in millions of times per second (e.g., 2450 MHz), these molecular magnets are unable to withstand the forces retarding their movements. The resistance to the rapid movement of the bipolar molecules creates friction and results in heat dissipation in the part of food material exposed to the microwave radiation (Yadav et al., 2012)

Microwave power of 900 W and 40 s, 60 s, 80 s and 100 s resulting in 36 kJ, 54 kJ, 72 kJ and 90 kJ/100 g energy inputs respectively were used for the present study. These energy inputs produced sorghum kernels with a final surface temperature ranging from 54.6±2 °C to 125±1 °C respectively for minimum (L = 36 kJ/100 g) and maximum (H = 90 kJ/100 g) energy inputs. Yadav et al. (2012) found that microwave heating of pearl millet grains, pre-conditioned between 12 % and 18 % moisture content, for 80 s at 900 W with the same frequency (2450 MHz) resulted in a significant reduction ($p < 0.05$) in lipase activity of flour. The authors did not report the grain surface temperature due to treatment. The authors reported a maximum reduction of ≈93% lipase activity of pearl millet grains conditioned at 18 % moisture level and microwaved for 100 s.

A limitation of the study is that the internal temperature of the kernels was not measured in this study. In order to stabilize flour, it should be stored cool and dry, usually at temperatures not higher than room temperature (25 ± 2 °C) in a dry well-ventilated place. However, it can be frozen indefinitely and during hot weather, it can be stored in the refrigerator if not kept in the freezer. Since the microwaving of the kernels was performed in a closed system, it was not possible to measure or record the internal temperature of the kernels. Rather, the maximum surface temperatures of the kernels obtained after microwaving of the kernels was measured using an infrared thermometer (Figure 5.2). Non-uniform temperature distribution within the kernels was another challenge. This could be because the microwave system used for the study was of a non-fluidized type design that did not enhance the continuous movement of the kernels within the system to allow uniform temperature distribution during operation. The maximum surface temperatures of the kernels after microwaving and roasting were 125 ºC (Figure 5.2) and 135.2 ºC (Figure 5.3) respectively; these were however lower than expected. However, probably if thermocouples are fixed in the kernels and connected to an electronic monitor, the setup could have offered a means of recording the internal temperature of the kernels while microwaving. This idea could have given useful information about the temperatures within the kernels due to microwave and roasting treatments.

Roasting also, a thermal treatment that was applied to sorghum grains before the flour-milling process with the aim of improving flour stability. A drawback of roasting is that it may reduce essential minerals (magnesium and potassium) and some phenolic compounds and fatty acids (but not the essential fatty acids) in samh seed, a drought-resistant cereal plant grown in arid and semi-arid region of Asia (Ahmed et al., 2020). Another limitation of roasting is that the process causes several changes in foods such as textural and colour changes, lipid alterations, and Maillard reaction product formation (Schlörmann et al., 2019). These changes could be detrimental to the nutrient benefits of the grain to humans. However, it should be emphasized that roasting also has merits in that it could improve the sensory attributes and consumer acceptance of food products.

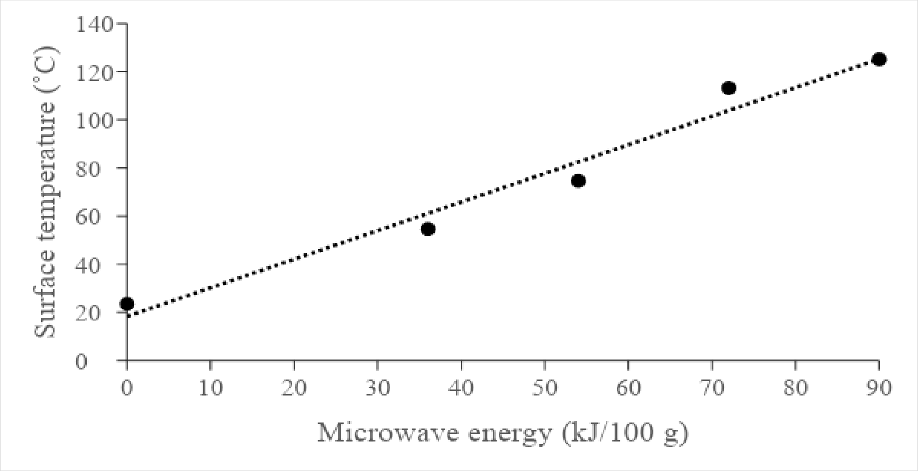


Figure 5.2 Relationship between the surface temperatures and microwave energy applied to wholegrain sorghum kernels

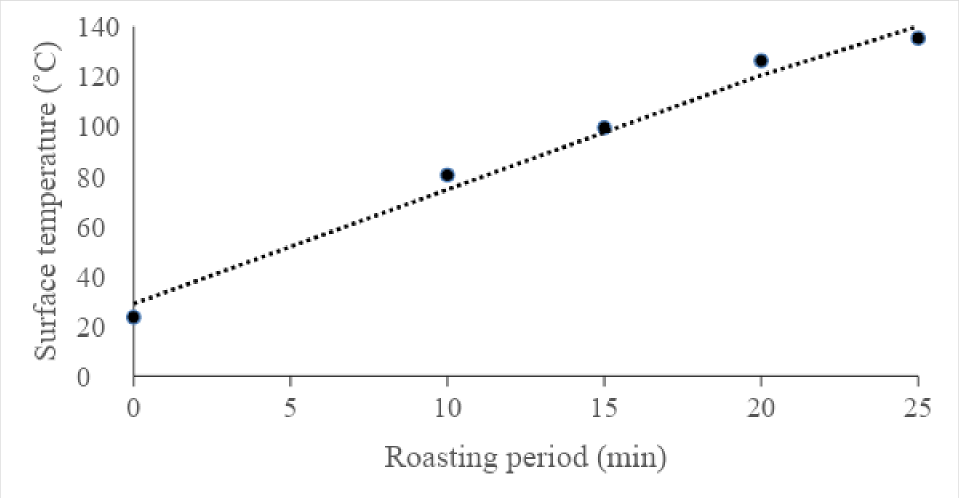


Figure 5.3 Maximum surface temperatures of wholegrain sorghum kernels recorded after roasting

