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Review

Sorghum grain as human food in Africa: relevance of content of starch and amylase activities

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Sorghum is a staple food grain in many semi-arid and tropic areas of the world, notably in Sub-Saharan Africa because of its good adaptation to hard environments and its good yield of production. Among important biochemical components for sorghum processing are levels of starch (amylose and amylopectin) and starch depolymerizing enzymes. Current research focus on identifying varieties meeting specific agricultural and food requirements from the great biodiversity of sorghums to insure food security. Results show that some sorghums are rich sources of micronutrients (minerals and vitamins) and macronutrients (carbohydrates, proteins and fat). Sorghum has a resistant starch, which makes it interesting for obese and diabetic people. In addition, sorghum may be an alternative food for people who are allergic to gluten. Malts of some sorghum varieties display α-amylase and ß-amylase activities comparable to those of barley, making them useful for various agro-industrial foods. The feature of sorghum as a food in developing as well as in developed countries is discussed. A particular emphasis is made on the impact of starch and starch degrading enzymes in the use of sorghum for some African foods, e.g. "tô", thin porridges for infants, granulated foods "couscous", local beer "dolo", as well agro-industrial foods such as lager beer and bread.

Key words: sorghum, α-amylase, β-amylase, starch, infant porridge, beer, couscous, dolo, tô, bread.

INTRODUCTION

Sorghum [*Sorghum bicolor* (L.) Moench], a tropical plant belonging to the family of Poaceae, is one of the most important crops in Africa, Asia and Latin America (Figure 1; Anglani, 1998). More than 35% of sorghum is grown directly for human consumption. The rest is used primarily for animal feed, alcohol production and industrial products (FAO, 1995; Awika and Rooney, 2004a). The current annual production of 60 million tons is increasing due to the introduction of improved varieties and breeding conditions. Several improved sorghum varieties adapted to semi-arid and tropic environments are released every year by sorghum breeders. Selection of varieties meeting specific local food and industrial requirements from this great biodiversity is of high importance for food security. In developing countries in general and particularly in West Africa, demand for sorghum is increasing. This is due to not only the growing population, but also to the countries policy to enhance its processing and industrial utilization (Akintayo and Sedgo, 2001). More than 7000 sorghum varieties have been identified (Kangama and Rumei, 2005); therefore there is a need of their further characterization to the molecular level with respect to food quality. The acquisition of good quality grain is fundamental to produce acceptable food products from sorghum. Sorghum while playing a crucial role in food security in Africa, it is also source of income of house-hold (Anglani, 1998). In West Africa, ungermina-

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Figure 1. *Sorghum bicolor* (L.) Moench.

ted sorghum grains are generally used for the preparation of “tô”, porridge, and couscous. Malted sorghum is used in the process of local beer “dolo” (reddish, cloudy or opaque), infant porridge and non-fermented beverages. Starch is the main reserve polysaccharide of the plant kingdom, and the principal source of carbohydrate from agricultural origin, being the end product of photosynthesis. Sorghum grains like all cereals grains are comprised primarily of starch. α-Amylases are endoenzymes that randomly split α-(1→4)-linkages in starch. β-Amylases on the other hand, are exoglucosidases releasing maltose units from starch. The purpose of this review was to overview the current knowledge on the relevance of starch content and the activities of amylases in sorghum food processing in West Africa.

BOTANICAL DESCRIPTION, PRODUCTION AND UTILIZATION OF SORGHUM

Description and production

S. bicolor is the fifth most important cereal crop after wheat, rice, maize, and barley in terms of production (FAO, 2005). Total world annual sorghum production is about 60 million tons from cultivated area of 46 millions ha. Most important producers are the United States, Nigeria, Sudan, Mexico, China, India, Ethiopia, Argentina, Burkina Faso, Brazil, and Australia (Figure 2). Burkina Faso is the world leader of sorghum production and consumption per inhabitant (FAO, 2005). Sorghum is a plant belonging to the tribe of Andropogoneae and the family of Poaceae. In 1753, Linnaeus described three species of cultivated sorghum: *Holcus sorghum*, *Holcus saccaratus* and *Holcus tricolor*. In 1794, Moench distinguished the genus *Sorghum* from the genus *Holcus*, and in 1805 Person suggested the name *Sorghum vulgare* for *Holcus sorghum* (L.). In 1961, Clayton proposed the name *Sorghum bicolor* (L.) Moench as the correct name for cultivated sorghum and this is currently the accepted one (Doggett, 1988).

