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Physico-chemical properties of flour, dough and bread from wheat and hydrothermally-treated finger millet

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ABSTRACT

Hydrothermally-treated (HTT) finger millet was prepared by tempering the grains twice with water (10:1) followed by incubation at about 25–30 °C in a woven polypropylene sack for 10 days. Hydrothermally-treated finger millet was darker and had higher α-amylase activity and lower starch digestibility than native (NAT) grains. The HTT finger millet was composited with wheat flour and used to prepare bread. Composite dough had higher dough stability, dough development time and degree of softening but lower dough energy, extensibility and resistance to extension than WHE dough. The higher specific volume and lower crumb firmness and chewiness of WHE-HTT compared to WHE-NAT bread was attributed to the high α-amylase activity and water absorption capacity of HTT finger millet. Wheat-HTT bread had higher dietary fibre, phytate and phenolic acid content but the same starch and protein digestibility as WHE bread.

1. Introduction

Bread is a source of several nutrients that have a positive effect on human health. The nutritional quality of bread can be improved further by partial substitution of wheat with wholegrain cereals. Composite bread has higher phenolic acid content, antioxidant capacity, dietary fibre and ash content than wheat bread (Ragaee et al., 2011; Koletta et al., 2014). However, partial substitution of wheat with wholegrain cereals decreases the physical quality of bread because the non-wheat flour dilutes gluten resulting in decreased dough strength and gas retention capacity. Consequently, composite bread has lower specific volume and poorer crumb properties compared to wheat bread (Ragaee et al., 2011; Koletta et al., 2014).

In order to avoid excessive loss of bread quality, wheat flour substitution is limited to about 30% (Ragaee et al., 2011; Hugo et al., 2000, 2003). In addition, modified rather than native cereal flours are used to improve the physical quality of composite bread. Hugo et al. (2000) found that composite bread containing boiled sorghum malt flour is softer and has better crumb structure and greater resistance to staling compared with the bread made with native sorghum flour. In another study, Hugo et al. (2003) showed that lactic acid fermented sorghum flour increases bread volume and decreases crumb firmness of wheat-sorghum bread. The retrogradation rate of composite bread can be retarded without adversely affecting bread quality by using steamed oat flour (Zhang et al., 1998) or pregerminated brown rice (Watanabe et al., 2004) instead of the corresponding native flours. However, promising results have not been achieved by using hydrothermally-treated flour in composite bread production. Miyazaki and Morita (2005) found that partial substitution of wheat flour with heat-moisture treated maize starch decreased loaf specific volume and increased crumb firmness.

An optimised method for preparing hydrothermally-treated (HTT) finger millet has been described by Shobana and Malleshi (2007). The grains are steeped in water at 20–70 °C for 2–16 h before they are steamed and dried. The purpose of this treatment method is to increase endosperm hardness so that it can withstand mechanical impact during decortication (Dharmaraj et al., 2015; Shobana and Malleshi, 2007). A traditional method for making HTT finger millet is also practised in sub-Saharan Africa. The grains are tempered with water (about 10:1) and incubated at about 25–30 °C for 10 days in a woven polypropylene sack, which is tightly covered with a polythene sheet. After incubation, the grains are washed, dried and milled. Although the grains are incubated at room temperature, the temperature in the centre of the sack rises to about 60–70 °C because they are densely packed and tightly wrapped with a polythene sheet. The traditional method for making HTT finger millet is a modification of the malting technique whereby

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grains are steeped in excess water before they are spread on perforated trays for 3–4 days at 25–30 °C to germinate before they are dried. The main differences between malting and the traditional method of making HTT finger millet relate to the moisture content of the grain, and the incubation temperature and time. Unlike malting, HTT finger millet does not germinate and is darker than the native grain.

The physico-chemical properties of HTT finger millet made by steaming (Dharmaraj et al., 2015; Dharmaraj and Malleshi, 2011; Shobana and Malleshi, 2007) and malted finger millet (Hejazi and Orsat, 2016; Makokha et al., 2002; Mbithi-Mwikya et al., 2000) has been reported but we have not come across any published work on the properties of traditionally-prepared HTT finger millet. Thus, the aim of this work was to characterize traditionally-prepared HTT finger millet and subsequently determine its impact on the physico-chemical properties of composite flour, dough and bread.