5.1.3 Accelerated shelf-life storage condition

Stability of aromas/flavours during storage of fat-containing foods are usually determined by subjecting such food items to accelerated storage conditions to simulate the shelf life of products (Wang et al., 2014). Accelerated storage tests have been used to investigate cereal flour samples and it was found to be a good predictor of storage stability (Qu et al., 2017; Deepa & Hebbar, 2017).

In our study, the sorghum flour samples were stored at 50 °C, and some physical and sensory changes were observed in some of the samples from week 3 of storage. Some of these changes included unpleasant rancid smell and the packages became oily with handling. Previous studies on accelerated flour storage tests showed that researchers employed different temperatures for testing. Deepa and Hebbar (2017) used 38 ºC for maize flour while Qu, et al. (2017) used 35 ºC for wheat flour. The temperature of 50 °C used in this study is exceptionally high but we have presented a new strategy to predict a long-term storage of sorghum flour using accelerated storage test conditions which, in addition to accelerate autoxidation also notably promote non-enzymic browning relevant for flour stability under tropical conditions. At 50 °C proteins could be denatured, and some essential nutrients such as vitamins may also volatilize (Nielsen, Stapelfeldt, & Skibsted, 1998)

Although accelerated shelf-life testing methods enable the estimation of shelf-life (Derossi *et al.*, 2016) the methods cannot guarantee agreement between what is estimated and what is observed experimentally, this can lead to discrepancies. In this study, several variables were studied in the accelerated shelf-life study, such as the sensory characteristics and chemical analysis (using indicators like fat acidity, *p*-anisidine). In this case, it is not enough to confidently report which of these indicators is most relevant for estimating the end of shelf-life of the product. Pedro and Ferreira (2006) proposed a new approach for estimating shelf-life by simultaneously considering several quality attributes, known as the multivariate accelerated shelf-life test (MASLT). The MASLT reduces the error of establishing product shelf-life based on a critical attribute but may set aside attributes that could change over time in only one product. This robust method might have given a beneficial advantage in understanding the relationship between attributes overtime periods.

5.1.4 Analytical methods

5.1.4.1 Total phenolic content and antioxidant activity assay methods

For this study, the Folin-Ciocalteu method described by Apea-Bah et al. (2014) was used to determine TPC in non-tannin and tannin sorghum. This method was chosen because of its simplicity and reproducible assay, which could be used for studying total phenolic antioxidants (Awika et al., 2003). The principle of this method is based on the reducing power of phenolic hydroxyl groups. Phenolic compounds react with the Folin-Ciocalteu reagent under alkaline conditions, through the dissociation of a proton from the phenolic hydroxyl group which results in the formation of a phenolate anion (Awika et al., 2003). The phenolate anion reduces the Folin-Ciocalteu reagent (a yellow acidic solution) to a blue molybdenum-tungsten complex (Naczk & Shahidi, 2004).

However, there is substantial variation in the values reported for the TPC in sorghums by different researchers, especially when the Folin-Ciocalteu method was used (Salazar-López et al., 2018). The explanation given for the inconsistencies was that the assay method presumably detected not only polyphenolic compounds but also detected other biological compounds that are formed during heat treatments of cereal grains (Wani et al., 2016). Compounds such as melanoidins formed during the roasting process, could presumably possess reducing or antioxidant properties (Zou, Yang, Zhang, He, & Yang, 2015). Thus, the roasting of sorghum kernels might have partially contributed to an elevated apparent concentration of TPC and antioxidant capacity as shown in research chapter 4.3 (Table 4.3.3) and described in some other studies (Jogihalli et al., 2017; Sharanagat et al., 2019).

Thus, the major limitation associated with the Folin-Ciocalteu assay method is that the reagent is not specific, as it detects all the phenolic hydroxyl groups in extracts (Schaich, Tian, & Xie, 2015). This implies that the assay method is highly probable to interfere from non-phenolic compounds. Non-phenolic compounds such as ascorbic acid, reducing sugars, sulphur dioxide, extractable proteins with phenolic rings can reduce the Folin-Ciocalteu reagent (Naczk & Shahidi, 2004). It is highly probable that the TPC of the extract may be overestimated especially if the sample contains a significant amount of proteins composed of phenolic amino acids including tyrosine with reducing properties (Naczk & Shahidi, 2004). It is therefore suggested that the Folin-Ciocalteu assay be used in combination with other methods such as LC/MS analysis. The LC/MS technique is more specific for determining phenolic compounds in the sample.

Several methods of assay can be used to evaluate the AOA of natural compounds in food systems including the Trolox equivalent antioxidant capacity (TEAC) assay or the 2, 2'-azinobis (3-ethyl-benzothaizoline-6-sulphonic acid) (ABTS) assay, 2,2-diphenyl-1-picrylhydrazyl ($DPPH^{\cdot}$), and Oxygen Radical Absorbance Capacity (ORAC) (Awika et al., 2003). However, of these methods, only two free radical assays are most used to assess AOA, notably ABTS and DPPH. A major setback when using the latter is colour interference of DPPH reagents with samples that contain anthocyanins which could lead to underestimation of AOA (Schaich et al., 2015). Extensive investigations by Awika et al. (2003) on methods to measure antioxidant activity have shown that the ABTS method was more suitable for sorghums than the DPPH or ORAC methods.

