

Physicochemical properties of starches with variable amylose contents extracted from bambara groundnut genotypes

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ABSTRACT

The physicochemical properties of starches extracted from five bambara genotypes were investigated. Bambara starch granules were predominantly oval shaped with a smooth surface and an average size of $26 \pm 0.2 \mu\text{m}$. The amylose contents (20–35%) varied significantly among genotypes. X-ray diffraction revealed the C-type pattern for all starches with relative crystallinity range: 29–35%. FTIR spectra of bambara starches showed variable peak intensities at 2931, 1655 and 860 cm^{-1} , which corresponds to C–H stretching, H_2O bending vibrations and C–O stretching, respectively. Bambara genotype with the highest amylose content showed the lowest intensity at wavenumber 2931 cm^{-1} . With the exception of oil absorption which was similar, swelling power, water absorption and paste clarity of starches were significantly different among genotypes. Genotype with high amylose content showed restricted swelling, low paste clarity and great ability to absorb water. All bambara starches displayed a shear thinning behaviour ($n < 1$).

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1. Introduction

Bambara groundnut (*Vigna subterranea*) is a good source of protein (19–21%) and carbohydrate (57–67%) (Kaptso et al., 2014; Sirivongpaisal, 2008; Onimawo, Momoh, & Usman, 1998), similar to legumes such as cowpea (Oyeyinka et al., 2013) and peas (Wang & Castonguay, 2014). The bambara plant is highly drought tolerant and thus, well adapted to the changing climate. However, bambara groundnut is neglected and under-utilized in Southern Africa. Traditionally, bambara is consumed by boiling freshly harvested grains and eaten as a relish with maize-meal porridge (Swanevelde, 1998). Matured grains are dried and ground into flour for making puddings. The under-utilization of many crops including bambara may be attributed to lack of sufficient research to unlock their potential and value addition.

The major carbohydrate of bambara grain is starch, which may have potential applications in the food industry. The starch contents of bambara may vary between 35 and 46% (Flour basis) (Afolabi, 2012; Sirivongpaisal, 2008; Adebowale, Afolabi, & Lawal, 2002). By microscopy, bambara has been found to contain round and irregularly shaped or polygonal starch granules (Kaptso et al., 2014;

Sirivongpaisal, 2008; Adebowale & Lawal, 2002) with an average size ranging from 6 to $61 \mu\text{m}$ depending on variety and source (Kaptso et al., 2014; Sirivongpaisal, 2008; Adebowale & Lawal, 2002). According to Kaptso et al. (2014), starch extracted from white bambara were larger ($10\text{--}35 \mu\text{m}$) than those extracted from black bambara ($6\text{--}15 \mu\text{m}$). In terms of starch composition, bambara starches have been found to contain varying amounts of amylose (21–28%) depending on source and variety (Kaptso et al., 2014; Sirivongpaisal, 2008). The amylose content of starch can significantly influence its functional properties including swelling and gelatinization (Xie et al., 2009; Stevens & Elton, 1971). Native starch consists of semi-crystalline structure and gelatinization, which involves heating of starch in water, disrupts the starch granular structure and causes changes from semi-crystalline to amorphous structure (Atwell, Hood, Lineback, Varriano-Marston, & Zohel, 1988). During the gelatinization process, starch granules absorb water and swell and the amylose leaches out of swollen granules, which causes an increase in viscosity of the medium (Hermansson & Svegmarm, 1996). Previous studies showed that high amylose maize starch exhibited higher viscosity (Xie et al., 2009). Further, the high amylose contents of different starches have been found to inhibit swelling during gelatinization (Tester & Morrison, 1990).

The molecular characterization of starch revealed differences in crystallinity patterns, which are associated with botanical origin.

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Based on X-ray diffraction patterns, starches have been classified as A-, B- or C-type polymorphs. The major difference between A and B is associated with the packing arrangement of double helices formed from short chains within the amylopectin molecule and their level of hydration (Imberty & Perez, 1988). The A-form adopts a closely packed structure with water molecules between each double helix, while the B-type is less densely packed and more hydrated in the central cavity (Cheetam & Tao, 1998; Imberty & Perez, 1988). C-type starches contain mixtures of A- and B-forms. Generally, A-type crystallinity has been reported for cereal starches, B-type for tubers, high amylose cereal starches or retrograded starches and the C-type for pulse starches. Studies on the structure of bambara starch revealed the C-type crystallinity (Afolabi, 2012), which is similar to most legume starches (Hoover, Hughes, Chung, & Liu, 2010). However, some authors reported the A-type crystallinity for some varieties of bambara (Kaptso et al., 2014; Sirivongpaisal, 2008). Variations in crystallinity patterns and amylopectin branch chain lengths have been found to influence starch functionality. For, instance, with the same chain length, starches with B-polymorph displayed a lower gelatinization temperature compared to starches with A-polymorph (Jane et al., 1999; Whittam, Noel, & Ring, 1990). Cai, Cai, Man, Zhou, and Wei (2014) found that gelatinization temperature and water solubility significantly negatively correlated with amylopectin short branch chain. The crystalline structure of starch is primarily a property of amylopectin. However, the linear chain of amylose can form double helices structure and thus contribute to crystallinity. The transformation of amorphous amylose to crystalline form during heating and melting has been reported in the literature (Singh, Lelane, Stewart, & Singh, 2010; Qi, Avalle, Saklatvala, & Craig, 2008; Nordmark & Ziegler, 2002).