2. Materials and methods

2.1. Materials

Baker's flour was purchased from Unga Ltd (Nairobi, Kenya). Native (NAT) and hydrothermally prepared (HTT) finger millet were purchased from a local market in Kisumu, Kenya. Hydrothermally-treated finger millet was prepared by the vendor by tempering the grains with water (10:1). The grains were put in a woven polypropylene sack and covered with a polythene sheet. The sack was incubated at room temperature (about 25–30 °C) for 5 days. After 5 days, the grains were removed, wetted with additional water (10:1) and incubated further for 5 days. Thereafter, the grains were sun-dried to about 10% moisture content. The grains were milled using a laboratory mill fitted with 1 mm screen. Wheat-native finger millet (WHE-NAT) and wheat-hydrothermally treated finger millet (WHE-HTT) flours were prepared at 70:30 ratios and stored at 4 °C prior to use. All baking ingredients (table salt, sugar, dry instant yeast, and vegetable fat) were purchased from a supermarket in Nairobi, Kenya.

2.2. Physico-chemical properties of finger millet

The colour of NAT and HTT finger millet grains was measured using a Chroma Meter CR-5 (Konica Minolta, Sakai Osaka, Japan) with a spot diameter view of 8 mm. Colour readings were taken at standard illuminant D65 and 10° observer. CIE-LAB colour spectrum of light-dark, red-green, and yellow-blue were recorded. The overall change in lightness ($\Delta L^* = L^*_{sample} - L^*_{reference}$) and colour [$\Delta E^* = (\Delta L^2 + \Delta a^2 + \Delta b^2)^{1/2}$] was measured using a Chroma Meter CR-10 also from Konica Minolta.

Moisture content was determined according to ICC No. 109/1 (ICC, 2008). Starch content was determined according to Ewers polarimetric method (ISO 10520:1997). Dietary fibre (K-TDFR-100A), digestible starch (K-RAPRS), α-amylase activity (K-CERA) and phytate content (K-PHYT) were measured using Megazyme assay kits (Megazyme Int. Ireland Ltd., Wicklow, Ireland). Protein, lipid and mineral content were determined according to ICC No. 105/2, 136 and 104/1, respectively (ICC, 2008). *In vitro* protein (IVPD) digestibility was determined as described by Almeida et al. (2015). Free phenolic compounds were determined by extracting samples (4 g) with 50 ml acetone-water mixture (50:50 v/v) for 2 h at 25 °C in a dark chamber followed by filtration and storage at 4 °C prior to further analysis. Sample extracts (0.2 ml) were vortex-mixed with distilled water (4.8 ml) and Folin-Ciocalteu reagent (0.5 ml) and then stored in a darkroom for 4 min before adding 20% w/v sodium carbonate solution (1.5 ml) and distilled water (3 ml). The mixture was vortexed-mixed and stored in a dark chamber at 37 °C for 1 h before measuring absorbance at 760 nm. Gallic acid was used as standard.

2.3. Physico-chemical properties of flours

Colour, moisture, protein, starch, fibre, mineral, phytate, free phenolic compounds and α-amylase activity of WHE and composite flours were determined as described earlier. Zeleny sedimentation value was determined according to ICC No. 116/1 (ICC, 2008). Falling Number was determined according to Hagberg-Perten method (ISO 3093:2009).

2.4. Rheological properties of dough

Farinograph properties of doughs were evaluated using a Brabender Farinograph-AT (Brabender GmbH & Co. KG, Duisburg, Germany) according to ICC No. 115-1 (ICC, 2008). Extensograph properties of doughs were evaluated using a Brabender Extensograph-E also from Brabender GmbH & Co. KG according to ICC No. 114/1 (ICC, 2008).

2.5. Physico-chemical properties of bread

Bread was made from WHE or composite flours. The other baking ingredients, weighed on flour-weight-basis, were: sugar (4%), active dry yeast (1.5%, Angel Yeast Co. Ltd, Beni Suef, Egypt), baker's fat (2.5%), salt (1.5%) and crumb softener (1%, Nutrisoft 55, BASF Personal Care and Nutrition GmbH, Illertissen, Germany). Farinograph water absorption capacity (WAC) of WHE, WHE-NAT and WHE-HTT was 61, 59 and 59.7%, respectively. The ingredients and additives were mixed using a spiral dough hook for 1 min at low speed and kneaded for 5 min at medium speed in a SP22HI planetary mixer (SPAR Food Machinery Mfg. Co. Ltd., Taichung Hsien, Taiwan). The dough was rested for 10 min, divided into 450 g pieces, manually rounded, and rested again for 15 min. The dough was manually shaped, loaded into baking tins (L x W x H: 205 × 105 × 70 mm) and proofed in a prover (National Mfg. Co., Lincoln, NE, USA) for 60 min at 32 °C and 80% relative humidity. After proofing, the tins were loaded into a preheated rotary oven (National Mfg. Co., Lincoln, NE, USA) at 200 °C for 22 min. The loaves were depanned and stored in paper bags in an incubator at 25 °C for 22 h before further analysis.