For this study, the TEAC assay method was chosen because of its unique advantages such as its simplicity, the speed of the analysis (approximately 30 min per sample) and it can be used over a wide pH range. It also has good repeatability; hence, its use is widely reported (Awika et al., 2003). The TEAC assay is a spectrophotometric-based technique that quantifies the relative ability of hydrogen-donating oxidants to scavenge the $ABTS^{\bullet+}$ in comparison with Trolox-a water-soluble vitamin E analogue (Awika et al., 2003). The principle of the TEAC assay is based on the neutralization of radical cations formed by single-electron oxidation of a synthetic ABTS chromophore to a strong absorbing $ABTS^{\bullet+}$ (Awika et al., 2003). The antioxidants reduce the radicals depending on the capacity, and concentration of the antioxidant and the duration of the reaction (Schaich et al., 2015). The ability of the sample to quench the free radicals is estimated by monitoring the colour at 734 nm using Trolox as the standard (Schaich et al., 2015). However, despite these advantages, the assay has a major limitation in that the $ABTS^{\bullet+}$ reagent is not stable and could react with any hydroxylated aromatics (Awika et al., 2003). Maillard reaction-produced melanoidins which have reducing properties could behave and react like Trolox, thus resulting in an overestimation of AOA.

For this study, only the ABTS assay was determined to quantify AOA. This (ABTS assay) may not give substantive trends in AOA. Using an additional assay like DPPH could have made the result adequate validity than only one method of assay. Previous studies had proposed that using more than one AOA activity test methods could allow for a meaningful comparison of antioxidant properties because the assays are based on different mechanisms (Awika et al., 2003; Schaich et al., 2015) and result from the different assays can be used to validate one another.

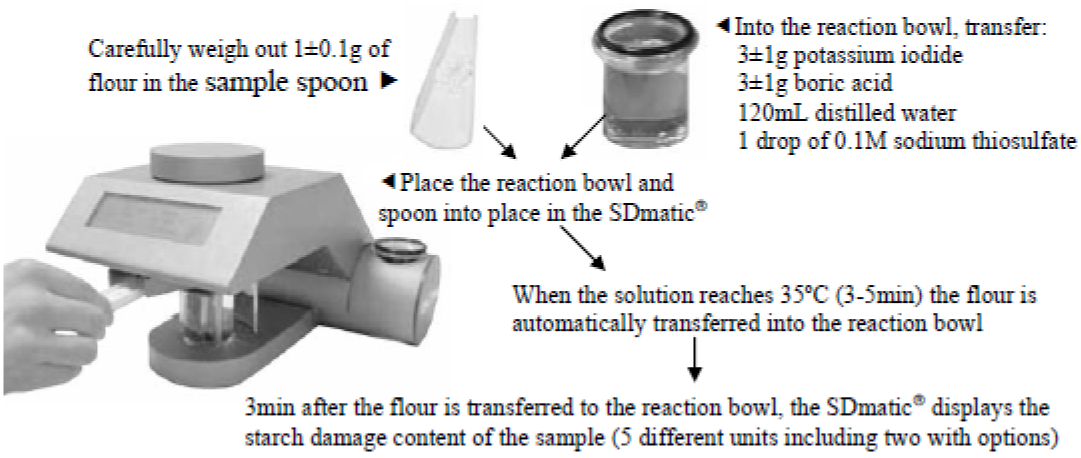
There have been some conflicting reports in previous studies on the effects of microwaving or roasting of cereal grains, sorghum on AOA. Whereas Sharanagat et al. (2019) reported a drastic decrease in AOA of flour due to roasting whole sorghum kernels despite an increase in TPC; Anyachukwu et al. (2019) reported a significant increase in AOA of flours of whole sorghum kernels due to roasting. The increase in the AOA despite the decrease in TPC indicates that the extracted phenolic compounds lack AOA and could have been masked by the Maillard reaction products (Sharanagat et al., 2019). In contrast, the present study showed an increase in AOA of sorghum flour as the levels of TPC decreased with increasing roasting time (refer to Table 4.3.3). This suggests that AOA of flour may not be exclusively attributed to the phenolics rather, Maillard reaction products that may have been formed during roasting, may have contributed to AOA of flour. Rao, Santhakumar, Chinkwo, Wu, Johnson and Blanchard (2018) also characterized phenolic compounds and AOA in sorghum grains. The authors found that there was not only a phenolic compound that is responsible for high AOA in sorghum rather it is the cumulative effect of various phenolic compounds.

Roasting like other dry heat treatment methods is known to promote the formation of Maillard reaction products at the expense of phenolics, the extent of which is a function of the roasting temperature and time (Bonafaccia, Marocchini, & Kreft, 2003). Maillard reaction products are mainly associated with some noticeable changes in the sensory properties of roasted foods, such as alteration in colour and flavour (Anyachukwu et al., 2019). Hence, as Maillard reactions and its products may have increased with increasing roasting temperature and time, AOA of sorghum kernel flours also increased. Maillard reaction products generated can also be attributed to enhanced antioxidant activity. This is because Maillard products could scavenge radical species that are known to promote the formation of hydroperoxides. However, with storage, the peroxide value of the control decreased. This was attributed to a decrease in hydroperoxides. The hydroperoxides are not stable and are transformed into secondary oxidation products (Wang et al., 2017).

