Physicochemical attributes and starch functional properties of high β-glucan sorghum inbred line

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Abstract

Purpose – Sorghum is a vital cereal crop and staple food for many peoples around the globe having good nutritional and health-promoting bioactive compounds and recently received great attention as gluten-free food. However, sorghum grains contain low *β*-glucans contents, dietary fibre polysaccharides with great technological and disease prevention properties, and improving the concentration of these compounds in sorghum is very important. Thus, the purpose of this paper is to investigate the physicochemical and starch properties of high *β*-glucan sorghum inbred line (Tabat-NL) in comparison with two commercial cultivars (Wadakar and Tabat-C).

Design/methodology/approach – Grain samples of sorghum cultivars: white colour and low tannin cultivar (Tabat-C), red colour and high tannin sorghum, and new inbred line of white sorghum cultivar (Tabat-NL) were carefully cleaned, examined for physical properties (colour, hectolitre and 1,000 kernel weights, and endosperm texture), and ground to flour and assessed for chemical composition (moisture, protein, ash, carbohydrate, sugars, fibre and *β*-glucan contents). The starch was extracted and investigated for morphological characteristics and functional properties.

Findings – The results showed that Tabat-NL grains contain significantly ($p = 0.05$) higher values of 1,000 kernel weight, hectolitre weight, total carbohydrate, amylopectin, dietary fibre and *β*-glucan compared to Tabat-C and Wadakar. Tabat-NL starch had greater ($p = 0.05$) gelatinization temperature, viscosity, bulk density, and water and oil holding capacities and lower ($p = 0.05$) acidity compared to Tabat-C and Wadakar.

Research limitations/implications – The outcomes of this study demonstrated that Tabat-NL grains had an excellent marketing and milling properties, health-promoting and disease-preventing potentials, and technological features for uses in functional and speciality foods.

Originality/value – To the best of our understating, this is the first study on the evaluation of sorghum cultivar with high *β*-glucan content and could thus provide the bases for further development and application of this important food grains.

Keywords Heterowaxy sorghum, Sorghum starch, *β*-glucan, Tabat, Wadakar

Paper type Research paper

Introduction

Sorghum (*Sorghum bicolor (L.) Moench*) represents the fifth largely produced cereal grains in the world with the production quantity of about 64 m tonnes in 2016 and haft of this quantity produced in Africa (FAOSTAT, www.fao.org/faostat/en/#data/QC, accessed 21 February 2018). It is widely consumed by poor peoples in many countries in Africa and Asia, where it represents the staple food and the main source of protein and calories for a wide range of population in these regions (Belton and Taylor, 2004). Sorghum is the leading cereal crop produced in Sudan with a total of 6.5 m tonnes in 2016 (FAOSTAT, www.fao.org/faostat/en/#data/QC, accessed 21 February 2018), where the climatic and soil conditions

World Journal of Science, Technology and Sustainable Development
Vol. 15 No. 4, 2018
pp. 313-324

2042-5945
DOI 10.1108/WJSTSD-03-2018-0017

are favourable for its production. In Sudan, sorghum grains are used in various types of meals and they are thus considered as the major and staple food in the country (Elkhalifa and Bernhardt, 2010). Nutritionally, sorghum contains many phytochemicals such as tannins, phenolic acids, anthocyanins, phytosterols and policosanols with high health potentials (Awika and Rooney, 2004). In addition, the grain sorghum has high amounts of slowly digestible starch, low digestibility protein, unsaturated fats, minerals mainly phosphorus, potassium, and zinc, and B-complex and fat-soluble vitamins (de Morais *et al.*, 2017). Moreover, sorghum protein, although is deficient of some essential amino acids such as lysine, mainly kafirins do not prompt an allergic response or an autoimmune reaction in humans (De Mesa-Stonestreet *et al.*, 2010). Consequently, sorghum is considered as safe cereal for consumption by people with coeliac disease (de Morais *et al.*, 2017) and, nowadays, it has been utilised in numerous gluten-free food products. Due to the great importance of sorghum grains as safe and staple food for large segment of population around the globe, several breeding and genetic transformation programs have been developed to improve the agronomical performance under different stress conditions, yields and end-use quality attributes of sorghum (Windpassinger, 2016) and still progressing.