Bread weight was determined using a UW1020H Shimadzu electronic balance (Shimadzu Corporation, Japan). Bread volume was determined by finger millet seed displacement in 7.5 l jug. Specific volume was calculated as bread vol/wt (cm^3/g). Breads were sliced into 20 mm thick slices. A portion of bread was freeze-dried and milled to pass via 500 μm sieve. Moisture, digestible starch, IVPD, phytates and free phenolic compounds were determined as described earlier. Crumb colour was determined as described earlier. Browning Index (BI) was calculated according to the following formula:

$$BI = \frac{[100(x - 0.31)]}{0}.17$$

Where

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

Where a* is redness,b* is yellowness, and L* is lightness.

Texture Profile Analysis of bread crumb (20 mm thick, 30 mm diameter) was measured using a 75 mm diameter aluminium cylinder probe (P/75) attached to a TA/XT-plus Texture Analyser with 50 kg load cell (Stable Micro Systems, Surrey, UK). The instrument settings were: 40 mm height calibration, 1 mms^{-1} pre-test speed, 5 mms^{-1} test speed, 5 mms^{-1} post-test speed, 10 mm target mode distance, 0.05 N trigger auto force, 200 pps data acquisition rate, and 5 s pause between the compression cycles. Crumb firmness, springiness, cohesiveness, chewiness and resilience were calculated from the Texture Profile Analysis graph using the instrument software.

2.6. Experimental design

All analyses were carried out at least in duplicate and results reported as mean ± standard deviation. Independent *t*-test was used to evaluate differences between NAT and HTT finger millet. A single-factor experimental design was used to evaluate effect of flour type on physico-chemical properties of flour, dough and bread. Results of the single-factor experimental design were subjected to one-way analysis of variance and differences in treatment means identified by Tukey's Test at a family error rate of 5%. All data were analysed using Minitab Release 14 statistics software (Minitab Inc., Pennsylvania, USA).

3. Results and discussion

3.1. Physico-chemical properties of finger millet

The physico-chemical properties of NAT and HTT finger millet are presented in Table 1. Hydrothermally-treated finger millet was darker and had lower starch digestibility and higher α-amylase activity than NAT finger millet. Starch, lipid, mineral and phytate content, and IVPD of finger millet were not affected ($p > 0.05$) by HTT. Protein and dietary fibre content of finger millet increased, whereas the content of phenolic compounds decreased after HTT. The dark colour of HTT finger millet could be due to oxidation of polyphenols and pigments such as anthocyanidins in grains (Dharmaraj et al., 2015; Shobana and Malleshi, 2007). Polyphenol oxidases catalyse oxidation of phenolic acids into dark short-chain polymers. The increase in protein and fibre content was attributed to enhanced α-amylase activity, which decreased starch content relative to other nutrients in HTT finger millet. The decrease in digestible starch content was attributed to re-association of starch polymers, which decreased structural defects in crystalline parts of starch granules, rather than amylose crystallization. This was confirmed using differential scanning calorimetry, which showed that NAT and HTT finger millet had similar melting enthalpies (9 J/g) and gelatinization temperatures (65–83°*C*) and lacked melting endotherms associated with amylose crystallization. The content of free phenolic compounds may have decreased in HTT finger millet because they readily form complexes with each other and with protein when heated, which makes them less extractable (Towo et al., 2003).

Traditionally prepared HTT finger millet differs from malted grain with respect to the moisture content of the grain, incubation time and temperature. Finger millet malt is made by steeping grains in water for 10–24 h prior to incubation at 22–30 °*C* until sprouts appear, usually within 48–96 h (Hejazi & Orsat, 2016, 2017). By contrast, HTT finger millet is made by tempering the grains with limited water (10:1) followed by incubation at 25–30 °*C* for 10 days. Because of the different processing methods, HTT finger millet has different physico-chemical properties from the malted grain. Malting finger millet causes grain germination, improves starch and protein digestibility and decreases phytate content (Hejazi and Orsat, 2016; Mbithi-Mwikya et al., 2000). By contrast, HTT did not result in grain germination, decreased starch digestibility and did not change IVPD of finger millet (Table 1). Nonetheless, some physico-chemical properties of HTT finger millet are similar to the malted grain. Hydrothermally-treated finger millet, like the malted grain, has lower starch content but higher protein and dietary fibre content and α-amylase activity than native grains (Hejazi and Orsat, 2017; Koehler et al., 2007; Mbithi-Mwikya et al., 2000). The nutrient composition of HTT finger millet made by steaming also differs from our results. Steaming finger millet does not change the gross composition of carbohydrate, protein and lipids; decreases ash and phytic acid content; and improves starch and protein digestibility (Dharmaraj and Malleshi, 2011; Shobana and Malleshi, 2007). The only similarity between HTT finger millet made by steaming and our results is with respect to development of dark coloured grains and reduction in the content of phenolic compounds after HTT.