So far, studies on bambara varieties grown in Southern Africa have been limited to breeding to improve agronomic characteristics. Under marginal growth conditions, bambara showed an improvement in yield from 0.3 to 4.2 t/ha (Madamba, 1995). Shegro, Jansen van Rensburg, & Adebola (2013) reported a wide genetic variability among 20 bambara groundnut accessions in South Africa using morphological quantitative markers. These studies also revealed some high yielding accessions. Although, the improvement in yield through conventional breeding is a positive outcome, breeding can significantly influence the composition of major components including starch of bambara grains. For instance, starches from newly bred Brazilian maize showed higher amylose contents compared to starches from locally grown varieties (Uarrota et al., 2013). Although, breeding efforts have been largely successful in Southern Africa, the knowledge of the physicochemical properties of starch from newly bred genotypes may be important to facilitate their selection, introduction and utilization. Hence, this study investigated the composition, structure and functional properties of starch extracted from five bambara genotypes.

2. Materials and methods

2.1. Plant materials

Five bambara groundnut genotypes, SB7-1, SB8-1, BMB-29, BMB-16 and SB-1-1 of the same species were obtained from Agricultural Research Council-Vegetable and Ornamental Plant Institute, Pretoria, South Africa. The accessions were collected in South Africa and evaluated for their agronomic characteristics such as days to 50% flowering, days to 50% maturity, plant height, terminal leaf length, terminal leaf width, leaf area number of leaves, petiole length, number of pods, pod mass, fresh weight, dry weight, harvest index, yield per plant and hundred seed weight at Rood-eplaal research farm in Pretoria, Gauteng province. The altitude of Rood-eplaal is 1168 m above sea level. The location receives

rainfall ranging from 350.00 mm to 431.30 mm and minimum and maximum recorded temperature ranged from 14.46 °C to 30.31 °C during the cropping season (2011–2012). The five genotypes used in this study were selected based on some agronomic traits such as high yield, high number of pod and maturity period for future improvement programme (Shegro et al., 2013).

2.2. Flour preparation

Bambara groundnut was dehulled by soaking 250 g of grains in 1 l of water for 12 h. The grains were manually dehulled and dried at 45 °C in hot air oven (D-37520, Thermo Fischer Scientific, South Africa). Dried dehulled grains were milled into flour using a Waring blender (HGBTWTS3, Torrington USA). The flours were sieved (355 µm), sealed and kept at 4 °C until analysed (Sirivongpaisal, 2008).

2.3. Starch extraction

Starch was extracted following the methods described by Sirivongpaisal (2008). Briefly, bambara flour was dispersed in 0.3% (w/v) NaOH solution at a ratio 1:10, respectively. The slurry was stirred at room temperature on an orbital shaker for 4 h. After shaking, the supernatant was decanted, distilled water was added and the resulting slurry was sieved (sieve aperture size: 180 µm). The starch suspension was left for 12 h to settle and the starch obtained was washed repeatedly with water, centrifuged at 10,000 × g and then neutralized with 0.1 N HCL. Extracted starch was dried at 45 °C in hot air oven (D-37520, Thermo Fischer Scientific, South Africa). Dried starch was kept at 4 °C until analysis. Starch yield was calculated as a ratio of dried starch to bambara flour. The purity of bambara starch extracts was assessed by analysing their protein, fat and ash contents using AOAC (2000) methods.

2.4. Grain composition

Moisture, fat and ash contents of bambara grains was determined using AOAC (2000) methods. Protein content was determined by Kjeldahl method (6.25 × N) and total carbohydrate was calculated by difference.

2.5. Colour

Tristimulus $L^* a^* b^*$ parameters of starch were determined after standardization using a colorFlex (A60-1014-593, USA). Snap shots in duplicates were taken and values were read directly from a digital print. Averages of the readings were computed and reported. Hue angle (H) and total colour difference (ΔE) were calculated using Eqs. (1) and (2), respectively (Falade & Okafor, 2014). Potato starch (Sigma Aldrich, South Africa) was used as a reference for comparison.

$$\Delta E = \sqrt{(\Delta L)^2 + (\Delta a)^2 + (\Delta b)^2} \quad (1)$$

$$\text{Hue angle} = \tan^{-1} \left(\frac{b}{a} \right) \quad (2)$$

2.6. Microscopy

Starch granule morphology was examined using Scanning Electron Microscope (EVO 15 HD SEM) with an accelerating potential of 4 kV. A thin layer of bambara starch was mounted on the aluminium specimen holder by double-sided tape. Starch samples was coated with a thin film of gold, with a thickness of about 30 nm and the micrographs were obtained (Li et al., 2014).

2.7. Amylose content

Amylose contents of the starches was determined by iodine binding method (Williams, Kuzina, & Hlynka, 1970).

2.8. X-ray diffraction

X-ray diffraction pattern of bambara starch was done using the methods of Li et al. (2014) with few modifications. X-ray diffractometer (Empyrean, PANalytical Netherlands) operating at 40 kV with a target current of 40 mA was used for the analysis. Starch samples were equilibrated at a temperature and relative humidity of 25 °C and 100%, respectively, in a low temperature incubator (MTIE10, Labcon, South Africa) for 12 h. The equilibrated samples were tightly packed in a rectangular glass cell and scanned over a region of 4 to 40 (2 θ)° at a scanning speed of 0.06°/min. The relative crystallinity of the starch was calculated using the following equation:

$$\text{Relative crystallinity (\%)} = \frac{100Ac}{Ac + Aa} \quad (3)$$

Ac is the crystalline area and Aa is the amorphous area on the X-ray diffractogram.

