4. CHAPTER V

Physico-chemical Properties of Starch Isolated from Sorghum Varieties of Different Polyphenol Content and Kernel Structure

ABSTRACT

To determine the relationship between sorghum grain polyphenol content, grain structure and starch properties, starch was isolated from ten sorghum varieties using an alkali steep and wet milling procedure. SV2, a tannin-free variety with white pericarp gave a white starch. Varieties having red or white pericarp and different polyphenol levels gave pink starches. The bright pink colour of these starches could not be removed. Hunter L, a and b values of starches were not correlated with grain polyphenol content. Grain appearance in terms of pericarp colour, presence or absence of pigmented testa, did not relate to the intense pink colouration of sorghum starches. Amylose content was significantly correlated ($r = -0.88$ at $P < 0.001$) to grain floury endosperm texture. Sorghum starches had higher peak viscosities than commercial maize starch. The time taken to reach peak viscosity (PV) from the initial viscosity rise was less for sorghum starches than maize starch. However, sorghum starches had higher rates of viscosity decrease, from PV to hot paste viscosity, than maize starch. There was a significant positive correlation ($P < 0.01$) between grain polyphenol content and starch pasting peak viscosity. Starch gel hardness was negatively correlated to pasting properties of rate of viscosity decrease and paste breakdown ($r = -0.78$ and -0.77, respectively) at $P < 0.01$. Peak gelatinization temperature (Tp) occurred over a narrow range of 66 to 69°C. Tp was negatively correlated to the floury endosperm portion of the grain ($r = -0.77$) at $P < 0.01$. It is concluded that sorghum

grain polyphenol content and grain characteristics influence its starch properties.

INTRODUCTION

Sorghum grain tends to be less consistent than maize in terms of kernel structure and colour (Rooney and Miller 1982). The observed pink colour of sorghum starch has been associated with pigments in the pericarp and endosperm of the grain (Freeman and Watson 1971; Norris 1971). Davis and Hoseney (1979) showed that starch could adsorb and retain condensed tannins when extracted from tannin-containing sorghum varieties. Studies by Subramanian et al (1994a) implicate alcohol-soluble components as the source of the dull colour of sorghum starch. The brightness of sorghum starch can be improved by washing with dilute NaOH solution (Yang and Seib 1995) or steeping the grain in alkali prior to wet milling (Chapter IV).

Alkali extraction has been applied in isolating *Amaranthus* starch (Perez et al 1993; Zhao and Whistler 1994; Wu et al 1995) and the method has also been proposed for starch extraction from cereals (Mistry 1991). Alkali extraction results in maize starch with high viscosity, high hydration capacity, and more heat and shear stability than the commercial maize starch (Mistry and Eckhoff 1992). NaOH-treated starches had higher peak viscosity and setback than when water, HCl and formaldehyde were used (Chapter IV). The advantages of using alkali solution for steeping sorghum grain include rapid water uptake (Dewar 1997; Chapter II) and polyphenol reduction (Reichert et al 1980; Chapter II). Enhanced water uptake is presumed to be due to the alkali opening up the pericarp cell walls (Dewar et al 1997). Alkaline conditions also promote oxidative polymerization of condensed tannins (Porter 1992), resulting in the formation of highly polymeric and probably nutritionally inactive compounds.

The objectives of this study were: 1) to isolate starch from sorghum varieties of different polyphenol content and kernel structure, using an alkali steep and wet milling; 2) to measure important physico-chemical properties, including pasting, textural, and thermal properties of sorghum starch; and 3) to determine the relationship between starch properties, kernel structure and polyphenol content of sorghum.

MATERIALS AND METHODS

Samples

Ten sorghum varieties grown under uniform field conditions in the 1996/97 season at Matopos, Zimbabwe, were used. The selection represented sorghum varieties differing in polyphenol content, endosperm texture and pericarp thickness. Chirimaugute, Chibonda, Mutode and DC-75 (a hybrid), are tannin-containing varieties. Katandanzara, Kasvikisire, Mukadziusaenda, Mukadzidzoka, Tsveta and SV2 (an improved cultivar) are tannin-free varieties. Katandanzara, DC-75 and SV2 have relatively corneous endosperms. Other varieties have an intermediate to floury endosperm texture. Mutode, Chibonda and DC-75 have thick pericarps. Pericarp thickness ranges from thin to medium in other varieties.

Starch Extraction

Starch was extracted following a combination of the methods described by Watson et al (1955), Perez et al (1993) and Zhao and Whistler (1994). This method has been used to isolate and characterise *Amaranthus* starch (Wu et al 1995). Sorghum grain (100 g) was steeped in 200 ml NaOH (0.25 %, w/v) at 5°C for 24 hr. The steeped grains were washed and ground with an equal volume of water using a Waring blender for 5 min at full speed. The slurry was filtered through a 200-mesh sieve (75 μm opening screen). The material remaining on the sieve was rinsed with water. Grinding and filtering was repeated on this material. After rinsing, the material still remaining on the sieve was discarded. The collected filtrate was allowed to stand for 1 hr. The filtrate was centrifuged at 760 x *g* for 10 min. The grey-coloured, top protein-rich layer was removed using a spatula. Excess water was added to resuspend the sample and centrifugation was done for 3 min. The washing and recentrifugation was repeated several times until the top starch layer was white. The starch was dried for 24 hr at 40°C.