Like most angiosperm (flowering plant) lineages, sorghum is thought to be ~200 million years old (Paterson et al., 2003). Sorghum, maize, rice and wheat diverged from a common ancestor only 50-70 million years ago (Paterson et al., 2003). The main races of cultivated sorghum are: bicolor, vulgare, caudatum, kafir, guinea, and durra (Deu et al., 1994; BSTID-NRC, 1996). Common names of sorghum vary from continent to country levels. The most encountered names are: kafferkoren, soedangras, suikergierst, or suiker-sorghum (The Netherlands), kaoliang (China), mtatam, shallu or feterita (East Africa), durra (Egypt), chicken corn, sorghum or guinea corn (United Kingdom), jola, jowar, jawa, cholam, bisinga, durra or shallu (India), kaffir corn (South Africa), milo, sorgo, sudangrass or sorghum (USA), milo (Middle East Africa) and great millet, guinea corn, feterita, sorghum or sorgho (West Africa). Sorghum is C4 crop, whom certain varieties also posses “stay green” genes that enable them to perform photosynthesis permanently. It is particularly adapted to drought prone areas: hot, semi-arid tropical environments with 400-600 mm rainfall-areas that are too dry for other cereals. Sorghum is also found in temperate regions and at altitudes of up to 2300 meters in the tropics. It is well suited to heavy soils commonly found in the tropics, where tolerance to water logging is often required.

Sorghum is a vigorous grass that varies between 0–6 m in height. It has deep and spread roots with a solid stem. Leaves are long (0.3-1.4 m) and wide (1-13 cm),

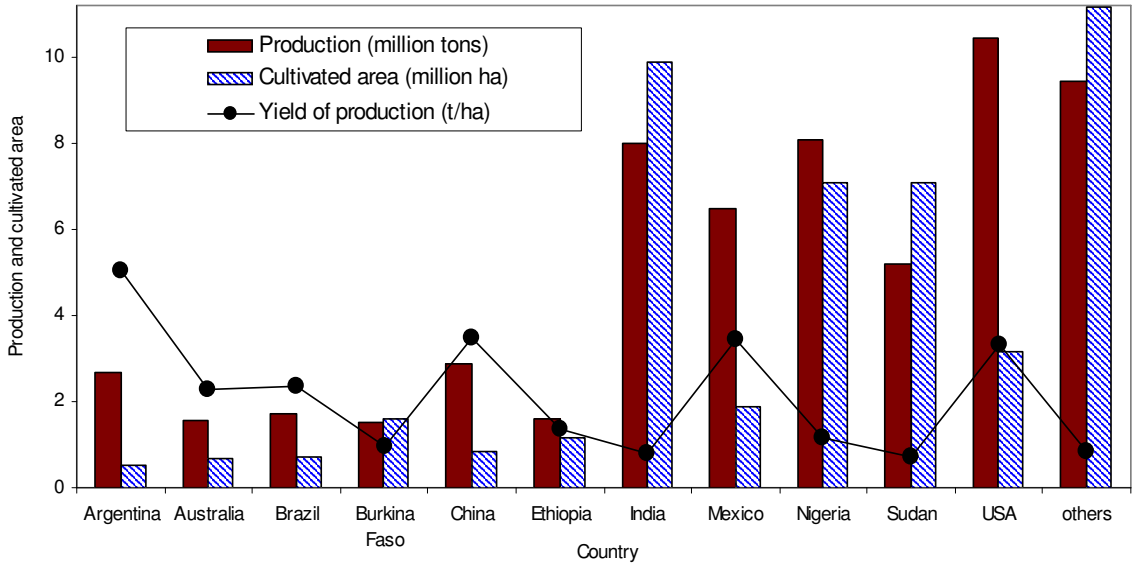

Figure 2. Annual sorghum production and cultivated area throughout the world. Data are from FAO (2005).

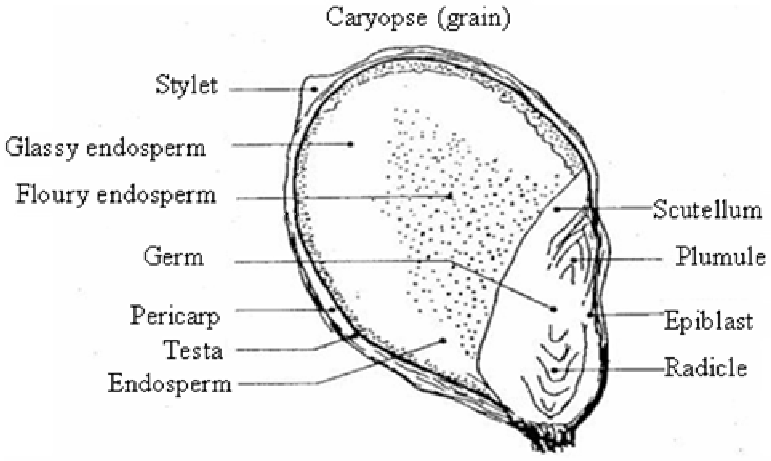

Figure 3. Structure of sorghum grain (Sautier and O'Deye, 1989). Reproduced with the permission of Harmattan Editions, Paris.

with flat or wavy margins. The flower is a panicle, usually erect, but sometimes recurved to form a goose neck (Figure 3). Grain or caryopse is usually covered by glumes. Glumes are the maternal plant tissues in the panicle that holds the developing caryopses after pollination. The caryopse is rounded and bluntly pointed, from 4–8 mm in diameter and varying in size, shape and color with variety (Figure 3). Caryopse color is an important trait that affects grain quality in sorghum.