2.9. Fourier transform infrared spectroscopy

Starch spectra were obtained using modified method of Afolabi (2012). Briefly, starch samples (3 mg) was mixed with 150 mg of FTIR-grade potassium bromide (KBR) and pressed using a 10 MPa mechanical compressor system for 8 min to obtain a transparent pellet. The pellet formed was transferred into the FTIR system (Varian 800, Scimitor Series) and spectra obtained for the samples in percentage transmittance mode from 400 to 4000 cm⁻¹.

2.10. Oil and water absorption capacity

The oil absorption capacity of bambara starch was determined as described by Falade and Okafor (2014) with few modifications. Briefly, one gram of each sample was weighed into a dry, clean centrifuge tube. Sunflower oil (10 mL) with density of 0.98 g/L was poured into the tube and properly mixed by vortexing. The suspension was centrifuged (Centrifuge Model: Ependorf 5810R, Germany) at 3500 $\times$ g for 30 min. Supernatant was discarded and the tube with its content reweighed. Gain in weight expressed, as a percentage of oil bound, was calculated as the oil absorption capacity of the sample. The same procedure was repeated for water absorption capacity by replacing oil with water.

2.11. Swelling power

Swelling power of bambara starch was determined by methods described by Madrugá et al. (2014). Briefly, starch samples (0.1 g starch in 10 ml of distilled water) were stirred and placed in a water bath for 30 min at temperatures ranging from 50 to 90 °C with constant stirring. The suspension were centrifuged (Centrifuge Model: Ependorf 5810R, Germany) at 3400 $\times$ g for 20 min and the supernatant discarded. Swelling power was obtained by weighing the swollen starch residue after centrifugation and dividing by original weight of starch on dry weight basis.

2.12. Paste clarity

The paste clarity was determined using the method described by Liu et al. (2014) with few modifications. Briefly, 1% starch (on dry weight basis) was prepared using distilled water. The suspensions were heated in a water bath at 90 °C for 30 min (with occasional

shaking). After cooling to room temperature, the percentage transmittance was determined at 650 nm against a water blank using a UV spectrophotometer (Jenway, 7305 Bibby Scientific UK). The paste clarity of the samples stored at 4 °C for 24, 48 and 72 h were also examined.

2.13. Rheology

The rheological properties of bambara starches were measured using the modified method of D'Silva, Taylor, and Emmambux (2011). Briefly, bambara starch (10% w/v) was gelatinized at 95 °C for 30 min in centrifuge tubes and rapidly transferred into the Rheolab (80732808, Anton Paar Austria) cup. Starch pastes were allowed to equilibrate at 60 °C for 10 min. The pastes were measured at shear rates ranging between 10 and 1000 s⁻¹. The data were fitted into a Power-Law Model (Barnes, Hulton, & Walters, 1989) as follows:

$$\tau = k\gamma^n \quad (4)$$

where τ is the shear stress (Pa), k is the consistency coefficient, (Pa s) ^{n} , γ is the shear rate (s⁻¹) and n is the flow behaviour index.

2.14. Statistical analysis

All experiments were conducted in duplicate. Data were analysed using analysis of variance (ANOVA) and means were compared using Fischer's Least Significant Difference Test ($p < 0.05$).

3. Results and discussion

3.1. Composition of bambara grains

Composition data showed greater similarity across bambara genotypes (Table 1). Carbohydrate (approx. 58%) and protein (approx. 24%) were the major components of bambara grains. Fat and ash contents of bambara genotypes were generally low. The protein contents of bambara from this study were slightly higher than those reported for bambara groundnut elsewhere (Adebawale et al., 2002; Onimawo et al., 1998; Sirivongpaisal, 2008).

Environmental growth conditions and genotypes may influence crop yield and grain composition. For instance, Jing et al. (2010) reported higher rice yield in subtropical environments than in tropical environments. However, the variation in protein contents of the rice genotypes was reportedly small. According to these authors, genotypic differences had more influence on grain composition than did the growth environments (Jing et al., 2010). Tahir, Lindeboom, Baga, Vandenberg, and Chibbar (2011) also found some variations in protein contents of lentil genotypes grown in the same environment.

3.2. Yield, purity, morphology and amylose content

The starch yields varied significantly ($p < 0.05$) among bambara genotypes with values ranging from 22 to 33% (Data not shown). Bambara genotype SB7-1 had the highest starch yield (approx. 33%) followed by SB8-1 (approx. 26%). The starch yield of bambara genotypes compares favourably with literature (Afolabi, 2012; Hoover et al., 2010; Sirivongpaisal, 2008).

The lightness (L^*) value (approx. 94) of bambara starches were very similar across genotypes (Table 2). These values compares favourably to that of the reference potato starch sample. The relatively high L^* values of starches is an index of purity. All the starch extracts had low contents of residual protein, ash and fat (Data not shown).