Table 1
Physico-chemical properties of native and hydrothermally-treated finger millet.

Parameter	Measured parameter (unit)	NAT	HTT	P-value
Grain colour	Lightness index (L*)	31.1 ± 1.31	19.0 ± 0.54	0.00
	Red-green index (a*)	11.8 ± 0.98	3.97 ± 0.73	0.00
	Yellow-blue index (b*)	13.6 ± 1.05	2.36 ± 0.49	0.00
	Overall change in lightness (ΔL*)[a]	–	−7.80 ± 0.70	–
	Overall colour change (ΔE*)[b]	–	11.2 ± 0.70	–
Starch	(g/100 g dm)	76.1 ± 1.00	71.9 ± 3.44	0.10
Protein	(g/100 g dm)	6.68 ± 0.02	7.52 ± 0.07	0.04
Lipid	(g/100 g dm)	1.90 ± 0.07	1.73 ± 0.02	0.19
Dietary fibre	Soluble dietary fibre (g/100 g dm)	0.37 ± 0.14	1.50 ± 0.05	0.01
	Insoluble dietary fibre (g/100 g dm)	11.4 ± 0.23	12.1 ± 0.15	0.02
	Total dietary fibre (g/100 g dm)	11.7 ± 0.27	13.7 ± 0.11	0.01
α-amylase	Activity (CU/g)	0.12 ± 0.02	11.7 ± 0.25	0.00
	Falling Number (s)	892 ± 23	247 ± 4	0.00
Mineral	(g/100 g dm)	2.98 ± 0.00	2.97 ± 0.00	0.27
Bioactive compounds	Phytate (mg/100 g dm)	844 ± 21	842 ± 100	0.97
	Free phenolics (mg gallic acid equivalents/100 g dm)	305 ± 9	83 ± 0	0.02
Digestibility	Digestible starch (g/100 g dm)	64.9 ± 1.39	58.6 ± 3.28	0.02
	Digestible starch (% of total starch)	85	81	–
	Resistant starch (g/100 g dm)	11.3 ± 0.42	13.3 ± 1.40	0.07
	Resistant starch (% of total starch)	15	19	–
	In vitro protein digestibility (% of total protein)	89.2 ± 2.24	83.6 ± 2.16	0.24

NAT - native finger millet; HTT - hydrothermally-treated finger millet.
Values reported as mean ± standard deviation.
[a] Change in lightness of hydrothermally-treated versus native finger millet grain.
[b] Change in colour of hydrothermally-treated versus native finger millet grain.

3.2. Physico-chemical properties of flours

The colour indices of WHE, WHE-NAT and WHE-HTT flours are presented in Table 2. Lightness and yellowness indices decreased, whereas redness index increased when WHE was partially substituted with NAT or HTT finger millet. The overall change in lightness and colour was higher in WHE-HTT than WHE-NAT due to the darker colour of HTT finger millet. The typical white colour of wheat flour is attributed to separation of white starchy endosperm from pigmented bran, whereas the yellow tinge is due to carotenoids in the endosperm (Barnes, 1986). Re-introduction of pigmented compounds from finger millet seed coat into WHE was thus responsible for the dark colour of composite flours. Furthermore, the darker colour of WHE-HTT compared to WHE-NAT

Table 2
Physico-chemical properties of wheat and wheat-finger millet flours.