β-glucans are a group of dietary fibre polysaccharides that found in many natural sources such as plant cereals (barley and oat), microorganisms (bacteria and yeast), algae and mushrooms (Zhu *et al.*, 2015). β-glucans have many functional and rheological properties including high viscosity, water and oil holding capacities (OHCs), and gelatinization temperatures (Izydorczyk and Dexter, 2008) as well as biological activities such as anticancer, antidiabetic, anti-inflammatory, immune-modulating and cholesterol lowering and properties (Izydorczyk and Dexter, 2008; Zhu *et al.*, 2016). In recent years, a great interest and research efforts have been directed towards producing, improving, isolating and characterizing of β-glucans from natural sources due to their huge health benefits, prebiotic and functional properties (Zhu *et al.*, 2016). Among cereals, β-glucans were chiefly found in barley and oats and to lesser extend in sorghum and other cereals (Harris and Fincher, 2009). In spite of the great importance of sorghum as staple food together with huge technological and health potentials of β-glucans, great efforts have been made to investigate the β-glucans contents in sorghum grains (Ermawar *et al.*, 2015; Onwurah, 2001). Genetic and breeding improvement of sorghum cultivars to accumulate high contents of β-glucans has been and still on rise by plant breeders all over the world. In this study, new inbred line (Tabat-NL) with high contents of β-glucans that was developed at the Department of Agronomy, Faculty of Agriculture, University of Khartoum, Sudan was investigated for physicochemical properties and starch characteristics of the grains in comparison with that of two popular Sudanese sorghum cultivars.

Materials and methods

Materials

Two Sudanese sorghum (*Sorghum bicolor (L.) Moench*) cultivars locally known as Wadakar (high tannin) and Tabat (low tannin) together with new inbred line of Tabat (having low tannin and high β-glucan) were obtained from Department of Agronomy, Faculty of Agriculture, University of Khartoum. Sorghum grains were manually cleaned from foreign materials and stored in polyethylene bags at 4°C for subsequent analysis. All chemicals are of analytical grade.

Physical properties of sorghum grains

Grain colour was determined as described by Rooney and Miller (1982). Briefly, 100 sorghum grains were counted out and spread evenly over the surface of a white paper, so that none of the grains is touching each other. The grains were examined by naked eyes and the numbers of white or coloured grains were counted. White or coloured sorghum grains were calculated as percentage of total sorghum grains. Batches containing $\geq$ 95 per cent of white or coloured sorghum grains were classified as white (or coloured) sorghums. Whereas batches containing $<$ 95 per cent white or coloured sorghum were classified as mixed colour grains. Colour tests were done in triplicate and means were obtained. Endosperm texture (proportion of corneous endosperm relative to floury endosperm) was determined according to the method of Rooney and Miller (1982). Briefly, 20 sorghum grains were cut into halves longitudinally, so that each half contains an equal portion of the germ and viewed with a magnifying lens. Corneous, intermediate and floury grains were determined by reference to a standard and calculated as a percentage of total sorghum grains. The 1,000 kernel weight was measured by weighing intact 1,000 sorghum grains on a sensitive balance (±0.01 g) and average weight of triplicate samples was calculated.

Preparation of sorghum flour
Sorghum flour was prepared by milling (2 kg) clean sorghum grains to fine flour (78 per cent extraction rate) using a hammer mill (Debarker Co. Ltd Beijing, China) to pass a 0.4 mm screen, and stored in polyethylene bags at 4°C for further analysis.

Chemical composition of sorghum flour
The amounts of moisture (AOAC method No. 925.10), fat (AOAC method No. 920.39), protein (AOAC method No. 984.13), fibre (AOAC method No. 985.29) and ash (AOAC method No. 923.03) were measured using the standard official method (AOAC, 2000). Total carbohydrate was calculated by subtracting the sum of protein, moisture, ash, fibre and fat from 100 per cent.

Analysis of sugars
The sugars (glucose, fructose, sucrose and maltose) concentrations were determined by HPLC following the standard method (AOAC, 2000). Briefly, flour samples and standards of glucose, fructose, sucrose and maltose were prepared in the same way and analysed using Supelco LC-NH2 column (Bellefonte, PA, USA). The HPLC system consisted of reverse phase-high pressure liquid chromatography (Shimadzu LC-IQ AD, Shimadzu Corporation, Kyoto, Japan) and refractive index detector Shimadzu 6A (Shimadzu Corporation) was used. The mobile phase was consisting of acetonitrile and water (80: 20, v/v) and the flow rate was 1.5 mL/min. The data were recorded using Chromatopack- CR7-A (Shimadzu Corporation, Kyoto, Japan), the areas under the peaks were calculated and results were reported as percentage (w/w).