5.1.4.2 Damaged starch content

Starch is a major component of cereal grains, including sorghum. Starch plays a major role in post-harvest processing and end-product quality (Wilson, Kaufman, Seabourn, Galant, & Herald, 2016). Heat treatment of cereal grains and milling of grains to flour can potentially lead to the disruption of starch granules, adversely affecting dough rheology, thus monitoring of starch damage is important (Qu et al., 2017). Enzymatic procedures such as the use of the Megazyme starch damage assay kit for quantifying starch damage content in cereal flours has generally been used (McAlliste, Black, Le Brun, Algeldeh, Dubat & Panozzo, 2008). In the present study, an alternative non-enzymatic methodology was used involving the SDmatic®, an instrument developed originally for determining starch damage in wheat flour (Fig 5.4). A previous study reported a strong correlation between the SDmatic® and Megazyme assay for determining starch damage content in flours (McAlliste et al., 2008). It was therefore considered suitable to harness the benefits of the simplicity, speed and precision of the operational method of the SDmatic®.

The principle of the SDmatic® assessment is based on the amperometrical measurement of starch damage by iodine absorption; with the starch damage and the iodine absorption showing a linear relationship (McAlliste et al., 2008). The SDmatic® instrument determines starch damage in cereal grain flours more rapidly than the enzymatic method of the Megazyme starch damage assay kit based on the enzymatic hydrolysis of starch to glucose and measurement of the concentration with glucose oxidase/peroxidase reagent providing a colorimetric result (McAlliste et al., 2008). Whereas the Megazyme assay is time-consuming (≈50 min per sample) and labour intensive; it yields accurate and reproducible results. The SDmatic generally takes less time (≈10 min per sample) and requires limited operator skills (McAlliste et al., 2008). However, the enzymatic method could lead to variations in enzyme activity and stability mainly due to temperature changes that may cause inconsistency in result over time.



Carefully weigh out 1±0.1g of flour in the sample spoon

Into the reaction bowl, transfer:
3±1g potassium iodide
3±1g boric acid
120mL distilled water
1 drop of 0.1M sodium thiosulfate

Place the reaction bowl and spoon into place in the SDmatic®

When the solution reaches 35°C (3-5min) the flour is automatically transferred into the reaction bowl

3min after the flour is transferred to the reaction bowl, the SDmatic® displays the starch damage content of the sample (5 different units including two with options)

Figure 5.4 Operating procedures of the SDmatic instrument (McAlliste et al., 2008)

5.1.4.3 Flour rancidity-lipolysis and lipid oxidation determinations

The level of rancidity in flours is often measured by determining the FFA content and peroxide value (Meera et al., 2011). The FFA content measures the amount of FFA that is liberated as a result of hydrolytic rancidity development (Deepa & Hebbar, 2017). The peroxide value measures the components produced by the early stages (primary products of oxidation) of oxidation of fatty acids, which determines the oxidative deterioration of lipids, by measuring the hydroperoxides. The *p*AV measures the secondary oxidation products (breakdown products of peroxides), notably ketones, aldehydes, alcohols and hydrocarbons (Viscidi et al., 2004). Owing to the fact that the hydroperoxides are unstable, they quickly decompose to secondary products (Kamal-Eldin, 2003) which are reportedly associated with rancid off-flavours in oxidised food systems. Given the unstable nature of hydroperoxides, peroxide value is often combined with other measurements to reveal the different products of oxidation, such as the pAV and thiobarbituric acid reactive species (TBARS) value (Kamal-Eldin, 2003). TBARS measures malondialdehyde, which are secondary products of lipid oxidation representative of aldehydes.

In this study, fat acidity content and *p*AV were used to predict lipid hydrolysis and lipid oxidation (oxidative rancidity) respectively. Fat acidity was analyzed by acid-base titration according to AACC Method 02-02 A (AACC, 2000). Lipid oxidation was analyzed in terms of anisidine value according to ISO Standard method ISO 6885 (ISO, 2008).

Analysis of volatiles in the headspace of a closed container of flour with gas chromatography methods is a common method for monitoring oxidative deterioration and determining fatty acid composition that correlates with off-flavour (Wang et al., 2017). Similarly, future study could measure non-volatile compounds using the LC-MS for better characterization of stored flour and relating it to the porridge. Such methods could possibly provide more in-depth knowledge of the specific compounds associated with the rancid off-flavours in the stored sorghum flour samples.

Donfrancesco and Koppel (2017) investigated the effect of sorghum fractions on dry dog food sensory properties using descriptive sensory analysis and gas chromatography-mass spectrometry (GC-MS) with a modified headspace solid-phase microextraction (SPME) method. Partial least squares regression was performed to identify significant correlations between sensory characteristics and detected aroma compounds. The study correlated the quantitative results of descriptive sensory characteristics with volatile compounds detected by SPME-GC-MS.

Fat acidity content and *p*AVs were measured to determine the initial and later-stage products formed by lipids breakdown (lipolysis) and its subsequent oxidation (oxidative rancidity) in flours, respectively (Kamal-Eldin et al., 2003). However, peroxide value was not considered appropriate to estimate lipid oxidation for samples because of its major limitation, instability of hydroperoxides (Wang et al., 2017). The limitation with the determination of peroxide value is that peroxide compounds are specifically intermediate products of autoxidation and are therefore not stable (Gorji, Smyth, Sharma, & Fitzgerald, 2016). Besides, the high flours storage temperature could cause peroxides to decompose quickly and could make their determination difficult, as peroxides would have transformed to other products. Although a high peroxide value is a definite indication of rancid fat, moderate values are not indications of the absence of rancidity but rather the depletion of peroxides after reaching high concentrations (Wang et al., 2017). Hence, the need for the determination of the *p*AV, which is a measure of the secondary oxidation products, such as aldehydes and ketones.

However, correlations between sensory assessments and chemical measurements are also vital. For example, rancid odour and flavour have been correlated with concentrations of aldehydes, and particularly hexanal, which is therefore called a marker molecule (Heiniö et al., 2003). Consider though that sensory characteristics are not usually related directly to individual compounds. Adequate and in-depth information is therefore needed to buttress the relationship between chemical compounds and sensory properties of foods. More advanced methods of detecting overall aroma patterns in foods have also been developed such as the electronic nose technique (Ruge et al., 2012), which was developed from the GC volatile methods.