Sorghum caryopse is composed of three main parts: seed coat (testa or pericarp), germ (embryo) and endosperm (storage tissue). In some sorghum genotypes the testa is highly pigmented. The presence of pigment and the color is a genetic character controlled by the R and Y genes (Waniska, 2000). The thickness of the testa layer is not uniform and is governed by the Z gene. In some genotypes there is a partial testa, while in others it is not apparent or is absent.

Distribution

It is believed that sorghum originated in Africa, more precisely in Ethiopia, between 5000 and 7000 years ago (ICRISAT, 2005). From there, it was distributed along the trade and shipping routes around the African continent, and through the Middle East to India at least 3000 years

ago. It then journeyed along the Silk Route into China. Sorghum was first taken to North America in the 1700-1800's through the slave trade from West Africa. It was re-introduced in Africa in the late 19th century for commercial cultivation and spread to South America and Australia. Sorghum is now widely found in the dry areas of Africa, Asia (India and China), the Americas and Australia.

Sorghum is genetically diverse. The world sorghum germplasms are deposited at the International Crop Research Institute for the Semi-Arid Tropics (ICRISAT, Patancheru) in India. ICRISAT holds about 36,000 germplasm accessions of this crop. The varieties are distinguished on the basis of morphological traits, differences in isoenzyme patterns and DNA polymorphism (Chantereau and Nicou, 1991; Ollitraut et al., 1989a, 1989b; Zongo, 1991; Tao et al., 1993; Vierling et al., 1994, Deu et al., 1994). The sorghum genome is currently sequenced (Paterson et al., 2003; http://fungen.org/Sorghum.htm). Sorghum has 2n=20 chromosomes and is estimated to contain 750 Mb being twice the genome of rice and six times the genome of *Arabidopsis* (Passardi et al., 2004). Thus, a rough estimate of the total number of genes in sorghum based upon the currently 107 652 known expressed sequence tag (EST) data would be between 35 000 and 40 000 (http://fungen.org/Sorghum.htm).

Worldwide utilization

Sorghum is grown in the United States, Australia, and other developed nations essentially for animal feed. However, in Africa and Asia the grain is used both for human nutrition and animal feed. It is estimated that more than 300 millions people from developing countries essentially rely on sorghum as source of energy (Godwin and Gray, 2000). The main foods prepared with sorghum are: tortillas (Latino America), thin porridge, e.g. "bouillie" (Africa and Asia), stiff porridge, e.g. tô (West Africa), couscous (Africa), injera (Ethiopia), nasha and kisra (Sudan), traditional beers, e.g. dolo, tchapallo, pito, burukutu, etc. (Africa), ogi (Nigeria), baked products (USA, Japan, Africa), etc. Tortillas are a kind of chips prepared from sorghum alone or by mixing sorghum with maize and cassava (Anglani, 1998). Nasha is a traditional weaning food (infant porridge) prepared by fermentation of sorghum flour (Graham et al., 1986). Ogi is an example of traditional fermented sorghum food used as weaning food, which has been upgraded to a semi-industrial scale (Achi, 2005). Injera is a local fermented pancake-like bread prepared in Ethiopia from sorghum (Yetneberk et al., 2004). Kisra is traditional bread prepared from fermented dough of sorghum (Mahgoub et al., 1999).

Tô is prepared by cooking slurry of sorghum flour. Thin porridges (usually used as weaning food) are also prepared in the same manner with less amount of flour to obtain a fluid end-product. Often sorghum porridges are characterized by thick pastes that may form rather stiff gels depending on variety used. Porridges prepared with malted sorghums have several order of magnitudes lower viscosities than those of non-malted sorghums (Malleshi and Desikachar, 1988; Dicko et al. 2006). These porridges are particularly useful for the formulation of weaning foods for infants because of their high energy density (Traoré et al, 2004). Furthermore the use of exogenous sources of α-amylase from higher West African plants is useful in reducing the viscosity of cereal porridges, including sorghum ones (Dicko et al., 2005).

Couscous is a steamed and granulated traditional African food originating from North Africa. The traditional method of preparing couscous is a steam-cook process in a special pot called "couscoussière". Couscous is prepared by mixing flour with water to obtain agglomerated flour-water mixtures. The agglomerates are then put on top of the "couscoussière". The stew cooks in the bottom pot while the granules are steamed on top. Sorghum varieties differ in their couscous-making ability. White sorghum varieties from tan plants yield the best couscous product (Galiba et al., 1988). Couscous quality criteria include size uniformity, color, stickiness, and mouth-feel (Aboubacar and Hamaker, 1999).