Amylose/Amylopectin Ratio

An iodine-binding spectrophotometric method using 0.2 % iodine in 2.0 % potassium iodide was used (Juliano et al 1981). Samples of starch (100 mg) were weighed in volumetric flasks (100 ml). One millilitre of ethanol (95 %) was used to wash the sample down the flask. Nine millilitres of NaOH (1 M) was added to the starch sample before heating the flasks in a boiling water bath for 10 min. The samples were cooled and the volume made up to 100 ml with distilled water. The contents were mixed vigorously to disperse the starch. Amylose/amylopectin standard mixtures were prepared to represent from 0 to 60 % amylose content. For the iodine colour development, an aliquot (5 ml) of each solution was taken to which 1 M acetic acid (1 ml) was added. The contents were mixed. The solutions were allowed to stand for 20 min after mixing with iodine solution (2 ml). Absorbance was read at 620 nm.

Pasting Profile Determination

Pasting properties of sorghum starches were determined using a Rapid Visco Analyser model 3D (RVA) (Newport Scientific, Narrabeen, Australia). A commercial maize starch (Sigma, St Louis, U.S.A.) was also analysed for comparison with sorghum starch. Sorghum starch (3 g, 14 % moisture basis) was mixed with 25 g of accurately weighed water in the aluminium canister. A programmed heating and cooling cycle was used, in which the mixture was held at 50°C for 1 min, heated to 95°C in 7.5 min at the rate of 6°C/min, held at 95°C for 5 min before cooling to 50°C in 7.5 min and holding at 50°C for 1 min (Bhattacharya et al 1997). Peak viscosity (PV), PV temperature, temperature at initial viscosity increase (Ti), time to reach PV (time at PV - time at initial viscosity increase), holding strength (hot paste viscosity) (HPV), cool paste viscosity (CPV), rate of viscosity decrease calculated as (PV - HPV)/(13.5 min - PV time), breakdown calculated as (PV - HPV), and setback calculated as (CPV - PV), were recorded. Two replicates per sample were analysed.

Texture Analysis

The stirring paddle was removed from the aluminium canister after RVA testing. The sample was allowed to stand for 24 hr at room temperature (about 20°C) for gelation to take place (Bhattacharya et al 1997). An SMS Model TA-TX2 texture analyser (Stable Micro Systems, Godalming, England) was then used to measure the textural properties of the sorghum starch gels. A standard two-cycle programme was used to compress the gels for a distance of 10 mm at a crosshead speed of 30 mm/min using a 7-mm cylindrical probe with a flat end. Textural parameters of hardness (maximum force on first cycle in

g) and cohesiveness (total positive work done on second cycle divided by total positive work done on first cycle, no units), and gumminess (cohesiveness x hardness in g) were automatically computed, from the force-time curve obtained, using the data processing software supplied with the instrument. Four repeat measurements were taken of each of the two gel replicates per sample.

Differential Scanning Calorimetry

Thermal properties of sorghum starches were determined using a Mettler DSC-20 differential scanning calorimeter (Mettler-Toledo AG Instruments, Naenikon-Uster, Switzerland) equipped with a ceramic sensor and a Mettler TC II data analysis station. Starch (2 mg, dwb) was weighed directly into a 40-μL aluminium standard pan and water added to give a final weight of 6.5 mg. The pan was covered with the lid and hermetically sealed. The sample was allowed to equilibrate at room temperature for at least 1 hr before running it on the differential scanning calorimeter. The sample was heated from 30°C to 120°C at the rate of 10°C per min. Gelatinisation parameters of onset (To), peak (Tp), and conclusion (Tc) temperature were determined. Gelatinization temperature range (Tc - To) was calculated. Gelatinization enthalpy (ΔH) in J/g was also recorded. Two replicates per sample were analysed.

Colour Determination

The colour of sorghum starches was determined using the Hunter Lab Colour Quest 45/0 LAV (Hunter Associates Laboratory, Inc. Reston, U.S.A.) equipped with Universal Software Version 3.1. The mean of three readings per sample was taken at different angles.

Statistical Analysis

The general linear model procedure of the Statistical Analysis System version 6.10 (SAS Institute, Cary, U.S.A.) was used for data analysis. Means were compared at the 5 % significance level using Fisher's least significant difference (LSD). Pearson correlation coefficients (r) were calculated among starch pasting, textural, and gelatinisation properties and grain polyphenol content and kernel characteristics using SAS Proc Corr.