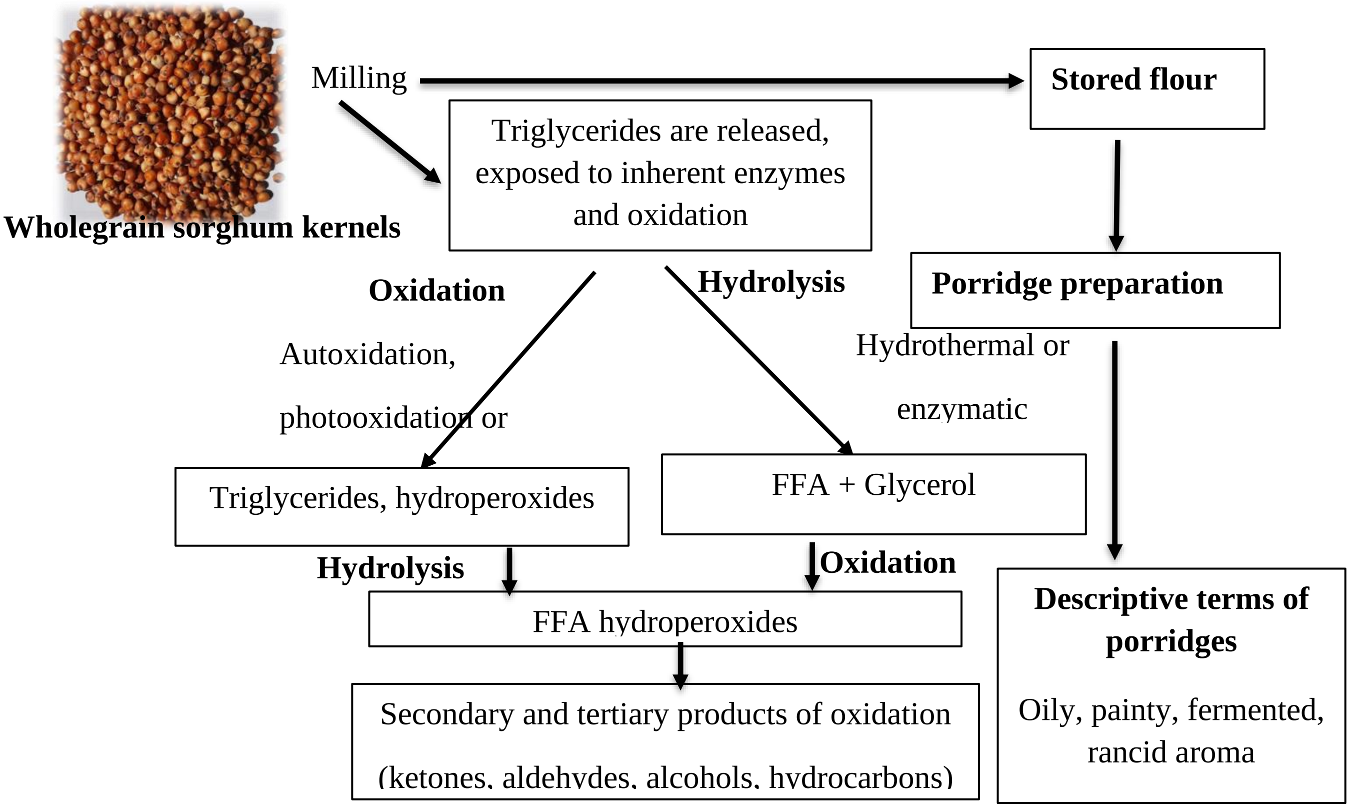


Figure 5. 5 Schematic diagrams for proposed hydrolytic rancidity of sorghum flour

5.1.4.4 Flour pasting viscosity

The total solids (10 %) content of samples used for rheometer measurements were the same as used for porridge preparation for the descriptive sensory evaluation in this study. The trend of the viscosity of flour paste measured by the rheometer varied from those reported for porridges by the descriptive sensory panels. The rheometer has been effectively used to study the pasting viscosities of flours and starch. However, the rheometer does not give extensive information related to the depolymerization of starch molecules. The use of a capillary viscometer to measure the intrinsic viscosity of starch might have been useful to determine possible depolymerization of starch molecules.

For this study, the PV and FV decreased due to the dry heat treatments (assessed at storage baseline) and throughout the storage period, the PV of flour pastes from untreated samples was significantly higher than those of heat-treated samples (Figure 4.2.3). Similarly, with storage, the PV of all the flour pastes decreased but the PV of treated samples remained the lower compared to that of untreated. However, peak and final viscosities alone, which was measured in the present study did not provide enough information on the changes which occurred after cooling such as the breakdown and set back viscosity.

5.1.5 Descriptive sensory evaluation

Sensory evaluation of food products is conducted using human subjects to assess and define the sensory attributes of products (Lawless & Heymann, 2010). The human subjects have been trained specifically for the evaluation. Instrumental applications to profile the sensory attributes of food products have not been able to fully replicate or replace the human response. The present study made use of a descriptive sensory panel for the evaluation of the sensory quality of porridges prepared from the flour of heat-treated wholegrain sorghum kernels.

For this study, steps were taken to recruit and train the panel before the actual evaluation of porridges. The recruitment exercise was done by sending electronic mails to potential panellists who were recently engaged in evaluating millet porridges. The panellists were mostly postgraduate students with an interest in research activities at the University of Pretoria. Ten students responded and they were trained with a wide range of sorghum porridges and other reference materials. Training sessions helped the panellists to become acquitted with the porridge samples and procedures. During the initial training period, panellists generated many descriptors and later consensus was reached on descriptors to use for the evaluation. Panellists identified the differences between porridges quantitatively using a line rating scale to determine the intensity of the sensory attributes in the porridge.