Analysis of β-glucan
The hot water and enzymatic hydrolysis treatments were used to isolate β-glucan from sorghum flour samples (Kvist and Lawther, 2005). Briefly, 10 g of sorghum flour samples were placed in test tubes and mixed with 50 per cent ethanol and sodium phosphate buffer (pH 6.5) and the tubes were incubated in water bath at 95°C for 60 min. Thereafter, the tubes were equilibrated to 50°C, before the addition of α-amylase (30 U/mL) and lichenase (50 U/mL) enzymes and then further incubated for 60 min at the same temperature. Acetate buffer (pH 4.0) was added and the tubes were centrifuged for 10 min, after which aliquots were removed and treated with β-glucosidase (2 U/mL) for 10 min. After that, the reaction mixture was incubated with glucose oxidase/peroxidase reagent for 20 min and then the absorbance was read at 510 nm against a reagent blank.

Extraction and characterisation of sorghum starch
Starch was extracted from sorghum grains following the method described by Alka *et al.* (2012). Briefly, 100 g sorghum grains were steeped in 200 ml of 25 per cent NaOH at 5°C for 24 h. After washing several times with water, the grains were ground in a blender with an equal

volume of water and the slurry was filtered through a 200-mesh screen. After repeated rinsing and filtering of the residue, the filtrate was allowed to stand at room temperature for 1 h and then centrifuged at 6,000×g for 10 min. Washing and centrifugation were repeated several times until the top starch layer was white. The starch was dried for 24 h at 40°C and the percentage recovery was determined on the basis of 100 g sample. The bulk density (BD) of isolated starch was determined by the weighing method using a measuring cylinder filled to the mark of 10 mL with sorghum starch, and then the content was weighed, and the results were expressed as grams per mL (Alka *et al.*, 2012). Gelatinization of sorghum starch at different temperature (50°C–75°C) was determined by the microscopic staining method (Lamb and Loy, 2005) using a monocular microscope (Model RMH-4, Radical Instruments, India) and the temperature at which more than 80 per cent starch granules seen red was reported as gelatinization temperature of such starch sample. Viscosity of sorghum starch was measured using Ford viscosity cup no. 4 (Standard Model VC005.003, EZ EM Corp., Westbury, NY, USA) as described by Bechtel and Fischer (1949). Water absorption capacity (WAC) and OHC were estimated following the method described by Claver *et al.* (2010). The results were expressed as millilitres of water or vegetable oil absorbed by gram samples. The titratable acidity was estimated by titrating sorghum starch solution against 0.1 N NaOH using phenolphthalein as indicator and the acidity was calculated as g lactic acid/100 g sample. The amylose content was determined using spectrophotometric method as described previously (Williams *et al.*, 1970). Briefly, 20 mg sorghum starch was vortex mixed with 10 mL of 0.5 N KOH for 5 min and the solution was made up to 100 mL with water. Thereafter, 10 mL aliquot was mixed with 5 mL 0.1 N HCl and 0.5 mL of iodine solution, then the volume was diluted to 50 mL and the absorbance of blue colour was measured at 625 nm. Amylopectin was calculated by subtracting the percentage of amylose from 100 per cent. Morphological examination of sorghum starches was obtained using a field emission scanning electron microscope (SEM) (SU8000, HITACHI, Tokyo, Japan). Starch samples were placed directly on aluminium pin mounts and coated with platinum/palladium and then photographed at an acceleration potential of 10 kV and a magnification of 600×, 1,000× and 4,000×.

Statistical analysis

The data were analysed using one way analysis of variance (ANOVA) on SPSS version 11.5 software (SPSS Inc., Chicago, IL, USA). Differences among treatments were detected according to Duncan multiple range test with a confidence level of 95 per cent. For physical and chemical characteristics of sorghum grains, significance of differences within varieties and mean values of the cultivars, ANOVA and least significant differences (LSD) were computed.

Results and discussion

Grains physical properties

The physical properties of the three sorghum cultivars (Wadakar, Tabat-C, Tabat-NL) are shown in Table I. Wadakar is a high tannin cultivar therefore its grain colour is red, while Tabat cultivar is low tannin cultivar thus it is characterised by its white colour grains.