RESULTS AND DISCUSSION

Swelling and Pasting Properties

Swelling and pasting properties of sorghum starches are shown in Table V-1. The mean initial swelling temperature (Ti) of sorghum starches was lower (69.4°C) than that of maize starch (73.6°C). Subramanian et al (1994b) also reported higher Ti values of 69 to 77°C for 7 sorghum starches. The differences in swelling temperatures possibly resulted from genetic variation in kernel structure of the varieties as most Zimbabwean sorghums have intermediate to floury endosperm (Chapter I). Peak viscosity (PV) temperature for sorghum starch ranged from 78.8 to 88.1°C. Maize starch had a higher PV temperature of 93.5°C. The results confirm the findings of by Abd Allah et al (1987) that sorghum starches had lower PV temperatures than maize starch. The lower swelling temperature of sorghum starch could have been due to the alkali treatment that caused some partial pre-gelatinisation (Chapter IV). Sorghum starches took less time (2.4 min) to reach PV than maize starch (3.5 min). Sorghum starch granules were thus easily swollen. The time to reach PV and PV temperature were positively correlated ($P < 0.001$) and both were negatively correlated ($P < 0.01$) to grain polyphenol content (Table V-2). During alkali steeping, polyphenols were presumably oxidatively polymerised to highly polymeric compounds that formed minor constituents of sorghum starches, thereby influencing the swelling properties. The higher PV temperature of starch from tannin-free varieties, SV2 and Mukadziusaenda, was further evidence that polyphenolic products were involved in granule swelling. The mean rate of viscosity decrease was 31.6 and 21.0 RVU/min for sorghum and maize starch, respectively. Presumably, the highly, swollen sorghum starch granules broke up easily. Subramaniam et al (1994b) also found a higher rate of viscosity decrease when they compared sorghum starches with maize starches. Starch from the tannin-rich variety, DC-75 had the highest rate of viscosity decrease whereas that from Kasvikisire, a tannin-free variety, had the lowest.

Peak viscosity (PV) of starches is related to the swelling power and indicates the water binding capacity of the starch as it occurs at the equilibrium point between swelling and polymer leaching which causes a viscosity increase, while rupture and polymer alignment cause a viscosity decrease (Newport Scientific 1998). The mean PV of sorghum starches (332 RVU) was markedly higher compared to that of maize starch (239 RVU). Thus sorghum starches had greater water binding capacity than maize starch. The pasting profiles shown in Figure V-1 depicts the greater swelling power of sorghum starches of DC-75, Chirimaugute, and SV2 compared to maize starch. However, the alkali extraction method could have enhanced PV of sorghum starch (Chapter IV). An alkali extraction process also gives maize starch with high viscosity and high hydration capacity than commercial maize starch (Mistry and Eckhoff 1992). PV was positively correlated ($P < 0.05$) to rate of viscosity decrease as excessively swollen granules break down easily. There was a significant positive correlation ($P < 0.05$) between PV and grain polyphenol content (Table V-2). The oxidatively polymerized products of polyphenols presumably appeared as minor starch constituents that enhanced granule swelling. Hence, DC-75, the tannin-rich variety, gave starch with highest PV (398 RVU) (Table V-1). The higher amylopectin content of DC-75 starch caused greater swelling. SV2 and Kasvikisire (both tannin-free) and Chirimaugute (medium-tannin) gave starch pastes with lowest PV (300 RVU) as their amylose content were relatively high (Table V-3).

Hot paste viscosity (HPV) is a shear thinning property of the starch (Newport Scientific 1998). Sorghum and maize starch had mean HPV of 117 and 133 RVU, respectively (Table V-1). There was a significant negative correlation ($P < 0.001$) between HPV and rate of viscosity decrease (Table V-2). In other words the higher the rate of viscosity decrease the lower the HPV. HPV was highest (132 RVU) in starches from Chibonda and Kasvikisire. Chibonda has polyphenols largely unextractable in methanol whereas Kasvikisire is tannin-free (Chapter I). There was no significant correlation between HPV and grain polyphenol content or endosperm texture. The relatively higher amylose content of both starches could have contributed to higher shear thinning. Starches from Mukadziusaenda, DC-75 and Mutode gave the lowest HPV. Starches with low shear thinning suggest that they are stable under hot conditions. Subramanian et al (1994b) concluded that hot pastes sorghum starches generally undergo more shear thinning than maize starches. My observation is similar to that of Yang and Seib (1996) who found low shear thinning from starches isolated from two commercial yellow grain sorghums. The viscosity of a starch paste is not entirely caused by swelling (Miller et al 1973) but the fine structure and molecular weights of the amylose and amylopectin fractions could be important in controlling shear thinning (Takeda et al 1988; Jane and Chen 1992). Several other authors (Steeneken 1987; Williams and Bowler 1982) have surmised that the degree of shear thinning may be related to the morphology and rigidity of the swollen granules.

On cooling a hot starch paste, a firm, viscoelastic gel is generally produced due to re-association of starch molecules (Newport Scientific 1998). Cool paste viscosity (CPV) is important in some food processing operations such as canning (Wu et al 1995). The mean CPV (244 RVU) of sorghum starches was similar to that of maize starch, as has been previously noted by Yang and Seib (1996). There was a significant positive correlation ($P < 0.001$) between CPV and HPV. Thus the same factors that influence shear thinning of sorghum pastes are also involved in final viscosity. Starches from tannin-free variety, Kasvikisire and tannin-rich variety, DC-75 had the highest (277 RVU) and lowest (208 RVU) CPV, respectively. A significant negative correlation ($P < 0.01$) was found between CPV and starch paste breakdown. Varieties, Kasvikisire and Chirimaugute having similar hardness scores but differing widely in polyphenol content (Chapter I), gave starches with the lowest breakdown values.