Dolo is a reddish, cloudy or opaque local beer prepared essentially from red sorghum malt (Hilhorst, 1986). The primary quality criterion of selection of sorghum varieties for beer is their potential to produce malt with high α-amylase and β-amylase activities (Verbruggen, 1996; Taylor and Dewar, 2001). The sorghum malting process starts by immersing the grain in water to activate hydrolytic enzymes. Traditional germination involves seedling growth in warm water-saturated air for 3 to 5 days (Hilhorst, 1986). The germinated grain is then dried to moisture content of 10-12%. The malt obtained is used to prepare dolo. Briefly, dolo preparation starts by mixing sorghum malt flour with water (1:10, w/v). The mixture is decanted and the supernatant (containing hydrolytic enzymes) is separated from the precipitate (containing starch). Water is added to the precipitate and the mixture is boiled to gelatinize starch, but the supernatant is not boiled. It is interesting to note that people, who originally prepare dolo ("dolotières"), empirically know that the supernatant contains "some things", e.g. enzymes that are thermolabile so they should not be boiled. After cooling, the precipitate is filtered to separate soluble components (starch, sugars, proteins, etc.) and the spent (used as animal feed). The mashing step (incubation of hydrolytic enzymes with their substrates) consists of combining the previous supernatant and the filtrate at 50-60ºC for 12-16 h, to obtain the wort. The wort is cooked, and then re-cooled overnight to room temperature (35-40ºC). The cooled wort is a sweet non-fermented beverage highly appreciated by children. It is traditionally called "soft

dolo". The fermentation (1-2 days) is initiated by addition of dried yeasts to the wort. The final product, dolo, is separated from yeasts by filtration. Characteristics of dolo are: alcohol content (2-4%, v/v), pH 4-5, stability at room temperature (12-16h), red color, and opaque appearance. In West African countries, the governments have encouraged the research on the preparation of lager beer from sorghum. However, except in Nigeria, until now it is not successful because of the lack of real financial support.

In most West African countries, sorghum alone accounts for 50% of the total cereal crop land area. Therefore, true food security will be hard to achieve in those countries without a significant improvement of the production, use, and marketing of this major staple cereal. The yield is 1000-3000 kg/ha, while in the other countries (Argentina, China and USA) it is 3000-4000 kg/ha (Figure 2) (FAO, 2005). The low production in West Africa is essentially due to biotic (insects, fungal diseases, weeds, etc.) and abiotic stresses (drought, logging, photoperiod, soil quality, etc.). Most of the cultivated varieties in this area have white, brown, yellow or red caryopses.

Sorghum alone is not considered as a bread making cereal because of the lack of gluten, but addition of 20-50% sorghum flour to wheat flour produces excellent bread (Anglani, 1998; Carson et al., 2000; Hugo et al., 2000, 2003). Among interesting features of sorghum utilization is biscuits and other cooked products (Olatunji et al., 1989). In the USA and Japan, sorghum utilization as human food is increasing because of its use in snacks and cookies (Rooney and Waniska, 2004). Sorghum has been intentionally introduced in China for food needs and it is becoming one of the most important crops in this country (Kangama and Rumei, 2005). The future promise of sorghum in the developed world is for wheat substitution for people allergic to gluten (Fenster, 2003). In addition, pasta products, such as spaghetti and macaroni made from semolina or wheat could be made with mixtures of composite flour consisting of 30-50% sorghum in wheat (Hugo et al., 2000, 2003). Pre-cooked sorghum flours mixed with vitamins and exogenous sources of proteins (peanuts or soybeans) are commercially available in many African countries for the preparation of instant soft porridge for infants. Sorghum can be puffed, popped, shredded and flaked to produce ready-to-eat breakfast cereals.

Sorghum starch is successfully applied for the production of bio-ethanol (Suresh et al., 1999; Aggarwal et al., 2001). In Nigeria and South Africa, sorghum is industrially used for the production of lager beer (Taylor and Dewar, 2001). More information on sorghum utilization for human nutrition can be found elsewhere (FAO, 1995; Anglani, 1998; Taylor and Dewar, 2001; Awika and Rooney, 2004a, Rooney and Waniska, 2004).

SORGHUM GRAIN COMPOSITION AND NUTRITIVE VALUE

Starch is the main component of sorghum grain, followed by proteins, non-starch polysaccharides (NSP) and fat (Table 1). The average energetic value of whole sorghum grain flour is 356 kcal/100g (BSTID-NRC, 1996). Sorghum has a macromolecular composition similar to that of maize and wheat (BSTID-NRC, 1996). However, sorghum contains resistant starch, which impairs its digestibility, notably for infants (FAO, 1995). This resistance is desired in other applications to fight human obesity and to feed diabetic people. Foods prepared from high tannin sorghums varieties have a longer passage in the stomach (Awika and Rooney, 2004a). Edible products incorporating slowly digestible starch are known to exhibit a low glycemic index and increase satiety (Shin et al., 2004).

Sorghum contains non-starch polysaccharides (NSP), mainly located in the pericarp and endosperm cell walls, with proportions in the kernel ranging from 2 to 7% depending on variety (Knudsen and Munck, 1985; Verbruggen et al., 1993). The NSP in sorghum grain are essentially constituted of arabinoxylans and other β-glucans representing 55% and 40% of the total NSP (Verbruggen et al., 1993; Hatfield et al., 1999). Verbruggen and co-workers (1993, 1998) found arabinoxylans from sorghum to be glucuronoarabinoxylans containing ferulic acid and *p*-coumaric acid. Arabinoxylans, being one of the major NSP present in sorghum cell walls, play an important role in the processing of sorghum for baking and brewing (Rouau, 1993; Verbruggen et al., 1998). The other β-glucans comprise cellulose (1,4-β-D-glucans), curdlan-type glucans (1,3-β-D-glucans), and lichenan-type glucans (1,3; 1,4-β-D-glucans) (Knudsen and Munck, 1985; Verbruggen et al., 1993, 1996, 1998). These β-glucans are predominantly water-unextractable, and form viscous and sticky solutions. In brewing, together with arabinoxylans, they are associated with processing problems like poor wort and beer filtration rates and the occurrence of haze (Aisien and Muts, 1987; Dufour et al., 1992). Sorghum also contains non-carbohydrate cell-wall polymers such as lignins with proportions constituting up to 20% of the total cell wall materials (Hatfied et al., 1999).