Table I. Grain physical properties of sorghum cultivars

Cultivar	Colour	Hectolitre weight (g/L)	1,000 kernel weight (g)	Endosperm texture (%)
Wadakar	Red	$718.10^{b} \pm 1.46$	$23.31^{b} \pm 0.17$	Floury $76.3^{b} \pm 0.11$
Tabat-C	White	$654.80^{c} \pm 3.66$	$20.56^{c} \pm 0.40$	Floury $77.8^{a} \pm 0.07$
Tabat-NL	White	$738.97^{a} \pm 1.59$	$25.43^{a} \pm 0.29$	Floury $72.8^{c} \pm 0.23$

Note: Mean ± SD ($n = 3$) value having different superscript letters in a column differ significantly ($p \leqslant 0.05$)

The new inbred line (Tabat-NL) of Tabat cultivar also has white grains. The colour of these three sorghum grains placed within the endosperm colours (white, yellow, red, brown or black) reported so far for sorghum grains (Althwab *et al.*, 2015; Waniska *et al.*, 2016). The hectolitre weight is significantly ($p \leqslant 0.05$) different between the three types of sorghum grains with the highest ($p \leqslant 0.05$) weight observed in Tabat-NL and the lowest in Tabat-C grains. Results were within the range reported for different Sudanese sorghum cultivars (Azharri *et al.*, 2010). The 1,000 kernel weight was also significantly ($p \leqslant 0.05$) high in Tabat-NL followed by Wadakar and Tabat-C, respectively. These results were well laid within the range (20.0–38.0 g) reported for several Sudanese (Azharri *et al.*, 2010) and Egyptian (Tag El-Din *et al.*, 2012) sorghum grains. The percentage of floury endosperm texture was the highest in Tabat-C (77.8 per cent), whereas that of Tabat-NL was the least (72.8 per cent). Similarly, Azharri *et al.* (2010) reported that the percentages of floury endosperm in three Sudanese sorghums were in the range of 65–73 per cent. Interestingly, Tabat-NL has the highest hectolitre and 1,000 kernel weights; however, it has the lowest floury endosperm texture percentage compared to other cultivars. These findings indicated that Tabat-NL has a higher ratio of corneous endosperm, which means that the grains of this new line are more resistant to insects and mould damage (Sang *et al.*, 2008; ICC, 2012). It is well known that the endosperm texture of sorghum grains is one of the major quality characters that strongly contribute to the storage, milling and processing of the grains into food products (Bean *et al.*, 2006). Overall, our findings demonstrated that the new inbred line has good grain physical characteristics and thus could have potentially high marketing and milling properties.

Proximate composition of sorghum flours

The proximate composition of sorghum grains was significantly ($p \leqslant 0.05$) varied among the three cultivars (Table II). The ash, protein and fat contents were higher ($p \leqslant 0.05$) in Wadakar cultivar compared to Tabat cultivars. The highest moisture and carbohydrate contents were observed in Tabat-C (8.58 per cent) and Tabat-NL (78.74 per cent), respectively. Tabat-NL had the least values of moisture, protein and fat, suggesting that the genetic modification of this cultivar possesses some effects on these constituents. Although it is significant, the differences of these constituents form that of parent cultivar (Tabat-C) was not so high. The findings of this study were comparable to those of Azharri *et al.* (2010) who reported that three Sudanese sorghum cultivars contain about 14.2–17.2 per cent protein, 3.6–4.0 per cent oil, 1.8–2.1 per cent fibre and 1.7–2.2 per cent ash. In addition, the results are also laid in the range of 9–14.1 per cent protein, 1.5–5.0 per cent oil and 1.2–7.1 per cent ash (Waniska *et al.*, 2016). Generally, sorghum grains are known to contain up to 12 per cent protein, 75 per cent carbohydrate, 4 per cent lipids, 3 per cent fibre and 2 per cent ash (Hwang *et al.*, 2002). Genetic makeup, agronomical practices (irrigation, fertilisation, harvesting, storage, etc.) and environmental conditions are the major factors that influence the chemical composition of sorghum grains.