The mean setback values for maize and sorghum starch pastes were 111 and 128 RVU, respectively (Table V-1). High setback is associated with syneresis, or weeping, during freeze / thaw cycles for example, and substituted starches are commonly used where this presents a quality defect (Newport Scientific 1998). Starch from the tannin-rich variety, DC-75 had the lowest setback (109 RVU). Chirimaugute, Kasvikisire and Katandanzara starches had the highest setback (>140 RVU).

Amylose Content and Textural Properties

The amylose content of sorghum starches ranged from 21.5 to 29.9 % (Table V-3). Thus varieties had normal, nonwaxy endosperm. There was a significant negative correlation ($P < 0.01$) between starch amylose and grain polyphenol content, floury endosperm and pericarp thickness (Table V-2). Hence, the higher the amylose content the more corneous the endosperm. Cagampang and Kirleis (1984) also reported a positive correlation between grain vitreousness and amylose content of 15 sorghum hybrids. Katandanzara, a tannin-free variety with corneous endosperm, had the highest amylose content. DC-75, the tannin-rich variety with relatively corneous endosperm, had the lowest amylose / amylopectin ratio. There was not a significant correlation between endosperm texture and polyphenol content (Chapter I).

The RVA was used as a cooker for the preparation of starch gels for textural measurements. Textural properties of sorghum starch gels are shown in Table V-3. The hardness of the starch gels ranged from 36.1 to 71.3 g. The tannin-rich variety, DC-75 gave starch with the softest gel. Chirimaugute, a variety of intermediate tannin content and floury endosperm, gave starch with the hardest gel. Gel firmness was presumably due to the amylose content of the starches. Grain floury endosperm and polyphenol content were both negatively correlated to amylose content (Table V-2). Cagampang and Kirleis

(1984) also prepared a firmer gel with starch from corneous rather than the floury endosperm of sorghum. Amylopectin starch polymers contribute more to solubilization (Jackson et al 1989) and retrogradation of starch (Cagampang and Kirleis 1984). Bello et al (1995) also reported increased soluble starch and a firmer, thick porridge texture as associated with a more corneous endosperm texture of sorghum. However, starch gel hardness was not significantly correlated to grain endosperm texture among the varieties studied (Table V-2). There was a significant negative correlation ($P < 0.05$) between gel hardness and pasting PV. Hence grain polyphenol content influenced gel hardness as PV was high in tannin-containing varieties. DC-75 gave the most cohesive starch gel while SV2 and Chirimaugute gave the least. Apparently, factors involved in gel hardness produce the opposite effect in gel cohesiveness. However, gel gumminess was presumably controlled by factors that control gel hardness. Gel gumminess was high in Chirimaugute and SV2 starches and low in DC-75 starch.

Thermal Properties

Table V-4 expresses the gelatinization temperatures of sorghum starches from the onset (To), peak (Tp) and conclusion (Tc) of gelatinisation. Gelatinization temperatures (GT) ranged from 60.1 (To) to 76.2°C (Tc). Taylor et al (1997) reported To and Tc values of 63.6 and 69.5°C respectively, for South African sorghums. However, GT values ranging from 71 to 80°C were reported by Sweat et al (1984) and Akingbala et al (1982) for sorghum starches. Tp values (72 to 75°C) reported for eight maize starches extracted in alkali (Mistry and Eckhoff 1992) were higher than those of sorghum starches. Thus GT of starches from Zimbabwean sorghums were lower than the literature values, as found by

Taylor et al (1997). The differences in GT can be explained largely by variation in genetic and environmental factors. Thermal properties could not be correlated to shear thinning properties as previously reported (Subramanian et al 1994). A significant correlation ($P < 0.05$) was found between Tp and starch amylose content. Thus starches with higher amylopectin content required lower temperatures to disrupt the molecular order of the granules. There was a significant correlation ($P < 0.01$) between endosperm texture and Tp and To. In other words, the more corneous the grain the higher the Tp or To. Similar observations had been reported on the latter when starches from the corneous endosperm gave higher Tp than those isolated from the floury types of three sorghum cultivars (Cagampang and Kirleis 1984). A significant negative correlation ($P < 0.05$) was found between To and grain polyphenol content (Table V-2). The oxidation products of polyphenols possibly contributed to molecular order disruption of granules resulting in lower To values of the starch. The significant negative correlation between To and grain pericarp thickness could not be explained. The enthalpy for gelatinization (ΔH) was highest for SV2 (8.3 J/g) and lowest for Tsveta (6.9 J/g). The two varieties differ in that SV2 is relatively more corneous and contains lower levels of phenolic acids than Tsveta (Chapter II). Thus the high phenolic acids of Tsveta grain could have undergone polymerisation resulting in products that lowered the energy needed to gelatinise starch. A significant negative correlation ($P < 0.05$) between ΔH and grain polyphenol content was also found. Thus starch from polyphenol-rich varieties required less enthalpy to completely gelatinise them.

