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

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A B S T R A C T

Wholegrain sorghum flour (WGF) is sensitive to rancid off-flavour development during storage. Microwave treatment of whole grain kernels (WGK) at 36 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 and anisidine 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.

1. Introduction

Sorghum is a staple food grain for nearly 500 million people in sub-Saharan Africa and Asia (ICRISAT, 2018). Wholegrain 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 Cardoso, Pinheiro, Duarte, Ana, & Ana, 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, Bhashyam, & Ali, 2011). Generally, wholegrain flour is much higher in lipids and has higher lipase activity than refined flour (Doblado-Maldonado, Pike, Sweley, & Rose, 2012). The fat content in wholegrain sorghum is typically 3.2–3.9 g/100 g and the fat contains 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 wholegrain kernels (WGK) 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. Free fatty acids 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, Seetharaman, de Kock, & Taylor, 2008), hydrothermal treatment (Yadav, Kaur, Anand, & Singh, 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

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that can maintain or improve the shelf life and nutritional properties of wholegrain 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, Changzhong, & Zaigui, 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, Wang, Liu, & Wang, 2017). Microwave treatment also reduced the production of free fatty acids 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 WGK 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 WGK as a potential strategy for stabilization of sorghum flour, with the aim of improving flour storage stability and its products' sensory attributes. The wholegrain 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.

2. Materials and methods

A process diagram of the study is given in Fig. 1S.

2.1. Materials

Red non-tannin sorghum grain(a blend of cultivars but 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.

2.2. Methods

2.2.1. 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 °C and 125±1 °C, 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 ziplock-type polyethylene bags and subjected to an accelerated storage test at 50 °C, (UV light-16 W/cm^2) for up to 6 weeks. At weekly intervals, flour samples were transferred to storage at −20 °C until analysed.

2.2.2. Porridge preparation

Soft porridges were prepared as described by Kayitesi, Duodu, Minnaar, & de Kock (2010). A slurry of 200 ml cold water (25±2 °C) 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 silicone paddle to prevent lump formation. After which, the porridge was simmered at low gas heat for 20 min with stirring at 5 min intervals.

2.2.3. 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, pp. 240–246). In the training, each panellist received porridges from flours stored for various periods and identified words used to describe the differences in sensory properties. During the training sessions, descriptors, definitions and scale anchors were developed for evaluation of the porridges (Table 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).

2.3. Analyses

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

2.3.1. Flour fat rancidity

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

2.3.2. 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.

2.3.3. Flour pasting properties

The pasting properties were measured using an Anton Paar Physica MCR 301 rheometer (Ostfildern, Germany). In the aluminium canister, 1.5 g flour was suspended in distilled water and adjusted to a total weight of 15 g. The operational condition was initiated by stirring the slurry at 960 rpm at 50 °C for 30 s, and then at 160 rpm for the remainder of the analysis cycle. The suspension was heated from 50 °C to 91 °C and held at 91 °C for 15 min before cooling down to 50 °C, at heating and cooling down rates of 5.5 °C/min. Here only the peak viscosity is reported because it can be related to the ease of swallowing of porridge.

2.3.4. Porridge colour instrumental analysis

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:

$$\Delta L^* = L^* - L_{U0} \tag{1}$$

$$\Delta a^* = a^* - a_{U0} \tag{2}$$

$$\Delta b^* = b^* - b_{U0} \tag{3}$$

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

Table 1
Sensory descriptors and evaluation guidelines used by the trained descriptive sensory panel to evaluate sorghum porridges from untreated and microwave-treated wholegrain sorghum flours during storage.

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	10 g/100 g 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

$$\Delta E = [(\Delta L^*)^2 + (\Delta a^*)^2 + (\Delta b^*)^2]^{1/2} \tag{4}$$

2.3.5. *Porridge texture instrumental analysis*

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 °C 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 analyser, 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.

2.3.6. *Porridge descriptive sensory evaluation*

The porridges to be evaluated were kept warm in a bain-marie set at

50 °C. 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 °C. Blind-coded samples were presented to panellists in a randomised 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, 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 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).