Available sugars in the sorghum flours

The reducing and non-reducing sugars of sorghum flours were assessed and the results are presented in Table III. The highest contents of fructose, glucose, sucrose and maltose were

Cultivar	Moisture	Ash	Protein	Fat	Total CHO
Wadakar	$7.23^{b} \pm 0.08$	$1.65^{a} \pm 0.02$	$11.43^{a} \pm 0.23$	$3.78^{a} \pm 0.12$	$75.91^{c} \pm 0.16$
Tabat-C	$8.58^{a} \pm 0.04$	$0.98^{c} \pm 0.01$	$10.65^{b} \pm 0.10$	$2.86^{b} \pm 0.08$	$76.93^{b} \pm 0.22$
Tabat-NL	$6.94^{c} \pm 0.03$	$1.41^{b} \pm 0.06$	$10.30^{c} \pm 0.17$	$2.61^{c} \pm 0.03$	$78.74^{a} \pm 0.31$

Note: Mean ± SD ($n = 3$) value having different superscript letters in a column differ significantly ($p \leqslant 0.05$)

Table II. Proximate composition (%) of raw sorghum flours found in Wadakar cultivar. With exception to maltose, the concentrations of all sugars were higher in Tabat-C than Tabat-NL. Overall, the new line has lower sugars compared to its parent and Wadakar cultivars. The concentration of both reducing and non-reducing sugars in the three sorghum cultivars is very low. Gassem and Osman (2003) reported slightly higher levels of glucose, fructose, sucrose and maltose in three sorghum varieties grown in Jazan province, Saudi Arabia. However, the glucose and fructose of most sorghum grains were in the range of 0.6–1.8 and 0.3–0.7 per cent, respectively (Waniska *et al.*, 2016). Sugar contents and composition are largely diverse among sorghum grains due to factors such as genetic characteristics, growing conditions and maturity stages when the grains are harvested (Anglani, 1998). Overall, lower sugar content in this study could make the grains of these sorghum cultivars significantly important from health standpoints as they could be consumed by diabetic peoples without major concern about elevation of blood sugar level.

Starch content, dietary fibre and β-glucan (%) of the sorghum grains

The results on starch content and composition, dietary fibre, and *β*-glucan contents of sorghum grains are presented in Table IV. The total starch was the highest in Wadakar (73.84 per cent), followed by Tabat-C (71.48 per cent), and then Tabat-NL (70.38 per cent). The total starch of the three sorghum cultivars was well comparable to the amounts 68.4, 71.2 and 71.4 per cent reported for waxy, heterowaxy and normal sorghum varieties, respectively (Sang *et al.*, 2008). In addition, starch represents the major components of sorghum kernel having a range of 75–79 per cent of dry matter (Waniska *et al.*, 2016). The ratio of amylose and amylopectin, the two major polymers in the sorghum starch, is very important characteristic that regulates the physicochemical and functional properties of the grains (Sang *et al.*, 2008). Based on amylose and amylopectin contents, both Wadakar and Tabat-C were classified as normal sorghum having 26.7 and 23.21 per cent amylose, and 73.3 and 76.79 per cent amylopectin, respectively, while Tabat-NL was known as slightly heterowaxy sorghum with amylose and amylopectin contents of 19.4 and 80.53 per cent. Normal sorghums are known to contain 20–30 per cent amylose and 70–80 per cent amylopectin, waxy sorghums contains 0.0 per cent amylose and up to 100 per cent amylopection, and heterowaxy sorghums contains 15 per cent amylose and 85 per cent (Sang *et al.*, 2008; Waniska *et al.*, 2016). The low amylose content of Tabat-NL makes it suitable for preparation of puddings, whereas the high amylose content of Wadakar and Tabat-C indicates them as good candidates with better gelling characteristics of cooked and cooled starches (Udachan *et al.*, 2012). Tabat cultivar is known as a normal sorghum; however, in this study, Tabat-NL was found to be the hetrowaxy type. This is probably due to the

Table III. Available sugars (%) in the sorghum flours

Cultivar	Fructose	Glucose	Sucrose	Maltose	Total
Wadakar	0.035 ± 0.08	$0.031^{a} \pm 0.02$	$0.38^{a} \pm 0.03$	0.023 ± 0.04	$0.471^{a} \pm 0.07$
Tabat-C	0.030 ± 0.01	$0.024^{b} \pm 0.00$	$0.27^{b} \pm 0.02$	0.001 ± 0.02	$0.328^{b} \pm 0.15$
Tabat-NL	0.029 ± 0.03	$0.017^{c} \pm 0.01$	$0.23^{c} \pm 0.09$	0.008 ± 0.00	$0.286^{c} \pm 0.20$