Starch Colour and Kernel Properties

The starches obtained generally were of different shades of pink (Figure V-2 a and b). Only SV2, a tannin free variety with white pericarp and no testa (Chapter I), gave a white starch. Apparently, the tan plant colour of SV2 was important in reducing the colour of the starch product. The other sorghum varieties have either red or white pericap and different levels of polyphenols. Starch colour is probably due to the presence of pigments in the pericarp that were leached into the endosperm during weathering in the field or during steeping for wet milling (Norris 1971). Hunter L (lightness), a (red to green) and b (blue to yellow) values of sorghum starches are shown in Table V-4. Grain pericarp colour, presence or absence of pigmented testa and polyphenol content did not correlate to the pink colour of sorghum starches. The starch colouration obtained even from grains that apparently looked white with a few red or purple spots, was remarkably intense. The explanation by Freeman and Watson (1971) that starch made from certain white-seeded cultivars could still be off-white due to carotenoid pigment in the endosperm was not a satisfactory explanation in this case. The colour changes of phenolics which occur when pH is increased generally result from ionization of the phenolic; the phenolate ion is generally more brightly coloured than the neutral phenol. In addition, the phenolate ion can complex with metals (especially iron) to form coloured complexes. Kennedy et al (1984) also found that in alkaline solution, flavan-3-ols or condensed tannins could undergo C-ring opening and rearrangement via radical reactions involving traces of oxygen. The radical anion intermediate formed in mild, alkaline solutions will then react further by a series of alternative annulation and ring migration reactions giving a host of products. These reactions could probably have caused the intense pink pigmentation of the starch. SV2 starch had the highest L value (90.5). However, Chibonda, a variety with white pericarp but containing pigmented testa underneath, gave the darkest starch. Varieties, Chirimaugute, DC-75, and Mutode also have pigmented testa beneath white, red and red pericarp, respectively (Chapter I). However, the polyphenolic compounds of Chibonda, which are unextractable in methanol (Chapter I), could have remained adsorbed to the starch during wet milling.

CONCLUSIONS

A tan plant colour is critically important to lower colour in tannin-free sorghum meant for production of white starch. Starch pasting properties of peak viscosity, peak viscosity temperature, and time to reach peak viscosity were significantly correlated to grain polyphenol content. Starch amylose content and gelatinization peak temperature were significantly correlated to grain endosperm texture. Hence the polyphenol content and kernel structure of sorghum varieties influence starch properties.

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Table V-1. Pasting and swelling properties of starches isolated from Zimbabwean sorghum varieties[1]

Variety	Ti (°C)	Rate (RVU/min)	TPV (°C)	Time (min)	PV (RVU)	HPV (RVU)	CPV (RVU)	BKD (RVU)	STB (RVU)
DC-75	69.5[b,2]	40.4[a]	79.9[f]	1.73[f]	398[a]	99[f]	208[h]	299[a]	109[f]
Chirimaugute	70.3[a]	26.2[g]	85.4[c]	2.53[c]	301[g]	125[b]	268[b]	176[h]	144[a]
Mutode	69.3[b]	34.1[c]	82.8[e]	2.24[d]	338[d]	102[e]	218[g]	236[c]	117[e]
Mukadzidzoka	67.9[d]	30.1[f]	82.0[e]	2.39[c]	326[e]	114[c]	232[f]	212[f]	118[de]
Chibonda	68.6[c]	29.7[f]	80.0[f]	1.92[e]	353[c]	132[a]	263[c]	222[e]	131[b]
Tsveta	68.1[d]	31.2[e]	78.8[h]	1.80[ef]	363[b]	124[b]	250[d]	240[b]	127[c]
Katandanzara	70.2[a]	30.3[ef]	86.8[b]	2.71[b]	315[f]	126[b]	263[bc]	189[g]	140[a]
Mukadziusaenda	70.3[a]	37.8[b]	87.8[a]	2.97[a]	324[e]	96[g]	218[g]	228[d]	122[d]
Kasvikisire	70.1[a]	24.4[h]	84.4[d]	2.40[c]	300[g]	132[a]	277[a]	168[i]	144[a]
SV2	70.0[a]	32.2[d]	88.1[a]	3.03[a]	304[g]	111[d]	245[e]	193[g]	134[b]
Maize starch	**73.6**	**21.0**	**93.5**	**3.5**	**239**	**133**	**244**	**106**	**111**
Mean (sorghum starch)	69.4	31.6	83.5	2.37	332	116	244	216	128
LSD (sorghum starch)	0.45	0.86	0.65	0.14	4.25	2.32	5.40	3.41	4.00

[1]Ti = temperature at initial viscosity rise, Rate = rate of viscosity breakdown, Time = time from initial to PV, TPV = temperature at peak viscosity, PV = peak viscosity, HPV = hot paste viscosity, HPV = holding strength at 13.5 min, CPV = cool paste viscosity, BKD = breakdown (PV-HPV), STB = setback (CPV-HPV).