Although ten blind-coded porridge samples were evaluated by panellists in a session, the order of sample evaluation was randomised and a 2 min break inserted evaluating five samples to avoid fatigue. The porridges to be evaluated were kept warm in a bain-marie set at 50 ºC. This is because the product mode of consumption is usually in a warm state. In this study the panel was reliable and were able to identify the differences between the porridges based on. The large standard deviations for average ratings for some of the sensory attributes indicate widespread differences in the perceptions of the panellists, contributing to no or small comparative differences noticed among the porridges (Tables 4.2.3 and 4.3.4). The evaluation process was rather laborious to the panellists due to high number of attributes (n=36) and samples (n=10). Therefore, to minimize limitations emanating from these factors, the use of panel performance measures and tools are encouraged. Training sessions specifically assisted the panel to become acquainted with the sorghum products, to reach consensus and agree on the attributes to be used before the actual evaluation, and the rating scale for the product quantification. Descriptive sensory was used to predict flour stability alongside the chemical methods. Regarding the multivariate statistical methods PCA used in this study is a very informative way to express the result at one sight but still better visualization of the results would have been reached perhaps by using partial least squares regression (PLSR) to predict sensory results from instrumental data.

5.1.6 Research findings

The focus of this research was mainly on stabilization of sorghum flour using dry heat treatment by microwaving or roasting of pre-conditioned wholegrain sorghum kernels. Sorghum, like other cereal grains, is known to remain stable longer when the kernels are intact compared to when milled to flour. However, its flour has a limitation, the flour is prone to deterioration through lipolysis and oxidation of the unsaturated fatty acids (Meera et al., 2011). Against this background, the main premise upon which this research is based was that dry heat treatments (by microwaving and roasting) of wholegrain sorghum kernels could be used as a potential technology to inactivate lipase enzymes which enable the onset of the lipid deterioration, intending to stabilize the flour. Therefore, the main findings of this research study in terms of the effects of dry heat treatments of sorghum kernels and how this affects the flour functionality, storage stability and porridge sensory characteristics will be discussed.

5.1.6.1 Effects of heat treatments of sorghum kernels on the total phenolic content and antioxidant activity

Studies presented in chapters 4.1 and 4.2 respectively show the effects of heat treatments by microwaving (Fig 4.1.1 and 4.1.2) and roasting (Tables 4.2.3) of sorghum kernels on the TPC and AOA of resultant flours. Generally, microwaving sorghum kernels decreased the TPC and AOA of sorghum flours, whereas roasting of sorghum kernels decreased the TPC of the resulting flours but increased the AOA.

5.1.6.2 Effects of heat treatments of sorghum kernels on flour pasting characteristics and water absorption and solubility indexes porridge texture

From this study, a significantly lower peak viscosity (PV) was recorded for flour from heat-treated sorghum kernels compared to untreated (Figures 4.2.3 and 4.3.2). This finding was probably primarily a result of the thermal damage to the starch (Figure 4.2.2). Also, disruption of the starch granular structure leads to a decrease in water uptake by starch and possible reduction of the ability of the starch to swell and hence decreasing PV (Luo et al., 2006). Besides, the formation of a protective layer on the granular surface of starch could inhibit water absorption due to the hydrophobic nature of lipids which may have formed complexes with starch (Sharma & Gujral, 2019). A possible benefit of reduction in PV is that porridge prepared from such flour may show higher energy density with low viscosity, thereby making the porridges more suitable and convenient to eat and swallow by infants (Moussa et al., 2011). Low meal viscosity has a faster eating rate and shorter oral sensory exposure than high meal viscosity which has longer oral sensory exposure. This is because a low meal viscous product flows rapidly in the mouth. Elsewhere, it was reported that more viscous porridge was consumed rather more slowly compared to those of high viscosity (Oladiran et al., 2017). This is because high meal porridge led to increased fullness or increased satiety (Zhu et al., 2013).

The results from this research study showed that heat treatment of sorghum kernels resulted in a decrease of flour water absorption and the solubility indexes. Upon heat treatment of kernels and milling to flours, the formation of a protective layer limiting water uptake probably explains the reduced viscosity of the porridge.

The observed decrease in water solubility and solubility index of flours after heat treatments may be explained by the following mechanisms. Microwaving of the sorghum kernels may have denatured the sorghum proteins through breakage of intra and intermolecular hydrogen bonds resulting in the unfolding of protein molecules and exposure of hydrophobic sites which could lead to reduced water and nitrogen solubility. It is also possible that at higher microwaving power and longer roasting time, crosslinking reactions may occur between proteins and other compounds leading to the formation of complexes with reduced solubility. Further, there could be a promotion of protein aggregation via electrostatic and/or disulphide interactions after microwaving sorghum kernels.

Microwaving of sorghum kernels disrupted starch molecular order resulting in the loss of birefringence as shown in the Figures 4.1.2. The lower flour paste viscosity upon microwaving sorghum kernel may be due to microwave-induced gelatinization of starch. The water solubility of the flours is elicited by the water-soluble components that include soluble protein and carbohydrates. Therefore, the reduced WSI could also be attributed to starch aggregation (Wang et al., 2014) as revealed by the microscopy study reported in research chapter 4.1.