Parameter	Measured parameter (unit)	WHE	WHE-NAT (70:30)	WHE-HTT (70:30)
Colour	Lightness index (L*)	89.9 ± 0.03^{c}	82.8 ± 0.64^{b}	80.1 ± 0.84^{a}
	Red-green index (a*)	0.45 ± 0.02^{a}	1.39 ± 0.11^{b}	1.55 ± 0.10^{c}
	Yellow-blue index (b*)	10.4 ± 0.11^{c}	7.82 ± 0.11^{a}	7.94 ± 0.27^{b}
	Overall change in lightness (ΔL*)[a]	–	−9.3 ± 0.5	−12.0 ± 0.7
	Overall colour change (ΔE*)[b]	–	10.0 ± 0.4	12.6 ± 0.6
Starch	(g/100 g dm)	78.5 ± 1.68	76.1 ± 0.39	74.2 ± 1.22
Protein	Quantity (g/100 g dm)	11.3 ± 0.04^{c}	10.0 ± 0.02^{a}	10.3 ± 0.01^{b}
	Zeleny sedimentation (ml)	27±0^{b}	15±0^{a}	15±0^{a}
α-amylase	Activity (CU/g)	1.64 ± 0.25^{a}	1.05 ± 0.15^{a}	3.79 ± 0.08^{b}
	Falling number (s)	386±1^{b}	454±1^{c}	309±6^{a}
Lipid	(g/100 g dm)	1.11 ± 0.07^{b}	0.57 ± 0.01^{a}	0.89 ± 0.12^{ab}
Dietary fibre	Soluble dietary fibre (g/100 g dm)	2.14 ± 0.03^{c}	1.26 ± 0.20^{a}	1.80 ± 0.06^{b}
	Insoluble dietary fibre (g/100 g dm)	2.63 ± 0.40^{a}	4.56 ± 0.25^{b}	4.96 ± 0.07^{b}
	Total dietary fibre (g/100 g dm)	4.76 ± 0.37^{a}	5.82 ± 0.15^{b}	6.76 ± 0.09^{c}
Mineral	(g/100 g dm)	0.65 ± 0.00^{a}	1.40 ± 0.01^{b}	1.44 ± 0.01^{c}
Bioactive compounds	Phytate (mg/100 g dm)	207±3^{a}	448 ± 12^{b}	454 ± 21^{b}
	Free phenolics (mg gallic acid equivalents/100 g dm)	76±3^{a}	123±4^{b}	84±3^{a}

WHE - wheat; WHE-NAT – wheat-native finger millet; WHE-HTT – wheat - hydrothermally-treated finger millet.
Values reported as mean ± standard deviation. Means in the same row with different superscript letters are significantly different from each other at $p \leq 0.05$. Means without superscript letters across rows are not significantly different at $p \leq 0.05$.
[a] Change in lightness of composite flour versus wheat flour.
[b] Change in colour of composite flour versus wheat flour.

was associated with oxidized polyphenols which were formed in HTT finger millet.

Wheat flour had the same ($p > 0.05$) starch content as composite flours but higher ($p < 0.05$) protein and fat contents and Zeleny sedimentation value. Total dietary fibre and mineral content increased when WHE was partially substituted with NAT or HTT finger millet. Partial substitution of wheat with whole cereal flours increases fibre and mineral content of composite flours (Ragaee et al., 2011; Koletta et al., 2014). Fibre and minerals are undesirable (from a technological perspective) in breadmaking because they interfere with gluten functionality resulting in low bread volume and high crumb firmness (Ragaee et al., 2011; Koletta et al., 2014). On the other hand, wheat with high quantity and quality of gluten gives dough with optimal rheological and gas retention properties and consequently bread with high volume and soft crumb (Goesaert et al., 2005).

The technological quality of wheat for breadmaking is also influenced by its α-amylase activity, which is inversely related to the Falling Number (Mangan et al., 2016). α-Amylase supports yeast activity in dough by increasing the level of fermentable sugars. It intensifies bread flavour and crust colour by producing reducing sugars from starch that participate in Maillard reactions. It also reduces dough viscosity during starch gelatinization thereby prolonging oven rise and increasing bread volume (Goesaert et al., 2005). Partial substitution of WHE with HTT finger millet decreased the Falling Number from 386 s in WHE to 309 s in WHE-HTT. By contrast, partial substitution of WHE with NAT finger millet increased the Falling Number from 386 s in WHE to 454 s in WHE-NAT (Table 2). The different Falling Numbers of the composite flours were attributed to the different α-amylase activities of NAT and HTT finger millet. High α-amylase activity in HTT finger millet enhanced starch hydrolysis in WHE-HTT resulting in low Falling Number, whereas low α-amylase activity in NAT finger millet (Table 2) and dilution effect by the flour increased the Falling Number of WHE-NAT.

Phytate content increased from 207 to about 450 mg/100 g dm when WHE was partially substituted with NAT or HTT finger millet. The content of free phenolics in WHE was 76 mg gallic acid equivalents/100 g dm and increased by 61% when WHE was partially substituted with NAT finger millet but did not change ($p > 0.05$) when WHE was partially substituted with HTT finger millet. The content of phytates and polyphenols in the composite flours reflected the amounts present in NAT and HTT finger millet but in lower quantities due to dilution by wheat flour.