Note: Mean ± SD ($n = 3$) value having different superscript letters in a column differ significantly ($p \leqslant 0.05$)

Table IV. Starch content, dietary fibre and *β*-glucan (%) of the sorghum flours

	Starch content (%)				
Cultivar	Starch	Amylose	Amylopectin	Dietary Fibre	*β*-glucan
Wadakar	$73.84^{a} \pm 0.02$	$26.70^{a} \pm 0.09$	$73.3^{c} \pm 0.06$	$1.58^{c} \pm 0.02$	$1.09^{c} \pm 0.04$
Tabat-C	$71.48^{b} \pm 0.16$	$23.21^{b} \pm 0.01$	$76.79^{b} \pm 0.11$	$5.12^{b} \pm 0.05$	$1.86^{b} \pm 0.01$
Tabat-NL	$70.38^{c} \pm 0.31$	$19.47^{c} \pm 0.03$	$80.53^{a} \pm 0.10$	$8.07^{a} \pm 0.12$	$7.32^{a} \pm 0.01$

Note: Mean ± SD ($n = 3$) value having different superscript letters in a column differ significantly ($p \leqslant 0.05$)

infusion of more β-glucan molecules that resulted in a change of the normal genetics of the variety, while the influence of environmental factors resulted in lower amylose content (FAO, 1995). Dietary fibre in Tabat-NL (8.07 per cent) was about 5-folds and 1.5-folds higher than that of Wadakar and Tabat-C cultivars, respectively. Similarly, it has been reported that the crude fibre content of sorghum grains was ranged from 0.4 to 7.3 per cent (Waniska *et al.*, 2016). Interestingly, Tabat-NL contains significantly ($p \leqslant 0.05$) higher value of β-glucan (7.32 per cent) compared to Tabat-C and Wadakar cultivars. Among cereals, barley contains high amounts of β-glucan comprising about 70 per cent (w/w) of the cell wall (Ermawar *et al.*, 2015), while sorghum contains about 0.1–1.5 per cent (w/w) in the grains and 0.12–1.7 per cent (w/w) in vegetative tissues (Ermawar *et al.*, 2015; Niba and Hoffman, 2003; Ramesh and Tharanathan, 2003). In addition, Harris and Fincher (2009) reported that β-glucan is varied among grasses with the highest being reported in barely (2–20 g/100 g), followed by oats (3–8 g/100 g), sorghum (1.1–6.2 g/100 g), rye (1.3–2.7 g/100 g), maize (0.8–1.7 g/100 g), triticale (0.3–1.2 g/100 g), wheat (0.5–1.0 g/100 g) and the lastly rice (0.13 g/100 g). In our study, the contents of β-glucan of Tabat-C (1.86 per cent, w/w) and Wadakar (1.09 per cent, w/w) were comparable to that reported in various sorghum cultivars. Amazingly, β-glucan of the improved inbred line was higher than that in sorghum cultivars reported so far (Abuajah *et al.*, 2016; Ermawar *et al.*, 2015; Harris and Fincher, 2009; Niba and Hoffman 2003; Ramesh and Tharanathan, 2003). The variation in β-glucan concentration in sorghum grains between these studies could be due to the varietal differences, maturity stage of the grains, environmental conditions, agronomical practices, and extraction and quantification methods of β-glucan. In this study, the new inbred line outscores (4-folds higher) the parents' cultivars in β-glucan contents suggesting its enrichment with this important compound. Although β-glucan in cereal grains has several influences on the industrial processes such as malting and brewing, it possesses several health benefits to humans (Ermawar *et al.*, 2015). In this regard, β-glucan has known to lower the plasma cholesterol and reducing the risks of type 2 diabetes, inflammatory bowel, colon cancer and coronary heart diseases (Ermawar *et al.*, 2015; Izydorczyk and Dexter, 2008). Collectively, the highest concentration of dietary fibre and β-glucan in Tabat-NL makes it an excellent candidate of healthier, functional and specialty foods.