2.3.7. *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, peak viscosity, 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 peak viscosity of flour pastes and storage period. Sensory attributes that described significant differences among porridges were analysed by principal component analysis. XLSTAT® software package (Addinsoft™, New York) was used for all analyses.

3. Results

3.1. *Flour fat rancidity*

At baseline (week 0), the fat acidity of the flour of untreated (U) WGK 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. 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*-anisidine value of U flour was significantly higher at week 0 than the L and H treatment flours, and increased more during the storage period.

3.2. *Flour damaged starch content*

Microwave treatment of WGK resulted in more damaged starch in the flours (Fig. 2). At flour storage baseline, the damaged starch content of L and H was nearly twice that of U. However, damaged starch in U had increased by 6 weeks storage but was still significantly lower than L and H.

3.3. *Flour paste viscosity*

At storage baseline and throughout the storage period, the peak viscosity of flour pastes from U was significantly higher than those of L and H (Fig. 3). With storage, the peak viscosity of all the flour pastes decreased but the peak viscosity of U remained the lowest.

3.4. *Porridge colour instrumental analysis*

Microwave treatment of WGK affected the instrumental colour parameters of the porridges (Table 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.

3.5. *Porridge texture instrumental analysis*

Firmness and stickiness of the porridges were not different at flour storage baseline. With flour storage, porridge firmness decreased, while stickiness increased gradually with all three treatments (U, L and H) (Fig. 4). Generally, the porridges from the L and H microwave treated flours were slightly more firm and stickier than the U controls.

3.6. *Porridge descriptive sensory evaluation*

The 36 sorghum porridge sensory descriptors and their definitions and rating scales that were developed and used by the panellists comprised aroma, appearance, taste/flavour, mouthfeel/texture and aftertaste attributes (Table 1). With baseline stored flours, microwaving the L and H treatments did not impact on any of these attributes, other than significantly intensifying the bland flavour ($p < 0.05$) of the porridges (Table 3). Hence, no difference in the brown colour of porridges prepared from U, L and H flours was detected by the descriptive sensory

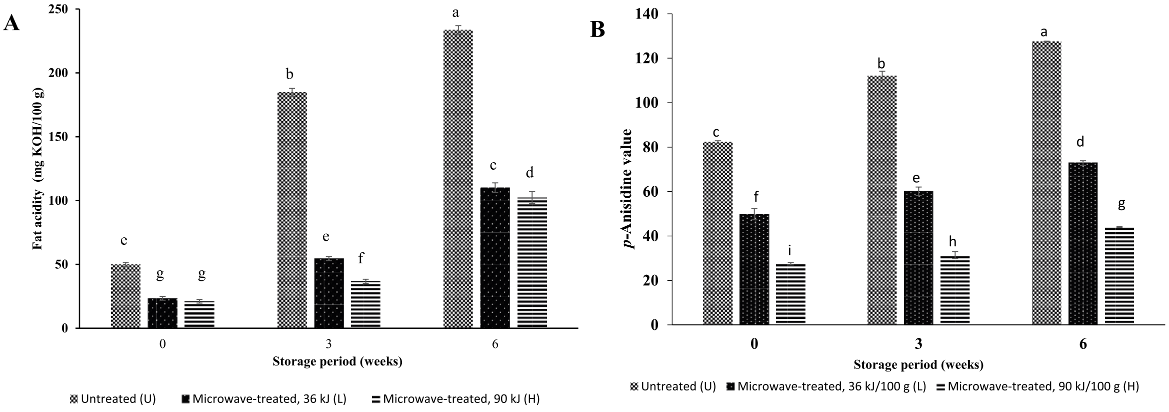

Fig. 1. Effects of microwave heat treatments of wholegrain sorghum kernels on the (A) fat acidity and (B) *p*-anisidine value of stored flours. Values with different letters are significantly different ($p < 0.05$).