5.1.7 Porridge sensory characteristics

In this study, the panel reported significant differences in some attributes of porridges from microwave-treated kernels flours stored for 6 weeks (Table 4.3.4). There were significant increases in the intensity of oily, painty, rancid and fermented aromas in the porridge of untreated kernel flour. Though, the effect of flour storage with time was not significant ($p \geq 0.05$) on the microwave-treated kernel flour. The differences were in the untreated flour and not in those microwave-treated. Of interest in this study was that the perception of differences in the porridges made from stored flours was detected as aroma by smelling yet not perceived in the mouth during consumption. This could mean that when smelling the porridges, attention of panellists is on aroma and when processing porridge in the mouth focus of panellists is split between flavour and texture rather than the aroma.

Also, the brown colour was observed in porridges by the descriptive sensory panel but no difference in the brown colour of porridges prepared from untreated and microwave-treated kernel flours was noticed. On the contrary, this observation was not in agreement with the instrumental L^* value (lightness) of porridge prepared from untreated kernel flour, which was slightly higher than that of microwave-treated at 90 kJ/100 g (Table 4.2.2).

For the roasted wholegrain samples, the panellist reported significant differences in some attributes of porridges from flours stored for 6 weeks. There were significant increases in the intensity of oily, painty, rancid and fermented aromas, bitter taste and grainy porridge of untreated sample with flour storage time (Table 4.4.5). Like the microwave-treated sample, the differences in the intensities of rancid indicators were synonymous with untreated kernel flour and not related to those of roasted samples. A significant increase in brown colour, grainy and glossy was associated with the roasted samples. However, with porridges from decorticated flours, the intensities of the attribute were lower. Rancid aroma, brown or darker colour and stickiness in the porridge of flours were the only attributes that were significant.

The unpleasant aromas are usually associated with oxidized foods and are due to the formation of volatile secondary products by unsaturated fatty acid oxidation (Duizer & Walker, 2016). The unpleasant aroma is peculiar to untreated flour during storage and not with those of heat-treated flour samples. Nantanga et al. (2008) observed an absence of unpleasant aroma in porridges made from flour from thermally treated pearl millet grains and attributed this to the inactivation of lipase before milling the grains.

The study showed that the heat treatments of kernels led to reduction in fat acidity and pAVs of the resulting flours during storage (Figure 4.2.1 and 4.3.1). Lower fat acidity values of heat-treated sorghum flours recorded over the 6 weeks storage period (at 50 °C) compared to the untreated flours shows that the heat treatments probably inactivated the lipase in the sorghum kernels. As expected, microwave treatment of sorghum kernels at 90 kJ/100 g was more effective at reducing fat acidity than the treatment at 36 kJ/100 g. Similarly, the roasting of sorghum kernels at 150 ºC for 25 min was more effective than the roasting treatment for 10 min. Reduction in fat acidity could be attributed to more thermal inactivation of lipase (Zhao et al. 2007).

With storage fat acidity of untreated flour increased rapidly by nearly 50 % compared to those of microwave-treated and roasted samples. This is due to the presence of active lipase and lipoxygenase enzymes. The flours from the heat-treated sorghum kernels had much lower *p*AV over storage compared to the flours from untreated samples (Figure 4.3.1, Tables 4.4.1 and 4.4.2). This means that the formation of secondary oxidation products in heat-treated kernel flours at a minimal level compared to that of untreated. Secondary oxidation products are associated with perceived unpleasant or rancid off-flavours in oxidized flours (Kamal-Eldin, 2003). Determination of secondary oxidation products in stored sorghum flours should be considered in the future study.

The bland flavour of microwave treated porridges (Figure 4.2.5) could have been as a result of heat treatments releasing some of the characteristic flavours formed during processing. This development could be of importance especially to consumers with sorghum-flavour allergies may appreciate porridge with bland flavours.

Porridge texture was measured in terms of firmness and stickiness, which are important sensory attributes of sorghum porridge from the consumer perspective (Aboubacar et al., 1999). The generally somewhat reduction in the firmness of the porridges of the microwave-treated kernel flours (Figure 4.3.4) could be a consequence of their flours’ having a higher damaged starch content. Interestingly, the sensory panel did not detect any obvious difference in porridge texture in terms of viscosity between the treatments (Figure 4.3.5). This could mean that the more obvious aroma differences between the porridges attracted greater attention by the sensory panellists than the slight differences in texture. Porridges from the microwave treated sorghum kernel flours were generally stickier than that from untreated sorghum kernel flour, as measured by texture analyser (Figure 4.3.4).

5.2 Summary of the main findings

The summary of the main findings in this study, the application of dry heat treatments of wholegrain sorghum kernels using microwave heat and roasting to stabilize the flour and porridge sensory characteristics can be presented as shown in Table 5.1 below

Table 5.1 Summary of the main findings on the effects of heat treatments of non-tannin and tannin sorghum grains

Heat treatments decreased moisture content in both non-tannin and tannin sorghum flours
Heat treatments reduced L* (lightness) and increased a* (redness) of flour
Heat treatments reduced fat acidity of sorghum flour
Heat treatments reduced total phenolic content, but antioxidant activity increased with roasting only
Heat treatment generally reduced the peak, breakdown, set back and final viscosities of sorghum flour pastes
Heat treatments did not affect the water absorption index of sorghum flours
Heat treatments reduced fat acidity and p-anisidine of flour at baseline and during storage compared to raw flour
Heat treatment resulted in more damaged starch in flours
Microwave heat treatment had no effect on porridge texture at baseline
Microwave heat treatment had no effect on porridge sensory attributes at baseline except to increase the bland flavour of the porridge
There was no effect of storage time on unpleasant aromas on flour from higher microwave treatment (90kJ/100 g).
Rancidity was clearly noticed in porridges from untreated kernels' flour, which increased with flour storage but porridges of roasted kernel flours were evaluated less rancid
Perception differences in the porridges of stored flours were only detected as aroma by smelling and not in the mouth during consumption
Porridges of microwave-treated flours were darker in colour with a sweeter aroma
Shelf-life of flours at 50 ºC is predicted as 4-6 weeks for microwave-treated compared to 3 weeks for untreated samples.
Descriptive sensory evaluation was established to as a means of predicting flour stability in place of chemical determination methods

5.3 Future research

The current research investigated the application of dry heat treatments of sorghum grains with intent to stabilize their flours using porridge sensory attribute as a predictor. Additional research is needed to predict consumer acceptability of the flours and porridges to quantify the reactions of consumers that depend on sorghum. Safety of consumers of the product is also important because literature has shown that some of the secondary oxidation products could be toxic (Kamal-Eldin, 2003). Thus, it should be considered for evaluation.