3.3. Rheological properties of dough

The farinograms of WHE and composite doughs are shown in Fig. 1. Water absorption capacity decreased from 61% in WHE to 59 and 59.7% in WHE-NAT and WHE-HTT, respectively. Dough development time (DDT), dough stability (DS) and degree of softening (DOS) are indicators of protein content and quality in wheat flour. The low DDT (1.35 min) and DS (1.35 min) of WHE was attributed to its low protein content and quality (Table 2). Dough development time increased from 1.35 min in WHE to 6.93 and 3.47 min in WHE-NAT and WHE-HTT, respectively. Dough stability increased from 1.35 min in WHE to 7.69 and 5.93 min in WHE-NAT and WHE-HTT, respectively. Degree of softening increased from 97 FU in WHE to 152 and 166 FU in WHE-NAT and WHE-HTT, respectively. Since finger millet protein has no functional value in breadmaking, the high DDT and DS in composite dough was attributed to hydration properties of dietary fibre. The major non-protein components that affect dough rheology are starch and non-starch polysaccharides. Non-starch polysaccharides have higher water-binding capacity than starch and override any negative effects due to dilution of gluten by starch (Izydorczyk et al., 2001). Non-starch polysaccharides improve dough elasticity by forming elastic networks and weak secondary bonds with other carbohydrates and proteins (Izydorczyk et al., 2001). They also delayed development and subsequent breakdown of gluten resulting in increased DDT and DS. However, the influence of non-starch polysaccharides on rheological properties of dough declined after they were fully hydrated. This was evident by the high DOS of WHE-NAT and WHE-HTT dough, which suggested that prolonged dough mixing enhanced interference of wheat gluten by non-starch polysaccharides leading to dough softening.

The extensograms of WHE and composite doughs are presented in Fig. 2. Dough energy and maximum resistance to extension at 45, 90 and 135 min decreased in the following order: WHE > WHE-NAT > WHE-HTT, whereas dough extensibility decreased in the following order WHE > WHE-HTT > WHE-NAT. Dough energy, extensibility and maximum resistance to extension are indicators of dough strength and are influenced by the quantity and quality of protein. These indices decrease when protein quantity is reduced or protein quality is disrupted (Koletta et al., 2014).

3.4. Physico-chemical properties of bread

Specific volume of bread declined from 3.89 cm^3/g in WHE to 2.99 and 3.33 cm^3/g in WHE-NAT and WHE-HTT, respectively (Table 3). The

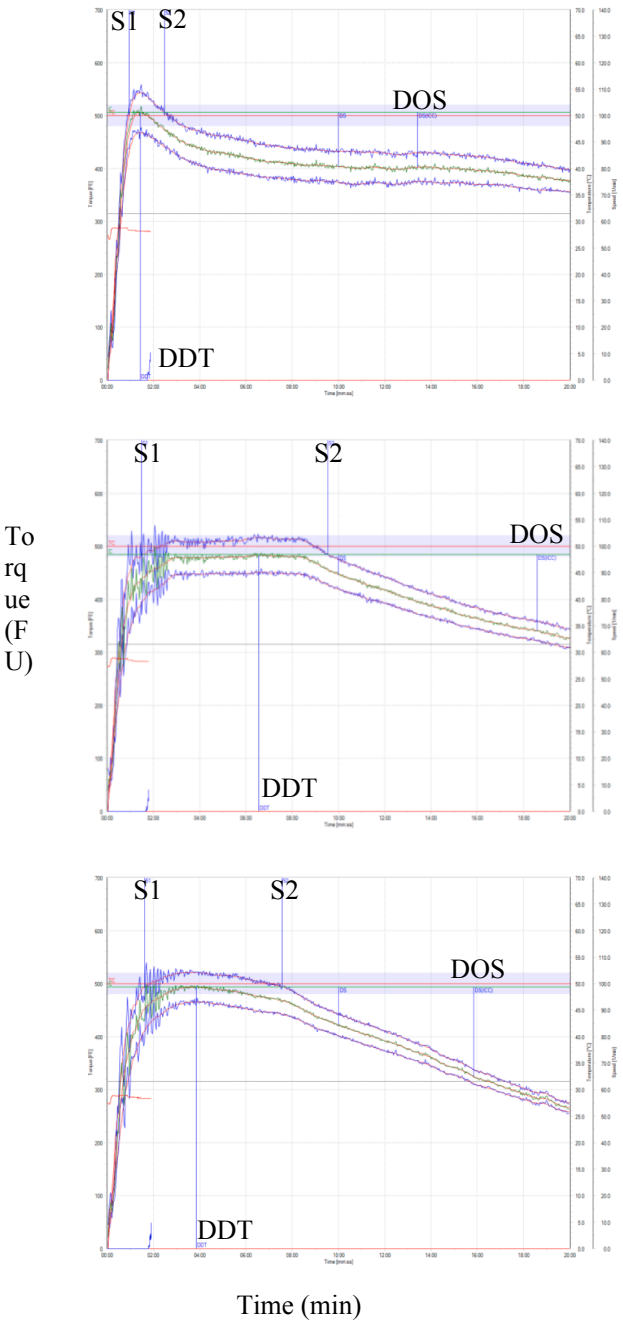

Fig. 1. Farinograms of wheat (top), wheat-native finger millet (middle), and wheat-hydrothermally-treated finger millet (bottom). DDT: dough development time (min); S2-S1: dough stability (min); DOS: degree of softening (FU).

negative impact of non-wheat flours on bread volume is due to dilution and disruption of gluten macromolecular network (Ragaee et al., 2011; Koletta et al., 2014). The higher specific volume of WHE-HTT compared to WHE-NAT bread was attributed to the high WAC and α-amylase activity of WHE-HTT. High WAC of flour enhances gluten hydration and improves the gas-holding capacity of dough, whereas high α-amylase activity reduces dough viscosity. These dough modifications result in prolonged oven rise and improve bread volume (Goesaert et al., 2005).