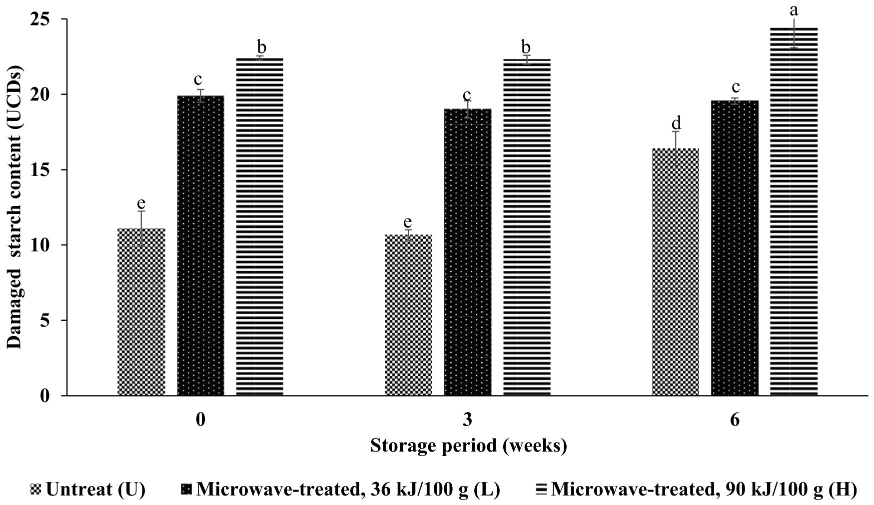

Fig. 2. Effects of microwave treatments of wholegrain sorghum kernels on the damaged starch content of stored flours. Values with different letters are significantly different ($p < 0.05$).

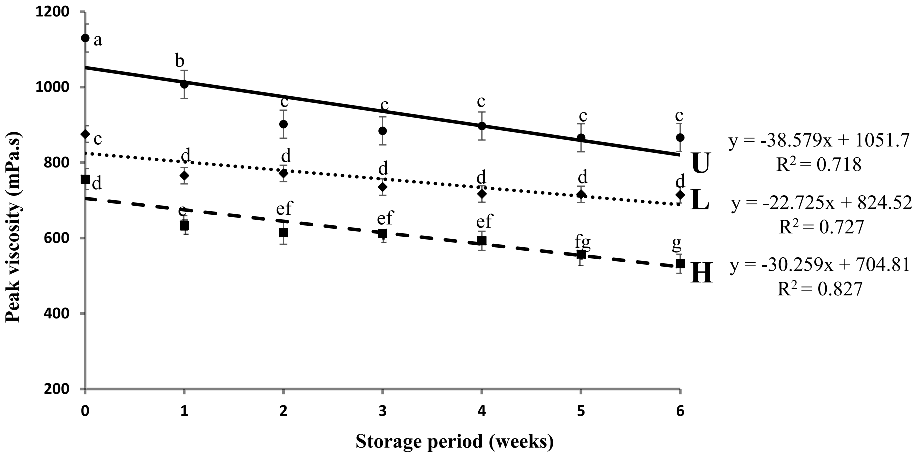

Fig. 3. Effects of microwave heat treatments of wholegrain sorghum kernels on the pasting peak viscosity of stored flours. Values with different letters are significantly different ($p < 0.05$). U = Untreated, L = Microwave treated, 36 kJ/100 g, H = Microwave treated, 90 kJ/100 g.

panel. 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 2).

Table 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 (the full dataset is given Table 1S). 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.

Fig. 5 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. Principal component 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). The 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 treated 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

Table 2
Effects of microwave treatments (L) and (H) of wholegrain 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}	4.3 b (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$^{)jk}$	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)^{fghi}	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

Values are the means of triplicate determinations. Standard deviations are in parentheses. *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. Means within the same column that do not share a superscript letter(s), differ significantly ($p < 0.05$).

at 50 °C is therefore predicted as 3 weeks for the untreated U, 4 weeks for microwave-treated L and more than 6 weeks for H.