The protein content in whole sorghum grain is in the range of 7 to 15% (FAO, 1995; Beta et al., 1995). Using the solubility-based classification (Jambunatan et al., 1975), sorghum proteins have been divided into albumins, globulins, kafirins (aqueous alcohol-soluble prolamins), cross-linked kafirins and glutelins. The kafirins comprise about 50-70% of the proteins (Hamaker et al., 1995; Oria et al., 1995; Duodu et al., 2003). α-Kafirins (23 and 25 kDa) make up about 80% of the total kafirins and are considered the principal storage proteins of sorghum, whereas β-kafirins (16, 18, and 20 kDa), and γ-kafirin (28 kDa) comprise about 5% and 15% of total

Table 1. Proximate composition of sorghum grain[a].

Macro-components (g/ 100g f. m.)		Essential amino-acids		Vitamins (mg/100g d. m.)		Minerals (mg/ 100g d. m.)	
Carbohydrates	65 - 80	Leu	832 -	Vit.-A	21 RE**	Ca	21
Starch	60 - 75	Ile	215 -	Thiamin	0.35	Cl	57
Amylose	12 - 22	Met/Cys*	190 -	Riboflavin	0.14	Cu	1.8
Amylopectin	45 - 55	Lys	126 -	Niacin	2.8	I	0.029
Non starch	2 - 7	Phe/Tyr*	567 -	Pyridoxine	0.5	Fe	5.7
Low M_w carbohydrates	2 - 4	Thr	189 -	Biotin	0.007	Mg	140
Proteins	7 - 15	Trp	63 - 187	Pantothenat	1.0	P	368
α-Kafirins	4 - 8	Val	313 -	Vitamin C	<0.001	K	220
ß-Kafirins	0.2 - 0.5	Arg*	500 -			Na	19
γ-Kafirins	0.7 - 1.6	His*	200 -			Zn	2.5
Other proteins	2 - 5						
Fat	1.5 - 6						
Ash	1 - 4						
Moisture	8 - 12						

[a]Sources: Verbruggen et al. (1993, 1996); FAO (1995), Hamaker et al., (1995), BSTID-NRC (1996), Glew et al. (1997), Duodu et al. (2003), Dicko et al. (2006). *Not strictly essential amino-acids,**RE = retinol equivalent; f.m. = fresh matter, d. m. = dry matter; NSP = non starch polysaccharides.

Table 2. Comparison of starch components and amylase activities[a] in ungerminated (g-) and germinated (g+) sorghum varieties.

Variety code	Total starch (%)		Amylose (%)		Amylopectin (%)		α-Amylase (U mg^{-1})		β-Amylase (U mg^{-1})	
	g-	g+	g-	g+	g-	g+	g-	g+	g-	g+
V1	66.1	58.1	21.5	14.8	44.6	43.3	1.4	12.8	3.5	5.4
V2	59.5	55.2	11.5	9.1	48.0	46.1	3.1	6.8	0.9	1.9
V3	59.5	56.2	10.2	9.2	49.3	47.0	0.6	1.7	1.2	2.8
V4	66.0	63.2	17.1	17.0	48.9	46.2	1.1	1.4	0.6	1.1
V5	66.5	60.2	16.1	10.0	50.4	50.2	3.4	7.9	1.3	1.7
V6	66.2	58.1	16.8	12.0	49.4	46.1	3.9	7.2	1.7	1.1
V7	68.5	58.1	16.7	12.8	51.8	45.3	4.3	5.6	2.2	4.6
V8	61.6	59.5	10.9	10.4	50.7	49.1	1.6	1.9	1.0	2.9
V9	65.2	61.6	12.3	9.2	52.9	52.4	0.2	1.9	1.7	3.9
V10	63.7	58.1	11.6	10.7	52.1	47.4	0.3	4.9	1.8	3.8
V11	61.6	59.5	12.6	10.7	48.9	48.8	0.6	0.9	1.9	8.7
V12	62.3	59.2	14.8	13.3	47.5	45.9	0.4	2.9	1.5	6.1
V13	62.5	56.7	11.0	7.3	51.5	49.4	2.5	3.9	1.1	4.0
V14	68.5	61.6	14.2	9.7	54.3	51.9	0.8	3.2	0.9	2.7
V15	62.3	60.8	14.3	12.9	48.0	48.0	5.3	6.0	2.1	2.8
V16	61.6	59.5	11.5	9.5	50.1	50.0	1.6	1.7	1.6	2.1
V17	60.2	59.3	12.6	12.2	47.6	47.1	6.9	8.4	1.7	2.6
V18	64.2	59.2	15.5	11.4	48.7	47.8	1.4	1.6	1.1	3.1
V19	61.6	57.5	10.9	10.1	50.7	47.4	11.3	11.5	2.0	4.7
V20	64.1	58.8	13.2	9.7	50.9	49.1	6.6	11.0	2.6	4.3
V21	62.5	61.6	10.8	10.1	51.7	51.5	1.2	8.7	1.3	8.7
V22	62.6	61.5	13.2	12.2	49.4	49.3	5.4	7.8	2.8	7.3
V23	64.5	59.2	14.3	12.9	50.2	46.3	1.1	1.7	1.6	3.6
V24	67.6	60.2	17.2	13.8	50.4	46.4	4.3	7.5	2.5	3.2
V25	61.6	59.1	11.6	11.4	50.0	47.7	4.0	16.4	2.7	1.7
V26	65.2	60.2	14.8	11.1	50.4	49.1	3.5	5.5	2.5	3.0
V27	66.1	60.2	15.6	10.9	50.5	49.3	1.4	1.8	1.0	0.9
V28	62.0	61.6	11.2	10.2	50.8	51.4	10.2	16.3	0.9	2.1
V29	65.1	59.8	15.7	12.0	49.4	47.8	4.8	6.4	2.0	2.0
V30	58.6	58.3	11.4	11.1	47.2	47.2	5.3	10.3	5.1	3.7
V31	57.2	55.2	11.5	10.0	45.7	45.2	4.9	13.8	2.0	5.4