Composite breads had lower ($p < 0.05$) lightness indices but higher ($p < 0.05$) redness and yellowness indices than WHE bread due to the inherent dark colour of NAT finger millet seed coat and additional coloured pigments formed during HTT. The higher overall change in lightness (ΔL*) and colour (ΔE*), and higher browning index of WHE-HTT compared to WHE-NAT bread was attributed to the cumulative effect of naturally occurring dark pigments in finger millet seed coat and coloured compounds formed during HTT.

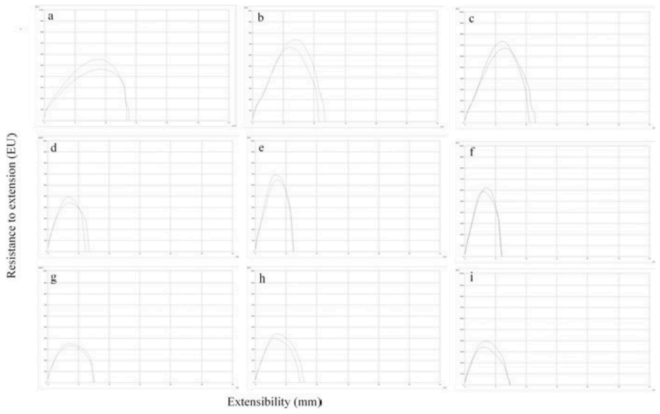

Fig. 2. Extensograms of wheat (a, b, c); wheat-native finger millet (d, e, f); and wheat-hydrothermally-treated finger millet (g, h, i). Extensograms were recorded at 45 min (a, d, g); 90 min (b, e, h); and 135 min (c, f, i).

Wheat bread had lower crumb firmness and chewiness but higher springiness, cohesiveness and resilience than WHE-NAT or WHE-HTT bread (Table 3). The typical foam structure of bread crumb is associated with changes that occur in gluten and starch during baking. Wheat dough has sufficient water that ensures gluten hydration for dough expansion and gas retention but limited starch gelatinization and swelling. When this dough is baked, it gives bread crumb with an elastic network of cross-linked gluten molecules and discontinuous phase of entrapped, partially gelatinized, swollen and deformed starch granules (Goesaert et al., 2005). The gluten elastic network was disrupted when WHE was partially substituted with NAT or HTT finger millet resulting in firmer and chewier crumb with decreased cohesiveness, springiness and resilience. The lower crumb firmness and chewiness of WHE-HTT bread, compared to WHE-NAT bread, was attributed to the high WAC and α-amylase activity of WHE-HTT dough. These factors were also responsible for the higher specific volume of WHE-HTT bread as explained earlier. The lower crumb springiness, cohesiveness and resilience of WHE-HTT bread, compared to WHE-NAT bread, suggested poor internal cohesion due to weak starch-protein network in WHE-HTT bread.

The digestible starch content as a fraction of total starch was more than 98%, whereas IVPD ranged between 80 and 83% for all breads (Table 3). Composite breads had higher total dietary fibre, phytate and phenolic compounds than WHE bread (Table 3). Bread is an important source of dietary energy and proteins in the human diet because it is rich in digestible starch (Ragaee et al., 2011) and has high IVPD (Angioloni and Collar, 2012). The dietary fibre and phenolic acid content of bread can be further improved by partial substitution of wheat with whole-grain flours (Ragaee et al., 2011; Koletta et al., 2014). Phytate is considered to be an antinutrient because it decreases mineral and protein bioavailability and inhibits enzyme activity (Konietzny and Greiner, 2002). The lower phytate content in WHE bread compared to composite breads can be attributed to naturally occurring phytases in wheat and baker's yeast, which degrade phytate during proofing (Türk et al., 1996) and thermal degradation of phytate during baking (McKenzie-Parnell and Davies, 1986). By contrast, the high phytate content of composite breads was associated with the high phytate content in NAT and HTT finger millet (Table 1).