4. Discussion

The much lower fat acidity of L and H flours over storage compared to U (Fig. 1) 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 the L and H WGK microwave treatments had much lower *p*-anisidine values over storage compared to the flours from U WGK (Fig. 1). Moreover, intense oily, painty, rancid and fermented aromas were associated with the porridges of stored flour from U but not those from the L and H treated flours, except for L week 6 storage (L_6) (Fig. 5). 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, pp. 129–131). 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 (Fig. 5) could have been as a result of the WGK 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 (Fig. 2) is attributable to thermal effects of microwave heating. Microwave treatment can disrupt the intermolecular forces between the starch and proteins and thereby increase 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, Kirleis, & Oumarou, 1999). The significantly lower peak viscosity of the flour pastes from L and H treated WGK compared to U (Fig. 3), as was also found by Sharanagat et al. (2019) with microwave roasting sorghum WGK, was probably primarily a result of the thermal damage to the starch (Fig. 2). Luo, He, Fu, Luo, and Gao (2006) attributed the reduction in the peak viscosity of thermally treated normal maize starch to the

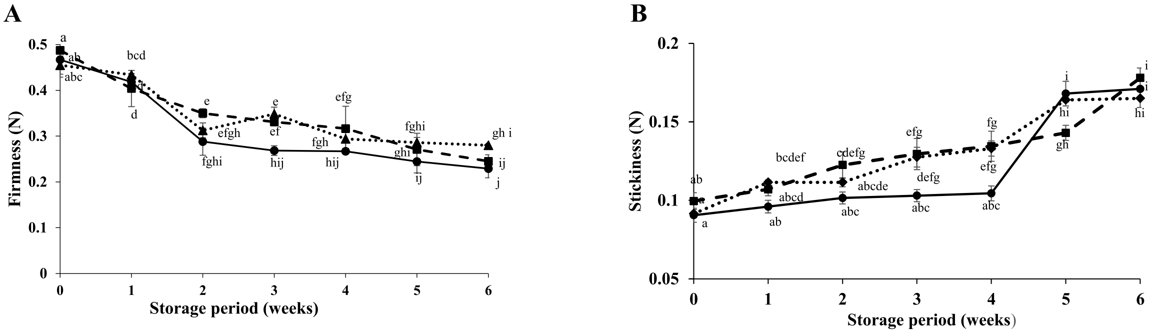

Fig. 4. Effects of microwave treatments of wholegrain sorghum kernels on the (A) firmness and (B) stickiness of porridges from stored flours. Values with different letters are significantly different ($p < 0.05$). Circles solid line = Untreated (U), Diamonds dotted line = Microwave treated 36 kJ/100 g (L), Squares dashed line = Microwaved treated 90 kJ/100 g (H).