Table 2. con td. Comparison of starch components and amylase activities[a] in ungerminated (g-) and germinated (g+) sorghum varieties.

V32	63.5	61.0	11.9	10.2	51.6	50.8	1.4	12.2	2.2	5.7
V33	65.5	61.6	12.5	9.9	53.0	51.7	2.2	13.5	1.2	3.4
V34	59.5	58.5	11.0	10.1	48.5	48.4	4.1	5.9	2.1	2.3
V35	65.0	62.0	14.8	12.1	50.2	49.9	3.4	4.9	3.1	1.9
V36	65.7	60.1	15.1	14.2	50.6	45.9	0.7	10.1	1.5	2.4
V37	66.2	63.8	14.7	12.6	51.5	51.1	1.3	2.0	13.0	9.0
V38	61.6	60.8	12.8	12.4	48.8	48.4	2.7	3.3	6.7	1.6
V39	63.5	60.1	13.5	13.3	50.0	46.8	1.8	14.6	1.6	2.0
V40	62.6	61.6	11.2	11.1	51.4	50.5	0.8	14.1	3.5	2.9
V41	63.5	60.2	14.2	11.4	49.3	48.8	3.7	13.7	3.4	4.8
V42	64.2	61.7	12.7	10.6	51.5	51.1	5.1	14.3	1.8	2.2
V43	64.4	59.5	15.3	11.1	49.1	48.4	1.7	12.1	1.2	2.4
V44	62.5	57.4	15.0	10.3	47.5	47.2	3.1	13.2	1.1	1.1
V45	59.5	58.7	13.5	13.0	46.0	45.7	0.8	16.1	2.9	3.4
V46	58.1	57.2	10.9	10.8	47.2	46.4	1.4	13.0	1.2	1.1
V47	61.6	58.2	12.7	11.7	48.9	46.5	2.3	10.1	12.5	13.9
V48	59.5	58.8	12.3	11.5	47.2	47.3	4.0	10.6	7.4	4.3
V49	59.5	58.1	11.9	11.4	47.6	46.8	0.8	12.4	1.0	2.1
V50	60.5	58.8	11.4	11.4	49.1	47.5	3.5	13.3	1.5	1.5
Mean	63.0	59.5	13.4	11.3	49.6	48.2	3.0	8.1	2.5	3.6
Range variation	57-69	55-64	10-17	9-16	45-54	43-52	0.4-11	0.9-16	0.6-13	0.9-14
Standard error	3.8		0.8		3		0.4		0.2	

[a]Specific activities (units/mg of protein). Data are from Dicko et al. (2006).

kafirins, respectively. The nutritional quality of sorghum proteins is poor because these kafirins are protease resistant (Badi et al., 1990; Oria et al., 1995; Anglani, 1998). However, a wide variability according to variety has been observed with respect to the levels of proteins in sorghum (Reddy and Eswara, 2002). The protein digestibility of sorghum may decrease upon cooking (Axtell et al., 1981; Taylor and Taylor, 2002), but pre-fermentation may increase the digestibility (Taylor and Taylor, 2002). The low digestibility is due to protein-protein, protein-carbohydrate, protein-(poly) phenol and carbohydrate-(poly) phenol interactions (Knudsen et al., 1988; Axtell, 1981, Hamaker et al., 1987; Cherney, et 1992, Taylor and Taylor, 2002).