Bambara starch showed oval shaped granules with a few granules round and irregular in shape (Fig. 1). All starch granules were

Table 1
Proximate composition of bambara groundnut (g/100 g).

Genotypes	Moisture	Protein	Fat	Ash	Total carbohydrate ^a
SB7-1	7.5 ^a ± 0.0	22.8 ^a ± 0.8	8.2 ^b ± 0.1	2.2 ^a ± 0.0	59.5 ^a ± 0.8
SB8-1	8.1 ^b ± 0.2	24.9 ^a ± 1.4	5.8 ^a ± 0.6	2.9 ^b ± 0.1	58.4 ^a ± 2.2
BMB-29	8.7 ^b ± 0.0	23.2 ^a ± 0.1	8.5 ^b ± 0.0	3.3 ^c ± 0.0	56.5 ^a ± 0.2
BMB-16	8.5 ^b ± 0.0	23.5 ^a ± 0.6	7.8 ^b ± 0.8	2.9 ^b ± 0.1	57.3 ^a ± 1.5
SB-1-1	7.5 ^a ± 0.1	25.4 ^a ± 1.3	6.6 ^a ± 0.1	2.2 ^a ± 0.0	58.4 ^a ± 1.1

Mean ± SD. Mean with different superscript along the column are significantly different ($p < 0.05$).

^a Total carbohydrate calculated by difference.

Table 2
Colour, moisture content, amylose content and relative crystallinity of bambara starch.

Genotypes	<i>L</i> [*]	<i>a</i> [*]	<i>b</i> [*]	ΔE	Hue angle	Moisture	Amylose	Relative crystallinity
SB7-1	94.9 ^b ± 0.1	−0.4 ^a ± 0.1	2.9 ^a ± 0.0	1.2 ^b ± 0.0	−81.7 ^b ± 0.0	8.9 ^a ± 0.3	26.7 ^c ± 0.1	34.3 ^a ± 0.1
SB8-1	94.3 ^b ± 0.1	−0.2 ^b ± 0.1	2.9 ^a ± 0.0	0.9 ^a ± 0.0	−86.7 ^a ± 0.0	9.1 ^a ± 0.2	30.7 ^d ± 0.6	33.8 ^a ± 0.1
BMB-29	93.8 ^b ± 0.1	0.1 ^c ± 0.1	3.8 ^b ± 0.0	1.8 ^b ± 0.0	89.8 ^c ± 0.0	8.5 ^a ± 0.1	35.1 ^e ± 0.2	29.4 ^a ± 0.1
BMB-16	91.8 ^a ± 0.1	0.1 ^c ± 0.0	7.3 ^c ± 0.0	5.9 ^c ± 0.0	89.3 ^c ± 0.0	8.6 ^a ± 0.7	19.6 ^a ± 0.3	35.3 ^b ± 0.1
SB-1-1	94.1 ^b ± 0.1	−0.1 ^c ± 0.0	2.5 ^a ± 0.0	0.7 ^a ± 0.0	−87.4 ^a ± 0.0	9.3 ^a ± 0.2	25.2 ^b ± 0.1	35.0 ^b ± 0.1

Mean ± SD. Mean with different superscript along the column are significantly different ($p < 0.05$).

smooth with no fissures or pin holes. The average length of the starch granules was approximately $26 \pm 0.2 \mu\text{m}$. The size and shape of bambara starch genotypes compared favourably with previous reports on pulse starches (Kaptso et al., 2014; Hoover et al., 2010; Adebawale & Lawal, 2002).

The amylose contents of bambara starches varied significantly ($p < 0.05$) from 20 to 35% (Table 2). Among studied genotypes, BMB-29 starch had the highest amylose content (approx. 35%) while BMB-16 starch showed the lowest value (approx. 20%). Previous studies have similarly reported some variations in amylose contents of starches extracted from bambara cultivars (Kaptso et al., 2014) and rice genotypes (Jing et al., 2010). Genotypic differences accounted for the main variation (68%) in amylose contents of rice starches compared to differences in environmental conditions (25% variation) (Jing et al., 2010). The variation in amylose contents among bambara genotypes from this study could be attributed to inherent genetic differences rather than the prevailing environmental conditions, since these genotypes were grown in the same location. The amylose contents of starches from this study are within the range of values previously reported for pulse starches such as cowpea and pigeon pea (Hoover et al., 2010).

3.3. Crystallinity pattern

X-ray diffractogram of bambara starch genotypes showed strong peaks at approximately 17, 20, 21 and 27 (2θ) and weak

peaks at around 6, 23, 31 and 35 (2θ) (Fig. 2) suggesting a C-type pattern. The C-type crystallinity is generally reported for pulse starches such as cowpea (Sandhu & Lim, 2008) and bambara (Afolabi, 2012). However, some authors have reported A-type pattern in bambara starch (Kaptso et al., 2014; Sirivongpaisal, 2008). This is very unusual for pulse starches. Kaptso et al. (2014) reported A-type crystallinity for two varieties of bambara possibly due to the absence of a peak reflection around $2\theta = 5.6$. According to literature, many authors have attributed a C-type crystallinity pattern for pulse starches where the peak at $5.6 (2\theta)$ appeared weakly (Sun et al., 2015; Cai et al., 2014) or absent (Guo et al., 2015; Kaur, Sandhu, & Lim, 2010; Sandhu & Lim, 2008). C-type starches may contain varying proportion of pure 'A' and 'B' polymorphs (Gernat, Radosta, Damaschun, & Schierbaum, 1990), which may influence the XRD reflection. A-polymorph reportedly showed strong reflection peaks at approximately 15, 23 and 27 (2θ), whilst B-polymorph showed characteristic strong peak at approximately 5.6, 17 and few small peaks at around 15, 20, 22 and 24 (2θ) (Cai et al., 2014). In this study, a weak peak at approximately $2\theta = 6$ and other strong peaks observed from the XRD diffractogram of bambara starches strongly suggest a mixture of A and B and hence these genotypes were classified as C-starch.