4. Conclusions

The aim of this study was to evaluate the effect of traditionally processed HTT finger millet on the quality of composite dough and

Table 3
Physico-chemical properties of wheat and wheat-finger millet bread.

Parameter	Measured parameter (unit)	WHE	WHE-NAT (70:30)	WHE-HTT (70:30)
Specific volume	(cm^3/g)	3.89 ± 010[c]	2.99 ± 0.29[a]	3.33 ± 0.15[b]
Crumb colour	Lightness index (L*)	74.47 ± 1.03[c]	48.27 ± 2.14[b]	35.37 ± 1.87[a]
	Red-green index (a*)	1.75 ± 0.24[a]	6.39 ± 0.45[c]	4.45 ± 0.25[b]
	Yellow-blue index (b*)	23.39 ± 0.85[c]	14.04 ± 0.42[b]	10.83 ± 0.50[a]
	Overall change in lightness (ΔL*)[a]	–	−11.0 ± 1.1	−16.1 ± 0.8
	Overall colour change (ΔE*)[b]	–	11.5 ± 1.1	16.8 ± 0.8
	Browning index	38.38 ± 2.02[a]	43.67 ± 3.44[b]	45.24 ± 2.37[c]
Crumb texture	Firmness (N)	2.60 ± 0.67[a]	6.62 ± 1.05[c]	4.55 ± 0.97[b]
	Springiness[c]	0.89 ± 0.03[c]	0.85 ± 0.02[b]	0.77 ± 0.03[a]
	Cohesiveness[c]	0.69 ± 0.03[c]	0.54 ± 0.02[b]	0.45 ± 0.02[a]
	Chewiness (N)	1.58 ± 0.31[a]	3.01 ± 0.46[c]	1.58 ± 0.36[a]
	Resilience[c]	0.27 ± 0.02[c]	0.20 ± 0.01[b]	0.16 ± 0.01[a]
Digestibility	Digestible starch (g/100 g dm)	77.2 ± 1.71[b]	74.9 ± 0.39[ab]	73.2 ± 1.21[a]
	Digestible starch (% of total starch)	98	99	99
	Resistant starch (g/100 g dm)	1.33 ± 0.16[b]	1.12 ± 0.01[a]	1.04 ± 0.04[a]
	Resistant starch (% of total starch)	2	1	1
	In vitro protein digestibility (% of total protein)	82.5 ± 3.73	80.3 ± 1.05	81.7 ± 3.82
Dietary fibre	Soluble dietary fibre (g/100 g dm)	2.05 ± 0.17[b]	1.84 ± 0.15[ab]	1.61 ± 0.03[a]
	Insoluble dietary fibre (g/100 g dm)	3.04 ± 0.06[a]	5.47 ± 0.25[b]	5.48 ± 0.11[b]
	Total dietary fibre (g/100 g dm)	5.08 ± 0.23[a]	7.31 ± 0.39[b]	7.09 ± 0.14[b]
Bioactive compounds	Phytate (mg/100 g dm)	129±1[a]	345±3[b]	384 ± 29[b]
	Free phenolics (mg gallic acid equivalents/100 g dm)	37±0[a]	106±0[b]	111±1[c]

WHE - wheat; NAT - native finger millet; HTT - hydrothermally-treated finger millet.
Values reported as mean ± standard deviation. Means in the same row with different superscript letters are significantly different from each other at $p \leq 0.05$. Means without superscript letters across rows are not significantly different at $p \leq 0.05$.
[a] Change in lightness of wheat bread versus composite breads.
[b] Change in colour of wheat bread versus composite breads.
[c] Dimensionless terms.

bread. Generally, composite doughs had poorer rheological properties than wheat dough, which was reflected in the quality of composite bread. Wheat bread had higher volume and better crumb properties than composite bread. Comparison of the composite breads showed that WHE-HTT bread had higher specific volume and softer crumb than WHE-NAT bread. However, the other crumb features of WHE-HTT bread were poorer than those of WHE-NAT bread. The different physical features of the composite breads were attributed to different α-amylase activities in NAT and HTT finger millet. Partial substitution of WHE with HTT flour did not have a negative effect on *in vitro* starch and protein digestibility and increased the dietary fibre, phytate and phenolic acid content of bread. Further work is required to develop optimal conditions for production of HTT finger millet.

Declaration of competing interest

The authors declare no conflict of interest.

CRediT authorship contribution statement

Calvin Onyango: Conceptualization, Methodology, Formal analysis, Investigation, Resources, Writing - original draft, Visualization, Funding acquisition. **Susan Karenya Luvitaa:** Investigation, Writing - review & editing. **Guenter Unbehend:** Investigation, Writing - review & editing. **Norbert Haase:** Conceptualization, Methodology, Resources, Writing - review & editing, Visualization, Supervision.

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