Morphological characteristics of the sorghum starch

The morphological characteristics of starch of the three sorghum types were investigated using SEM and the results are shown in Figure 1. There are no clear differences in the shape of the starch granules of the three grains cultivars. Generally, the shape of sorghum starch granules appeared as polygonal or spherical. The surface of the granules is relatively smooth with some small hollows representing the fingerprints of native protein bodies. These findings were comparable to those of Ahmed *et al.* (2016) who investigated the starch characteristics of various types of grain and sweet sorghum varieties from Sudan and China, and they observed polygonal or spherical shapes of the starch granules. In addition, similar observations on the starch granule shapes were also reported for sorghum grains from America (Benmoussa *et al.*, 2006) and India (Singh *et al.*, 2010). It is well known that granules of sorghum starch in corneous endosperm have polygonal shapes and those in the floury endosperm are spherical with the size range of 2–30 µm (Schober and Bean, 2008). In this study, the SEM micrograph showed starch granules with heterogeneous sizes (small, medium and big size) of the three cultivars. The diameter of the smallest granule was about 3–5 μm and that of the biggest was about 24–26 μm with the average size of most granules being 13–16 μm. These observations were comparable to those reported by Ahmed *et al.* (2016) who reported an average granule size of 13.8–16.7 for sorghum starches from different sweet and grain sorghum cultivars. In addition, a similar range (4–26 μm) of granule size has been reported for white and red sorghum cultivars (Gaffa *et al.*, 2004). The heterogeneity and variation in grain sizes could be due to the differences in the genetic

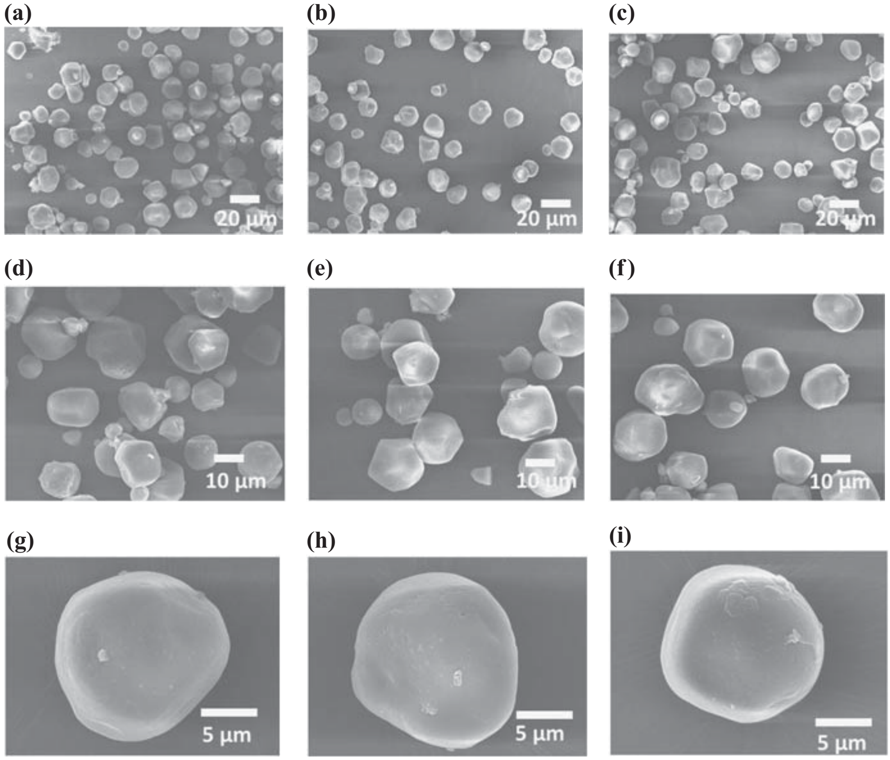

Figure 1.
SEM images of starch granules of the three sorghum cultivars

Note: Tabat-NL (A, D and G), Tabat-C (B, E and H) and Wadakar (C, F and I) captured at different magnifications of 600× (A, B and C), 1,200× (D, E and F) and 4,000× (G, H and I)

makeup, environmental conditions and agronomical practices. Overall, our findings revealed that there is no remarkable difference in the morphological characteristics between the new inbred line and other commercial cultivars.