The relative crystallinity of bambara starches varied from 29.4 to 35.3% (Table 2). Starch extracted from bambara genotype BMB-29 had lower relative crystallinity (approx. 29%) compared to starches from other bambara genotypes. According to previous studies, amylopectin molecules form the crystalline structure in starch granules, therefore, it is expected that relative crystallinity will be inversely related to amylose content (Kaur et al., 2010; Sandhu & Lim, 2008; Hizukuri, 1985; Hizukuri, Kaneko, & Takeda, 1983). The relatively lower relative crystallinity of BMB-29 starch could be attributed to its relatively higher amylose content (Table 2). Comparable relative crystallinity values have been reported for pulse starches such as lentil starch (Kaur et al., 2010) and bambara starch (Kaptso et al., 2014; Afolabi, 2012).

3.4. Fourier transform infrared spectroscopy

FTIR spectra of bambara starches showed characteristic band with peak at 2931 cm^{-1} in the region of $2800\text{--}3000 \text{ cm}^{-1}$, that could be attributed to C–H bonds stretching (Fig. 3). The amylose/amylopectin ratio may influence the absorbance of starch in this region. As discussed above, the amylose contents (Table 2) of starches were significantly ($p < 0.05$) different among genotypes and this seemed to have influence the peak intensity at

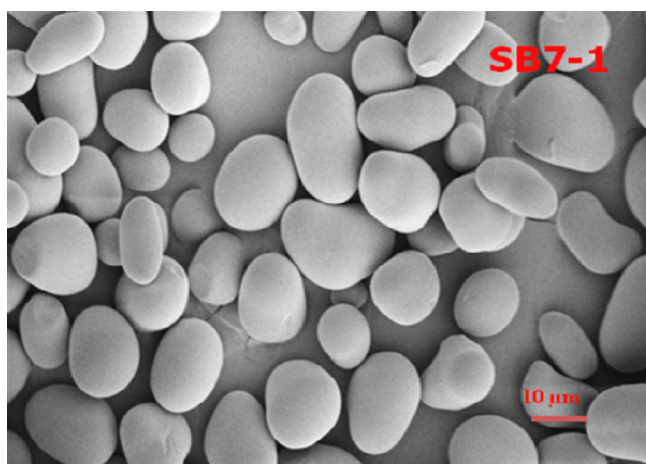


Fig. 1. Representative micrograph of starch isolated from bambara genotypes.

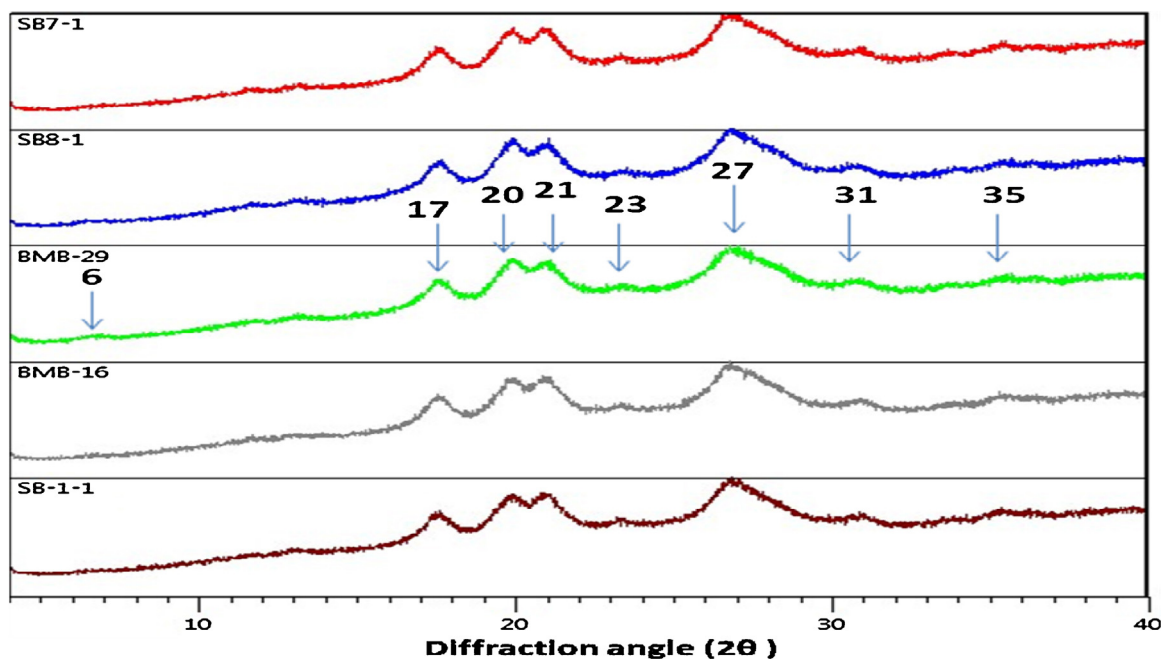


Fig. 2. Diffractograms of bambara starches.