[2]Values within the same column with different letters are significantly different at $p<0.05$.

Table V-2. Pearson correlation coefficients (r values) of the sorghum starch properties, grain structural characteristics and polyphenol content[1,2]

	Tp	To	Tc	Tr	ΔH	Ti	Rate	Time	TPV	PV	HPV	CPV	BKD	STB	L	Hard	Amy	Van	Et
To	0.94***																		
Tc	0.82**	0.70*																	
Tr	-0.41	-0.62	0.12																
ΔH	0.38	0.33	0.36	-0.06															
Ti	0.86**	0.82**	0.65*	-0.44	0.18														
Rate	0.33	0.08	0.44	0.37	0.54	-0.004													
Time	0.54	0.62	0.15	-0.69*	0.41	0.63	-0.12												
TPV	0.67*	0.73*	0.31	-0.66*	0.39	0.79**	-0.09	0.97***											
PV	-0.27	-0.49	0.10	0.79**	-0.01	-0.50	0.66*	0.81**	-0.78**										
HPV	-0.49	-0.36	-0.41	0.04	-0.72*	-0.12	-0.88***	-0.18	-0.18	-0.32									
CPV	-0.26	-0.11	-0.30	-0.17	-0.63	0.17	-0.90***	0.11	0.13	-0.56	0.95***								
BKD	-0.05	-0.28	0.23	0.64*	0.24	-0.37	0.85**	-0.61	-0.59	0.94***	-0.61	-0.80**							
STB	0.04	0.18	-0.12	-0.38	-0.45	0.47	-0.83**	0.41	0.46	-0.75*	0.77**	0.93***	-0.89***						
L	-0.25	-0.24	-0.08	0.23	0.36	-0.20	0.06	0.18	0.09	-0.07	-0.12	-0.11	-0.01	-0.07					
Hard	-0.36	-0.14	-0.58	-0.43	-0.24	0.04	-0.78**	0.32	0.27	-0.69*	0.57	0.67*	-0.77**	0.69*	0.18				
Amy	0.73*	0.82**	0.40	-0.69*	0.43	0.62	-0.01	0.67*	0.72*	-0.58	-0.35	-0.14	-0.35	0.13	0.03	0.02			
Van	-0.60	-0.73*	-0.32	0.67*	-0.46	-0.52	0.14	-0.86**	-0.83**	0.75*	0.21	-0.01	0.55	-0.26	-0.21	-0.12	-0.85**		
Et	-0.77**	-0.80**	-0.53	0.53	-0.60	-0.61	-0.13	-0.53	-0.60	0.39	0.42	0.25	0.17	0.03	0.21	0.14	-0.88***	0.71*	
Pt	-0.66*	-0.76*	-0.43	0.58	-0.64*	-0.47	-0.17	-0.48	0.52	0.35	0.55	0.38	0.10	0.14	-0.14	0.09	-0.87***	0.71*	0.83**

[1]Tp = peak gelatinization temperature, To = onset temperature of gelatinization, Tc = conclusion temperature of gelatinization, Tr = Tc-To, ΔH – gelatinization enthalpy, Ti = temperature at which viscosity begins to increase, Rate =rate of viscosity breakdown, Time =time from initial increase to PV, TPV =temperature at PV, PV =peak viscosity, HPV =holding paste viscosity, CPV =final or cool paste viscosity, BKD =breakdown (PV-HPV), STB =setback (CPV-HPV), L =Hunter L value, Hard = hardness, Amy = amylose, Van = polyphenol content, Et = % floury endosperm, Pt = pericarp thickness.

[2]***, **, * = $P < 0.001$, 0.01, and 0.05, respectively; n=10.

Table V-3. Endosperm texture, starch amylose content and gel properties of Zimbabwean sorghum varieties

Variety	Floury endosperm[*] (%)	Amylose (%)	Hardness (g)	Cohesiveness	Gumminess (g)
DC-75	31.9	21.5[g,1]	36.1[g]	0.63[a]	22.8[g]
Chirimaugute	63.0	28.7[b]	71.3[a]	0.48[e]	33.9[a]
Mutode	45.1	28.1[bcd]	58.2[cd]	0.48[de]	28.1[e]
Mukadzidzoka	71.9	27.1[de]	56.5[de]	0.52[c]	29.1[de]
Chibonda	69.7	28.3[bc]	59.2[cd]	0.56[b]	32.9[ab]
Tsveta	51.4	28.2[bc]	59.6[c]	0.51[cd]	30.1[cd]
Katandanzara	28.4	29.9[a,2]	53.8[e]	0.56[b]	29.9[cde]
Mukadziusaenda	48.1	26.0[f]	47.5[f]	0.53[c]	25.0[f]
Kasvikisire	38.1	27.1[e]	59.8[c]	0.48[de]	28.9[de]
SV2	39.9	27.4[cde]	66.9[b]	0.47[e]	31.5[bc]
Mean	48.8	27.2	56.9	0.52	29.2
LSD		0.99	2.78	0.03	1.93

[1]Hard = hardness, cohes = cohesiveness, gumm =gumminess, chew = chewiness.
[2]Values within the same column with different letters are significantly different at $p<0.05$.
[*]From Chapter 1.