Table 3
Descriptive sensory ratings of porridges from wholegrain sorghum flours at baseline storage (week 0) from untreated (U_0) and microwave treated (L_0) and (H_0) whole grain 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)^{a}	6.7 (1.4)^{a}	6.6 (2.4)^{a}	0.994
	Earthy	3.5 (2.9)^{a}	3.6 (2.0)^{a}	3.0 (2.9)^{a}	0.734
	Sweet	3.1 (3.0)^{a}	4.5 (3.1)^{a}	2.3 (2.5)^{a}	0.070
	Roasted	2.7 (2.7)^{a}	3.8 (2.9)^{a}	2.2 (2.3)^{a}	0.191
	Burnt	1.5 (2.1)^{a}	1.0 (1.6)^{a}	0.9 (1.4)^{a}	0.494
	Sorghum	5.3 (2.5)^{a}	6.6 (2.0)^{a}	5.8 (2.9)^{a}	0.271
	Wet cardboardy	2.6 (2.7)^{a}	2.1 (2.5)^{a}	2.6 (3.0)^{a}	0.771
	Starchy	4.6 (3.0)^{a}	3.5 (2.9)^{a}	2.9 (3.0)^{a}	0.208
	Oily	2.3 (1.9)^{a}	1.9 (2.0)^{a}	1.3 (2.1)^{a}	0.311
	Painty	2.3 (2.6)^{a}	0.9 (1.0)^{a}	1.6 (2.2)^{a}	0.141
	Rancid	1.7 (1.7)^{a}	1.6 (2.0)^{a}	1.0 (2.0)^{a}	0.412
	Fermented	2.9 (2.2)^{a}	2.1 (2.4)^{a}	1.4 (2.0)^{a}	0.146
	Wheaty	3.3 (3.3)^{a}	3.2 (3.3)^{a}	2.8 (2.6)^{a}	0.856
	Cooked maize meal porridge	2.2 (3.7)^{a}	1.2 (1.4) a	1.7 (1.5)^{a}	0.214
	Fruity	1.4 (3.1)^{a}	2.8 (3.0)^{a}	1.0 (1.9)^{a}	0.070
	Spicy	1.0 (1.4)^{a}	0.7 (1.0)^{a}	0.5 (0.9)^{a}	0.291
	Grassy	1.3 (2.0)^{a}	1.8 (2.2$^{)}$ ^{a}	1.9 (2.3)^{a}	0.699
Appearance	Brown colour	7.6 (3.9)^{a}	7.4 (2.4)^{a}	7.5 (2.1)^{a}	0.976
	Specks	6.0 (3.2)^{a}	6.5 (2.7)^{a}	7.0 (2.7)^{a}	0.600
	Viscosity	6.9 (2.1)^{a}	7.9 (1.8)^{a}	7.8 (1.3)^{a}	0.161
	Glossy	7.8 (1.7)^{a}	8.2 (1.5)^{a}	8.2 (1.7)^{a}	0.686
	Sticky	5.5 (2.3)^{a}	5.3 (2.2)^{a}	5.5 (2.6)^{a}	0.956
Taste/ flavour	Bitter taste	2.3 (2.2)^{a}	1.5 (2.3)^{a}	1.8 (2.6)^{a}	0.589
	Sour taste	1.6 (2.0)^{a}	1.4 (2.1)^{a}	1.6 (2.5)^{a}	0.934
	Sweet taste	1.6 (2.2)^{a}	1.4 (1.9)^{a}	1.2 (2.2)^{a}	0.846
	Starch flavour	4.8 (3.0)^{a}	3.4 (2.8)^{a}	3.7 (3.1)^{a}	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)^{a}	2.4 (2.2)^{a}	2.6 (2.4)^{a}	0.555
	Grainy	4.8 (2.7)^{a}	4.2 (2.7)^{a}	4.0 (3.2)^{a}	0.650
	Astringent	4.0 (2.2)^{a}	3.2 (2.1)^{a}	2.8 (2.4)^{a}	0.239
Aftertaste	Bitter	1.5 (1.3)^{a}	1.4 (2.2)^{a}	1.9 (2.6)^{a}	0.717
	Oily	1.3 (1.9)^{a}	1.9 (2.0)^{a}	1.3 (1.8)^{a}	0.349
	Rancid	1.5 (2.2)^{a}	1.2 (2.2)^{a}	1.3 (2.2)^{a}	0.905
	Sour	1.6 (1.7)^{a}	1.0 (1.8)^{a}	1.2 (2.3)^{a}	0.725
	Sweet	0.9 (2.0)^{a}	1.2 (1.0)^{a}	0.9 (1.7)^{a}	0.796
	Residual particles	3.5 (2.8)^{a}	3.4 (2.7)^{a}	2.8 (3.3)^{a}	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 1. Attributes printed in bold indicate a significant difference among treatments ($p < 0.05$). Values within the same row that do not share a superscript letter(s), differ significantly ($p < 0.05$).

disruption of starch granular structure leading to a decrease in water uptake by starch and 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 peak viscosity is that porridges of higher energy density with low viscosity could be achieved, thereby making the porridges more suitable for infant feeding (Moussa, Qin, Chen, Campanella, & Hamaker, 2011).