The fat in sorghum grain (mainly present in the germ) is rich in polyunsaturated fatty acids (Glew et al., 1997). The fatty acid composition of sorghum fat (linoleic acid 49%, oleic 31%, palmitic 14%, linolenic 2.7%, stearic 2.1%, etc.) is similar in content to that of corn fat, but it is more unsaturated (Knudsen et al., 1988; Adeyeye and Ajewole, 1992; FAO, 1995).

Sorghum is a good source of vitamins, notably the B vitamins (thiamin, riboflavin, pyridoxine, etc.), and the liposoluble vitamins A, D, E and K.

Sorghum is reported to be a good source of more than 20 minerals (BSTID-NRC, 1996). Sorghum is also rich in phosphorus, potassium, iron and zinc (Glew et al., 1997; Anglani, 1998). Zinc (an important metal for pregnant women) deficiency is more common in corn and wheat than in sorghum (Hopkins et al., 1998).

Effect of germination on sorghum composition

The physiological maturity of sorghum grain generally occurs 50 days after anthesis, and marks the end of nutrient delivery and the beginning of senescence, and caryopse desiccation (Waniska, 2000). The mature grain is then harvested and stored. In a dormant stage, it is characterized by dehydration and a dramatic decrease of metabolic activity. Germination is induced by rehydration of the seed, which increases both respiration and metabolic activity thus allowing the mobilization of primary and secondary metabolites (Limami et al., 2002). Therefore, the biochemical composition between ungerminated and germinated kernels is different.

Germination induces the synthesis of hydrolytic enzymes, e.g. starch degrading enzymes, and proteases. The reduction of phytic acid, some flavonoids and proanthocyanidins has been observed during germination (FAO, 1995; Traoré et al., 2004). The breakdown of protease resistant prolamins (Mazhar and Chandrashekar, 1993) and the increase of the availability of minerals (iron, zinc, etc.) and essential amino acids (principally Lys, Tyr and Met) upon germination has also been reported (FAO, 1995; Anglani, 1998). Germination of sorghum is important for the preparation of weaning foods with low paste viscosity and high energy density (Malleshi and Desikachar, 1988). While germination usually has positive aspects, it is important to note that it increases the content of nitrilosides (cyanogenetic β-glycosides, e.g. dhurrin) of the grain (Ahmed et al., 1996;

Traoré et al., 2004). These compounds release cyanide (prussic acid) which may be removed either by heating the flour or removing shoots, roots and the germs, but removing the latter reduced the content in α-amylase (Uvere et al., 2000; Traoré et al., 2004). Upon germination, the initially low content of vitamin C is strongly increased (Taur, et al., 1984).

STARCH AND STARCH DEGRADING ENZYMES IN SORGHUM GRAIN

Starch

Starch is the primary source of stored energy in cereal grains. Starch is deposited as granules in the endosperm cells, being the main constituent of the endosperm. Sorghum starch granules have diameters ranging from 5 to 25 µm (average 15 µm). Sorghum starch has a specific particularity because of its high gelatinization temperature (70-75ºC), which decreases its industrial application (Dufour et al., 1992; Taylor, 1992). Native starch granules are essentially insoluble in cold water. The term "gelatinization" is used to describe the swelling and hydratation of granular starches (Zobel, 1984). Starch gelatinization is the disruption of molecular orders within the starch granule manifested in irreversible changes in properties such as granular swelling, native crystalline melting, loss of birefringence, and starch solubilization. These changes render all or part of the material in granules soluble and consequently enable to contribute to food properties such as texture, viscosity, and moisture retention (Whistler and BeMiller, 1997). The point of initial gelatinization and the range over which it occurs is governed by the starch structure. Sorghum starch is classified as type-B, e.g. a moderate swelling starch compared to type-A starches (potato, tapioca, waxy sorghum, etc.), which are high swelling starches (Beta and Corke, 2001). The retrogradation involves reassociation of the molecules and occurs when the starch is cooled, and this is dependent on the ratio of amylose and amylopectin. Enzymatic sorghum starch hydrolysis or chemical treatment can improve its technological properties (Zhang et al., 1999).

Regardless of the botanical source, starch is structurally composed of two high molecular weight homopolysaccharides known as amylose and amylopectin. Amylose content in mature sorghum grain is varietal dependent. While waxy sorghums do not contain amylose (level < 1%), the content of amylose in normal sorghums is ranging from 10 to 17% (w/w, fresh weight basis) (Table 2), constituting approximately 20-30% of starch. There is no significant difference between red and white sorghum grains in their starch contents (Dicko et al., 2006). The screening of starch content in 50 sorghum varieties before and after germination showed that there is an inter-varietal difference of content in these compounds (Dicko et al. 2006).

Amylose is composed of essentially homogenous linear units of α-(1→4)-D-glucopyranose, which can form helicoidal structures in solution (Manners, 1974; Jarvis and Walker, 1993). The interior of the helix is hydrophobic, allowing amylose to form a complex with free fatty acids, iodine, etc. (Fennema, 1985). There is a significant inter-varietal difference of content of amylose among sorghum varieties (Beta and Corke, 2001; Dicko et al., 2006). Although, some varieties contained relatively little amylose, waxy sorghum were not found among cultivated sorghums in West Africa (Dicko et al., 2006). This is probably because cultivated varieties were primarily selected and bred for tô, for which high amylose content is required (Bello et al., 1999; Trouche et al., 2000).