Table V-4. Thermal properties of starches isolated from Zimbabwean sorghum varieties[1]

Variety	To (°C)	Tp (°C)	Tc (°C)	Tr (°C)	ΔH (J/g)
DC-75	61.9^{cd,2}	68.0^{b}	76.2^{a}	14.3^{a}	7.85^{ab}
Chirimaugute	62.3^{c}	67.5^{bc}	74.3^{c}	12.0^{d}	7.15^{bcde}
Mutode	62.3^{bc}	67.7^{bc}	75.3^{b}	13.0^{bcd}	7.50^{bcde}
Mukadzidzoka	61.2^{d}	66.5^{d}	73.9^{c}	12.7^{cd}	7.70^{abcd}
Chibonda	60.4^{e}	66.3^{de}	74.4^{c}	14.0^{ab}	7.10^{cde}
Tsveta	60.1^{e}	65.8^{e}	74.2^{c}	14.1^{ab}	6.90^{e}
Katandanzara	62.2^{c}	68.0^{b}	75.4^{b}	13.2^{abcd}	7.00^{de}
Mukadziusaenda	63.2^{a}	68.7^{a}	75.7^{ab}	12.5^{cd}	7.80^{abc}
Kasvikisire	63.0^{ab}	68.0^{bc}	75.9^{ab}	12.9^{bcd}	7.25^{bcde}
SV2	61.9^{cd}	67.5^{c}	75.2^{b}	13.3^{abc}	8.25^{a}
Mean	61.8	67.4	75.0	13.2	7.45
LSD	0.72	0.51	0.79	1.22	0.70

[1]Tp = peak gelatinization temperature, To = onset temperature of gelatinization, Tc = conclusion temperature of gelatinization, Tr = (Tc-To), Δ*H* = gelatinization enthalpy
[2]Values within the same column with different letters are significantly different at $p<0.05$.

Table V-5. Hunter L, a, and b colour values of starches isolated from Zimbabwean sorghum varieties of different kernel properties and polyphenol content[1]

Variety	Testa*	Pericarp colour*	Total polyphenol*+	L	a	b
DC-75	Yes	Red	6.29	81.1[2] (0.01)	3.90 (0.02)	4.11 (0.02)
Chirimaugute	Yes	White	3.78	77.9 (0.01)	4.51 (0.02)	4.36 (0.02)
Mutode	Yes	Red	3.25	81.5 (0.01)	5.81 (0.02)	5.34 (0.01)
Mukadzidzoka	No	Red	0.66	84.1 (0.03)	4.30 (0.03)	4.66 (0.02)
Chibonda	Yes	White	0.52	75.9 (0.01)	4.30 (0.01)	4.74 (0.02)
Tsveta	No	Red	0.32	87.9 (0.01)	2.20 (0.01)	4.66 (0.02)
Katandanzara	No	White	0.19	81.7 (0.01)	4.95 (0.02)	4.95 (0.02)
Mukadziusaenda	No	White	0.18	79.2 (0.01)	3.47 (0.03)	4.58 (0.03)
Kasvikisire	No	White	0.05	81.4 (0.02)	4.95 (0.02)	4.95 (0.02)
SV2	No	White	0.00	90.5 (0.01)	-0.34 (0.00)	5.47 (0.01)
Mean			1.52	82.1	3.81	4.76

[1]Hunter L, a, and b values.
[2]Mean and standard deviation.
*From Chapter 1; +mg/100g.