The generally somewhat higher firmness of the porridges of the L and H treatments (Fig. 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 (Fig. 5). 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 (Fig. 4). The greater starch damage of the L and H flours (Fig. 2) was probably responsible. However, no difference in porridge stickiness was detected by the descriptive sensory panel (Fig. 5). As with porridge texture, this may have been masked by other sensory attributes.

The lower L* value of the porridges from the H treatment (Table 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 WGK processing (Purlis, 2010). With the U treatment, the increase in porridge L* value (Table 2) and in painty, oily and rancid aroma sensory attributes (Table 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.

5. 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 peak viscosity from microwave treated WGK suggests that the treatment has the 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 WGK microwave treatment, the determination of consumer acceptability of the porridges is recommended. Additionally, the economic viability of the treatment needs to be assessed.

Table 4
Effects of microwave treatments L and H of wholegrain sorghum kernels on sensory attributes* of porridges prepared from stored wholegrain 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}

Values are the means of duplicate determinations. Standard deviations are in parentheses. Values within the same column that do not share superscript letter(s), differ significantly ($p < 0.001$). The definition and rating scale (0 = Not intense/present; 10 = Very intense/present) of attributes are shown in Table 1. *Note only sensory attributes that described significant differences ($p < 0.05$) for the interaction effect (treatment X storage) among the porridge samples are presented. See Table 1S for the full set of results.

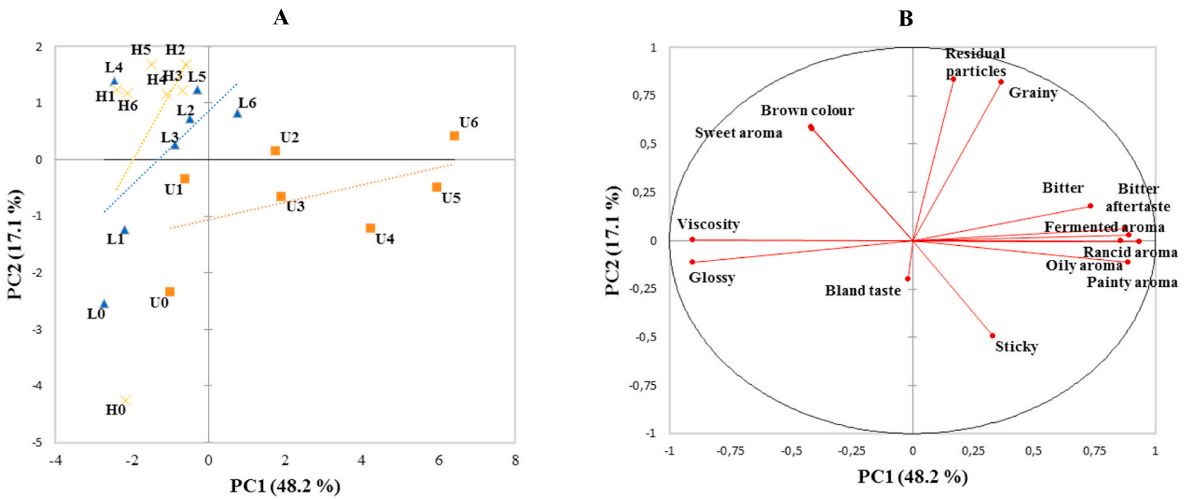

Fig. 5. Principal component analysis (PCA) score (A) and loading (B) plots of the sensory attributes of porridges prepared from the flours of untreated and microwave treated wholegrain sorghum kernels stored for up to 6 weeks. U = Untreated, L = Microwave treated, 36 kJ/100 g, H = Microwave treated, 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.

Disclosure statement

The authors declare no conflict of interest.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

CRediT authorship contribution statement

Olalekan J. Adebowale: Investigation, Methodology, Data curation, Formal analysis, Writing - original draft. **John R.N. Taylor:** Supervision, Funding acquisition, Conceptualization, Methodology, Writing - review & editing. **Henriëtta L. de Kock:** Supervision, Funding acquisition, Conceptualization, Methodology, Writing - review & editing.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.lwt.2020.109827.

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