Functional properties of the sorghum starch

The functional properties (gelatinization temperature, viscosity, BD, water and OHCs, and acidity) of sorghum starch are depicted in Table V. With exception of acidity, Tabat-NL showed the highest values of all tested properties. Gelatinization temperature of Tabat-NL was the highest (68.0°C) and that of Wadakar was the least (61.4°C). These observations were comparable to the range 64.0°C-77.8°C reported for more than 180 sorghum genotypes form different regions (Udachan *et al.*, 2012; Zhu, 2014) demonstrating great diversity of gelatinization temperature among sorghum genotypes. Increased gelatinization temperature of Tabat-NL

Table V.
Functional properties of the sorghum starch

Starch	Gelatin. temp (°C)	Viscosity (sec)	BD (g/mL)	WAC (mL/g)	OHC (mL/g)	Acidity (g/100 g as LA)
Wadakar	$61.40^{c} \pm 0.04$	$8.00^{c} \pm 0.01$	$0.69^{c} \pm 0.01$	$1.14^{b} \pm 0.04$	$6.15^{c} \pm 0.04$	$1.06^{a} \pm 0.02$
Tabat-C	$64.01^{b} \pm 0.07$	$9.00^{b} \pm 0.08$	$0.71^{b} \pm 0.03$	$1.09^{c} \pm 0.11$	$6.86^{b} \pm 0.06$	$0.81^{b} \pm 0.01$
Tabat-NL	$68.00^{a} \pm 0.21$	$10.00^{a} \pm 0.11$	$0.75^{a} \pm 0.30$	$1.26^{a} \pm 0.10$	$7.05^{a} \pm 0.21$	$0.89^{c} \pm 0.04$

Note: Mean ± SD value having different superscript letters in a column differ significantly ($p < 0.05$)

starch could be attributed to the low amylose alongside with the high amylopectin contents in this new line compared to the other two cultivars. Waxy and heterowaxy starches without or with low amylose content are reported to have higher gelatinization temperature than normal type starches (Pedersen *et al.*, 2007). In addition to the genetic makeup, environmental conditions and isolation approaches could also influence the gelatinization temperature of sorghum starches (Zhu, 2014). Viscosity of Tabat-NL (10.0 sec) starch was higher compared to that of Tabat-C (9.0 sec) and Wadakar (8.0 sec). Udachan *et al.* (2012) reported similar viscosity values (8.0–10.0 s) of the sorghum starches isolated from four Indian cultivars. It is well known that β-glucan chain has the ability to occupy large hydrodynamic volumes and thus form viscus solutions (Izydorczyk and Dexter, 2008). In this sense, increased solubility of Tabat-NL could be due to its high β-glucan content. Gelatinization temperature and viscosity are the main important mixing and pumping features operations in various food industries (Gaffa *et al.*, 2004) suggesting the suitableness of Tabat-NL to these industrial process conditions. BD was also high in Tabat-NL followed by Tabat-C and lastly Wadakar proposing that Tabat-NL is not suitable for the preparation of infant foods (Elkhalifa *et al.*, 2005). Results were within the range (0.71–0.75 g/mL) reported by Alka *et al.* (2012) and Elkhalifa and Bernhardt (2010) for different sorghum cultivars. Tabat-NL gave the highest value for WAC compared to both Tabat-C and Wadakar, implying that the new inbred line could be good for dough making. Tabat-NL also gave the highest OHC compared to Tabat-C and Wadakar, which means it has better oil holding property than the other sorghum samples. Increased water and OHCs in Tabat-NL could be attributed to its high β-glucan contents compared to other cultivars as β-glucan chain could hold large volumes of water and oils (Izydorczyk and Dexter, 2008). The higher water and OHCs of sorghum starch of Tabat-NL propose that this new line would be useful in formulation of foods, where water oil holding properties are important considerations (Elkhalifa *et al.*, 2005). Acidity as lactic acid was highest in Wadakar followed by Tabat-NL and lastly by Tabat-C and the pH followed the same pattern as expected. Overall, it is clear that the starch of Tabat-NL possesses good functional properties and could thus pave the way for the utilisation of this new line in various food applications.

Conclusion

In this study, physicochemical and starch functional properties of new sorghum inbred line (Tabat-NL) were investigated and compared to other popular Sudanese sorghum cultivars (Tabat-C and Wadakar). The findings revealed good grain physical properties and starch functional characteristics of Tabat-NL compared to Tabat-C and Wadakar. In addition, Tabat-NL had low sugars, protein, fat contents compared to other cultivars. Moreover, Tabat-NL had the highest dietary fibre and β-glucan contents than the two cultivars. These findings demonstrated that Tabat-NL could have high marketing and milling properties, health benefits and applicability in various types of functional and speciality foods. Future studies shall specifically focus on incorporation of this new line in different foods and profound *in vitro* and *in vivo* characterisation of the developed products.

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