wavenumber 2931 cm^{-1} . Bambara genotype BMB-29 with relatively high amylose contents (Table 2) showed weak peak intensity compared to other genotypes. Previous studies also attributed the variation in FTIR peak intensities at this wavenumber (2931 cm^{-1}) to differences in amylose and amylopectin contents of starches from potato, corn, wheat starches and waxy starch (Kizil, Irudayaraj, & Seetharaman, 2002). A broad band in the region of $3000\text{--}3600$ with peak at 3414 cm^{-1} could be attributed to OH stretching (Zhang & Han, 2006; Ottenhof, MacNaughtan, & Farhat, 2003). Below 800 cm^{-1} , that is, at low wavenumbers, FTIR of bambara starches exhibited complex vibrations as a result of the skeletal mode vibration of glucose pyranose ring. This is in agreement with previous reports (Zeng, Li, Gao, & Ru, 2011). The sharp band at 1655 cm^{-1} could be attributed to H_2O bending vibrations (Zeng et al., 2011). Vibrations due to absorbed water in the amorphous

regions of starch have been observed in a broader infra-red range (Kizil et al., 2002; Cael, Koenig, & Blackwell, 1974). Kizil et al. (2002) attributed the vibration at 1642 cm^{-1} to water molecule in the non-crystalline region of starch. Further, these authors reported that the intensity of the observed peak may be related to the starch crystalline types as potato starch with B-type polymorph displayed a sharper peak than other starches with A-type. All the bambara genotypes from this study showed the C-type polymorph (Fig. 2) consisting of the mixture of A and B (Gernat et al., 1990). The variation in peak intensity at 1655 cm^{-1} may be attributed to variation in proportion of A and B of the respective genotypes. The stretching of C–C and C–O bonds is normally observed in the region of $1300\text{--}800\text{ cm}^{-1}$ (Capon, Robert, Colonna, Brogly, & Planchot, 2007). The peaks occurring at 1164 cm^{-1} in bambara starches may be attributed to coupling mode of C–O and C–C stretching, while

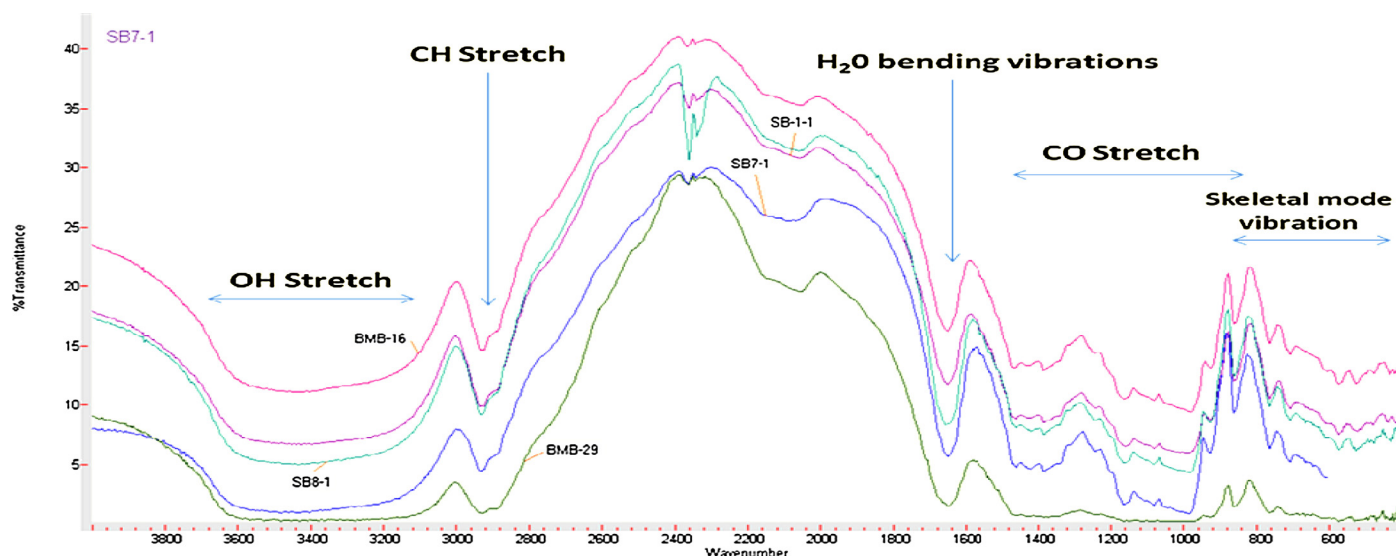


Fig. 3. FTIR Spectra of a bambara starches.