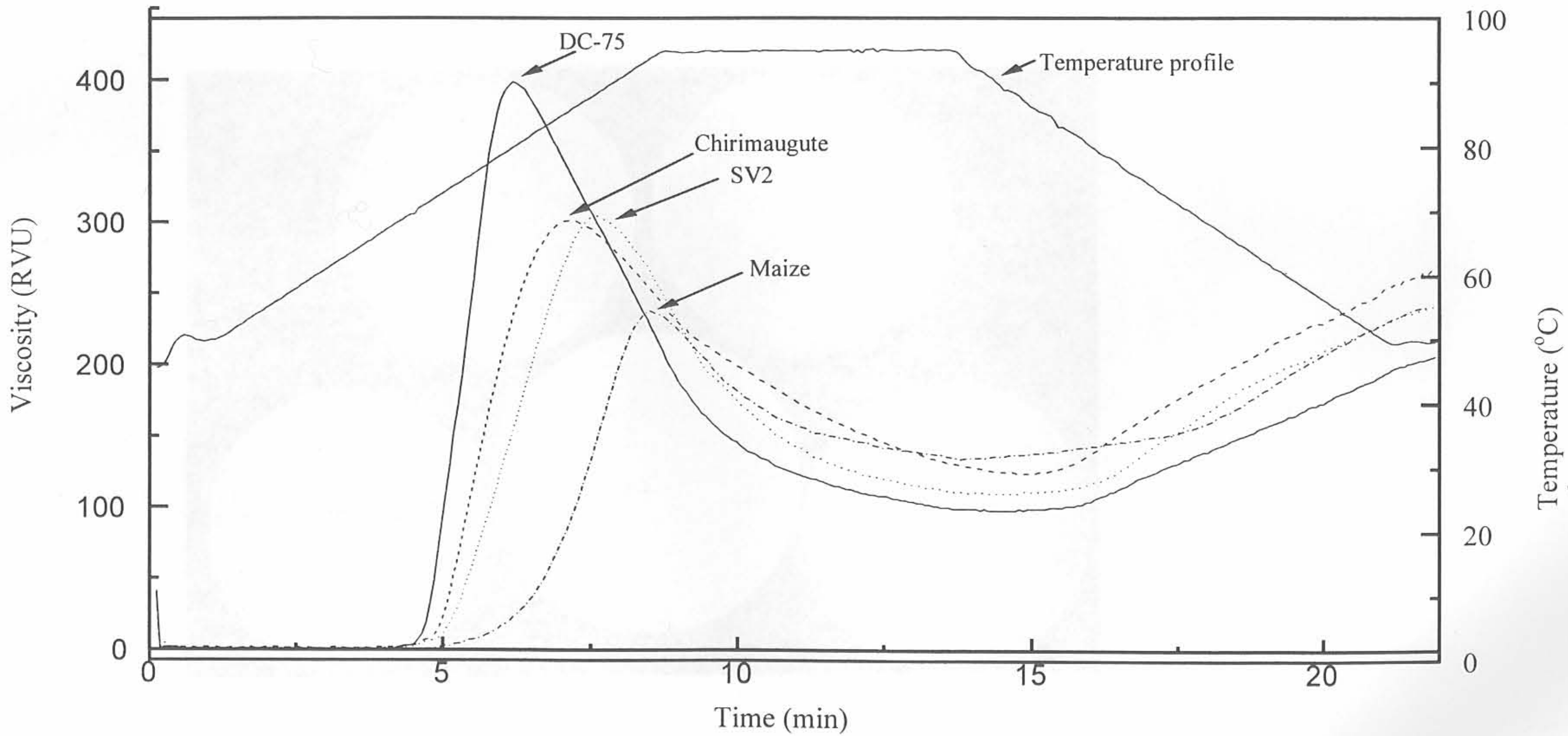

Figure V-1. RVA pasting profiles of sorghum starches compared to maize starch. DC-75 and Chirimaugute are tannin-containing varieties and SV2 is a tannin-free variety.

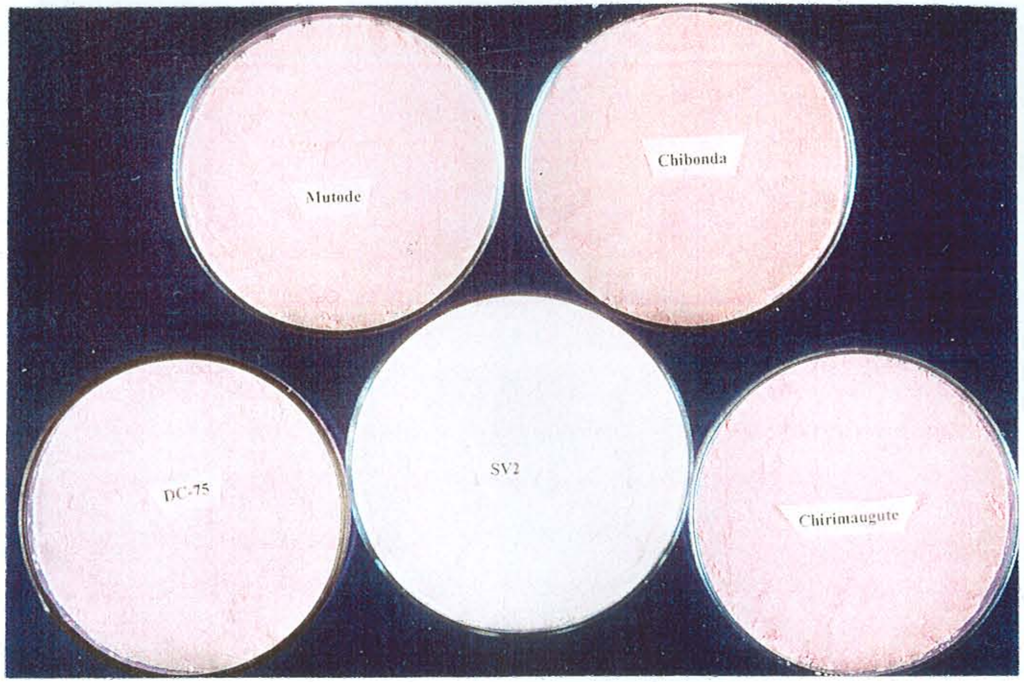

Figure V-2. (a) Photographs illustrating different colours of sorghum starches from tannin-containing (DC-75, Mutode, Chirimaugute and Chibonda) and tannin-free (SV2) varieties.

Figure V-2. (b) Photographs illustrating different colours of sorghum starches from tannin-free varieties (Katandanzara, Kasvikisire, Tsveta, Mukadzidzoka, Mukadziusaenda).