The accelerated storage condition conducted at 50 ºC (under UV light 16W/cm^2 for 6 weeks) could be a new approach to predicting a long-term storage of sorghum flour. The method could be standardized and validated on a commercial scale. The method should be compared to traditional long-term storage tests, and should include more heat classes and flour at different moisture content.

Moreover, it would be of interest to identify the compounds associated with aroma and flavours perceived in oxidised sorghum flours using SPME-MS techniques. This will probably help to identify the possible correlation between sensory attributes and compounds identified.

The economic viability of the treatment methods should also be evaluated. The cost of the technologies and practicality of including the technology in the current sorghum value chain should be investigated. Once the cost implication is ascertained, recommendations can be made for the potential target sector (commercial/industrial or domestic home uses) that can adopt the technology of flour stabilization.

Furthermore, stabilization of sorghum flour should not be restricted to red sorghum as used in this study, other varieties like white tan and other sorghum hybrids should be considered for investigation as well. Collaborative research could be of interest in this regard especially with Texas A & M University in Purdue because the institution is known for breeding hybrid sorghum lines (Mezgebe, Abegaz, & Taylor, 2018). Also, collaboration with ICRISAT which perhaps has the largest collection of diverse global sorghum germplasm collection, could as well be considered.

6. CONCLUSIONS AND RECOMMENDATIONS

This study has highlighted the significance of heat treatments using microwave heating and roasting, as a potential strategy to produce wholegrain sorghum kernel flours with improved storage stability and porridge sensory characteristics. The sorghum types, non-tannin and tannin showed improved TPC after the heat treatments. The phenolic content of tannin types could be responsible for the observed antioxidant capacity of resulting flours after heat treatments. Heat treatment by microwaving and roasting of conditioned wholegrain sorghum kernels generally improves the extractability of phenolic compounds leading to an increase in TPC and antioxidant capacity of resultant flours. Sorghum kernels, probably with a more compact cotyledon and thicker seed coat, offer more resistance to splitting during microwave treatment which results in exposure of phenolics to more internal heat.

The flours from microwave-treated wholegrain sorghum kernels can potentially be used as ready-to-use functional food ingredients or in complementary foods. This is because microwaving of wholegrain sorghum kernels induces changes in the physicochemical properties of proteins and starch molecules that affect the functionalities of the resultant flours e.g. reduced PV and FV of flour pastes. Heat treatment of wholegrain sorghum kernels decreases the sorghum flours pasting viscosity, water absorption and solubility indexes of resultant flours as a result of water-induced dilution of intercellular compounds. The results show that heat treatment of pre-conditioned sorghum kernels could be used as a pre-treatment method in the production of value-added sorghum flour.

This study provides important information and understanding on how heat treatment by microwaving and roasting of pre-conditioned wholegrain sorghum kernels affect the physicochemical and functional properties of sorghum flours, flour stability and sensory characteristics of the flour porridge. However, there is need for further research to determine the optimum conditions of conditioning and heat treatment required to limit the action of endogenous enzymes responsible for oxidation of lipids in flour. Furthermore, flours from microwaving and/or roasting of wholegrain sorghum kernels could be analyzed for compounds responsible for the rancid off-flavours in stored flours, and consumer acceptance of porridge made from the flours.

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8. PUBLICATION, PRESENTATION AND POSTERS FROM THIS RESEARCH

Publication

Adebowale, O.J., Taylor, J.R.N. & de Kock, H.L. (2020). Stabilization of wholegrain sorghum flour and consequent potential improvement of food product sensory quality by microwave treatment of the kernels. LWT-Food Science and Technology, 132, 109827. Retrieved on July 12, 2020 from https://doi.org/10.1016/j.lwt.2020.109827

Conference posters

Adebowale, O.J., Taylor, J.R.N., & de Kock, H.L. (2019). Effect of microwaving sorghum grain on sensory characteristics of cooked porridge from flour stored for up to 6 weeks at 50 ºC. 23rd Biennial International Congress and Exhibition of the South African Association for Food Science & Technology (SAAFoST), Johannesburg, South Africa. 1st – 4th September 2019.

Adebowale, O.J., Taylor, J.R.N., & de Kock, H.L. (2019). Microwaving of sorghum grain: effects on shelf-life of flour as evaluated based on the sensory characteristics of porridge. 13th Pangborn Sensory Science Symposium, Edinburgh, Scotland. July 28th –August 1st, 2019.

Adebowale, O.J., Taylor, J.R.N., & de Kock, H.L. (2017). Towards improving the stability of sorghum flour: The role of microwaving and roasting sorghum grain. 22nd SAAFoST Biennial International Congress and Exhibition, Century City, Cape Town, South Africa, 3-6th September 2017.

Conference oral presentation

Adebowale, O.J., Taylor, J.R.N., & de Kock, H.L. (2018). Effect of roasting time of sorghum grain on the phenolic concentration, antioxidant activity and browning index of their flour. “Sorghum in the 21st Century” Conference, Century City, Cape Town, South Africa. 9-12th April 2018. ***Second prize recipient of the Lloyd W. Rooney Sorghum Student Oral Research Paper Award.***