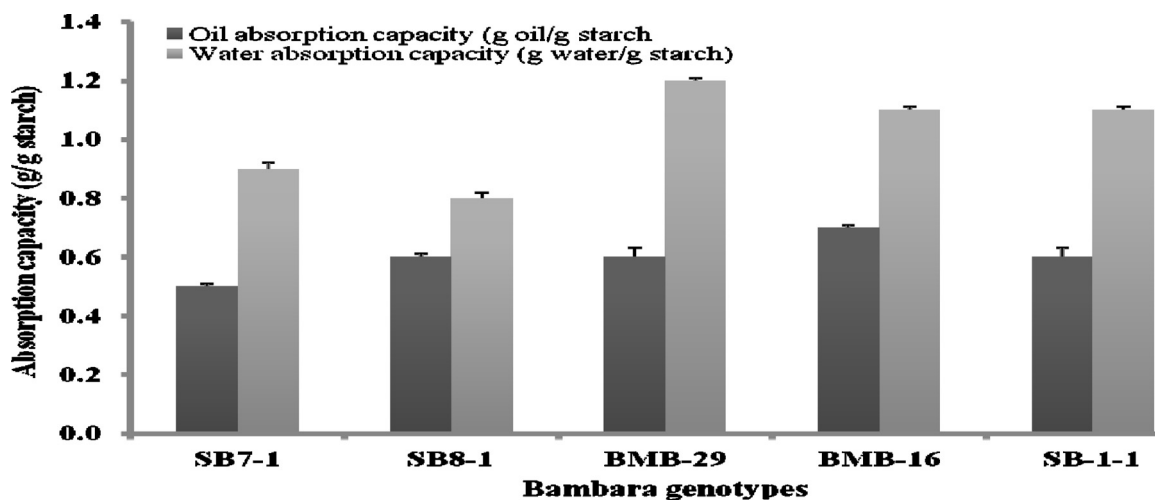


Fig. 4. Oil and water absorption capacities of bambara starches. Error bars indicate standard deviation ($n=2$).

peaks at 860 and 928 could be attributed to C–O stretching. Comparative peaks have been reported in the literature (Capon et al., 2007; Kizil et al., 2002).

3.5. Water and oil absorption capacities

The water absorption capacities of bambara starches differed across genotypes (Fig. 4). Among the studied genotypes, BMB-29 starch showed the greatest ability to absorb water (1.2 g water/g starch). The significantly ($p < 0.05$) higher water absorption capacity of BMB-29 starch compared to starches from other genotypes could possibly be attributed to its higher amylose content (approx. 35%) (Table 2). Similarly, high water absorption capacity has been reported for Chinese yam and chick pea starches containing higher amylose contents (Shujun et al., 2006; Singh, Singh Sandhu, & Kaur, 2004). Unlike with the water absorption, the oil absorption capacities of bambara starches were not very different among genotypes (Fig. 4). Approximately 0.6 g of oil was absorbed per g starch. The oil absorption capacities and water absorption capacities of the starches from the bambara genotypes were similar to those previously reported for bambara landrace varieties (Adebowale et al., 2002; Sirivongpaisal, 2008).

3.6. Swelling power

Bambara starches showed a progressive increase in swelling power as temperature increased (Fig. 5). However, a sharp increase in swelling power was observed between the temperature range of 80 and 90 °C. This may be attributed to starch gelatinization.

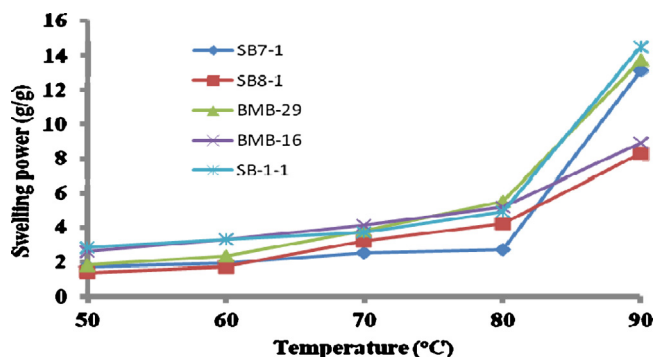


Fig. 5. Swelling power of bambara starch as a function of temperature.

Previous studies on bambara starch reported similar gelatinization temperature range (77–93 °C) (Kaptso et al., 2014; Afolabi, 2012; Sirivongpaisal, 2008). Starch extracted from bambara genotype BMB-16 and SB-1-1 with lower amylose contents (Table 2) showed higher swelling power between 50 and 80 °C. The swelling power of the starches above 80 °C followed the order SB-1-1 > BMB-29 > SB7-1 > BMB-16 > SB8-1. Comparative studies on non-waxy and waxy maize starches indicated that amylose content of starch restricts its swelling behaviour (Ratnayake, Hoover, & Warkentin, 2002). Although, the variation in the swelling power of bambara genotypes may be associated with differences in amylose contents of starches, other factors such as molecular structure of amylopectin and the magnitude of interaction within the amorphous and crystalline regions may also play a role as indicated in previous studies (Singh, Singh, Kaur, Singh Sodhi, & Singh Gill, 2003). The swelling power in this study is similar to those reported for bambara landrace (Sirivongpaisal, 2008; Adebowale et al., 2002).

3.7. Paste clarity

Among studied genotypes, BMB-29 starch showed the lowest paste clarity (Fig. 6), which could be attributed to its relatively high amylose content (Table 2). During paste formation, starches with relatively higher amylose contents have higher tendency to leach into the surrounding medium and thus forming a cloudy paste. However, during storage at 4 °C, all the starches showed a sharp decrease in paste clarity (75–87%) within 24 h. Beyond 24 h storage, the paste clarity remained almost constant throughout the storage period for all the starches. The reduction in paste clarity values may be attributed to aggregation and slow recrystallization of amylopectin (Gani, Haq, Masoodi, Broadway, & Gani, 2010). Similar time-dependent decrease in paste clarity have also been reported for canna starch cultivars (Thitipraphunkul, Uttapap, Piyachomkwan, & Takeda, 2003), rice starch (Ashwar et al., 2014), and chestnut starch (Gani et al., 2010).

3.8. Rheology

As expected, gelatinized bambara starches showed a decrease in viscosity with increasing shear rates (Fig. 7) suggesting a breakdown in starch structure by the applied shear stress. This behaviour, typical of pseudo-plastic macromolecules, varied across bambara starch genotypes. Among the bambara genotypes, BMB-29 starch showed the highest viscosity within a shear rate range of 10–100 s⁻¹, which may be associated with its relatively high

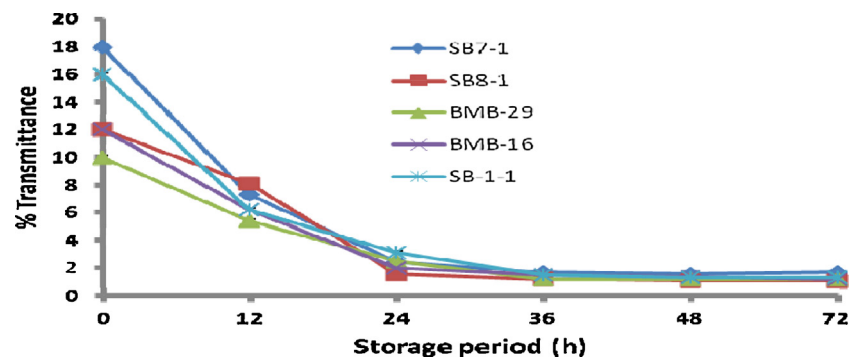


Fig. 6. Paste clarity of bambara starch genotypes as affected by storage (4 °C).

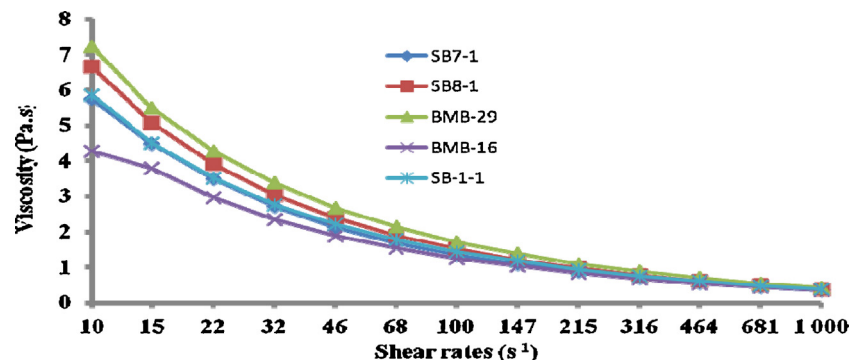


Fig. 7. Rheogram of bambara starch genotypes.

Table 3

Power-Law model coefficients of gelatinized bambara starch genotypes.

Genotypes	<i>N</i>	<i>K</i> (Pa.s) ^{<i>n</i>}	<i>r</i> ²
SB7-1	0.1 ^a ± 0.1	1.8 ^b ± 0.0	0.9 ^a ± 0.1
SB8-1	0.1 ^a ± 0.1	1.7 ^b ± 0.0	0.9 ^a ± 0.0
BMB-29	0.1 ^a ± 0.1	1.5 ^a ± 0.1	0.9 ^a ± 0.1
BMB-16	0.1 ^a ± 0.1	1.7 ^b ± 0.0	0.9 ^a ± 0.0
SB-1-1	0.1 ^a ± 0.1	1.7 ^b ± 0.0	0.9 ^a ± 0.1

Mean ± SD. Mean with different superscript along the column are significantly different ($p < 0.05$). *K*: Consistency index, *n*: flow behaviour index, *r*²: correlation coefficient.

amylose content (Table 2). Possibly, the shear induced during gelatinization process may have enhanced the solubilization of amylose into the surrounding starch medium, which may have enhanced the viscosity of the starch pastes. Xie et al. (2009) reported a similarly high viscosity for maize starch with higher amylose content compared to maize starch with lower amylose.

Power-Law model was applied to describe the flow behaviour of bambara starches. The flow properties of the starches followed the Power-Law model with the correlation coefficient ($r^2 \geq 0.9$) close to 1 (Table 3). Flow behaviour index ($n \sim 0.1$) was similar across starch genotypes (Table 3). However, the consistency index (*K*) of the starches varied among bambara genotypes (1.5 to 1.8 Pa.s^{*n*}) (Table 3).

4. Conclusions

Bambara genotypes are relatively good sources of carbohydrate including starch. Starches isolated from bambara genotypes consists of predominantly oval shaped granules. Bambara starches contain variable amounts of amylose which significantly influence their functional properties such as water absorption, swelling, paste clarity and viscosity. All bambara starches display the C-type

crystallinity pattern. FTIR of all bambara starches present the same characteristic bands in the finger print regions (1300–800 cm^{−1}) with some variation in peak intensities at 2931 cm^{−1} and 1655 cm^{−1} which could be attributed to differences in amylose contents and degree of crystallinity of genotypes.

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