Amylopectin is constituted of short chains of α-(1→4)-D-glucopyranose (majority 10-20 units in sorghum starch) branched to α-(1→6)-D-glucopyranoses to form a highly ramified structure (Blennow et al., 2001). The content of amylopectin is varietal dependent. The content of amylopectin in sorghum is ranging from 45 to 54% (w/w, fresh weight basis) (Table 2). Contrary to amylose the levels of amylopectin in sorghum varieties are not significantly different (Dicko et al., 2006).

There are relationships between the levels of starch component and sorghum utilization for several foods. Content of starch and starch components such as amylose and amylopectin may give directions for the selection of sorghum varieties for specific foods (Dicko et al., 2006). For instance, in "tô" preparation, the formation of a thick paste linked to high amylose content is necessary. On the other hand, sorghum varieties with low viscosity are desired in the formulation of weaning foods with high energy density (WHO, 1998). In that case low amylose content and high α-amylase activities are determinant. Since amylose has a higher gelatinization temperature than amylopectin (Whistler et al., 1984), sorghum with low amylose content could be targeted for industrial brewing. Amylose is more susceptible to retrogradation than amylopectin and waxy sorghum is less viscous than normal sorghum (FAO, 1995). Low amylose-containing sorghum varieties are also preferred for extrusion-cooking because they give better functional characteristics of the extrudates, such as enzyme-susceptibility and solubility (Gomez et al., 1988). Sorghum varieties with low amylose content may be recommended for infant porridges preparation.

α-Amylase and β-amylase

Starch degradation in plants is accomplished by α-amylase [α-1,4-D-glucan 4-glucanohydrolase, EC 3.1.1.1], β-amylase [α-1,4-D-glucan maltohydrolase, EC 3.1.1.2], amyloglucosidase [α-1,4-glucan-glucohydrolase, EC 3.1.1.3] and starch phosphorylase [1,4-α-D- glucan

Table 3. Apparent determinant (bio)chemical markers for sorghum food processing.

Food	Grain color	Germination	Starch content	Amylose content	α-amylase and β-amylase	References
Tô	white	no	high	high	low	1, 2,3, 4
Dolo	red	yes	high	high	high	2, 3, 5
Couscous	white	no	medium	low	medium	2, 3, 5
Infant porridge	white	yes	high	low	high	3, 5, 6, 7, 8
Industrial beer	white	yes	high	low	high	9, 10, 11, 12, 13
Bread	white	no	high	high	high	1, 11

[1]Gomez et al., 1988; [2]Trouche et al., 2000; [3]Dicko et al. 2006, [4]Bello et al., 1990; [5]Dicko et al. 2006; [6]Malleshi and Desikachar, 1988; [7]Traoré et al., 2004; [8]Thaoge et al., 2003; [9]Dufour et al., 1992; [10]Taylor and Robbins, 1993; [11]FAO, 1995; [12]Nwanguma and Eze, 1995; [13]Uriyo and Eigel, 2000.

: phosphate α-D-glucosyltransferase, EC 2.4.1.1] action on α-(1→4)-linkages (Manners, 1974). Amylases are hydrolytic enzymes, which depolymerize starch according to a classic acid-base mechanism. α-Amylases are endo-enzymes that randomly split α-(1→4)-linkages in starch with retention of anomeric configuration of glucose residues. β-Amylase is an exoglucosidase acting from the non-reducing end, releasing β-maltose units from starch, hence the name β-amylase (Kaplan and Guy, 2004). The β-maltoses released undergo mutarotation into α-maltose (and Akerman, 1973; Dicko et al., 2000). Both α-amylase and β-amylase cannot split the α-(1→6)-linkages in amylopectin. Therefore, the degradation of starch by these enzymes is incomplete. In addition, plant amylases scarcely hydrolyze raw starch: their action is lower than 5% hydrolysis (Dicko et al., 1999).

Sorghum amylases were first detected in 1928 and partially purified since that time by solvent fractionation (Patwardhan and Norris, 1928). The starch-liquefying or dextrinizing power is referred to α-amylase activity, while the starch-saccharifying or saccharolytic power is referred to as β-amylase activity. Sorghum α-amylases and β-amylases occur as glycosylated (2-3 glycoforms), anionic (p*I* 4-5) isoenzymes of different molecular weights (Mundy, 1982; Okon and Uwaifo, 1984). Two α-amylase isoenzymes with molecular masses of 41.5 and 42.7 kDa (Mundy, 1982) and three β-amylases with molecular masses of 20, 40 and 60 kDa were purified from sorghum grain (Okon and Uwaifo, 1984). Red sorghum grains have generally higher amylase activities than white ones (Dicko et al., 2006).

One of the constraints of utilizing sorghum varieties in industrial brewing is the low activity of starch degrading enzymes. For instance, in Nigeria, sorghum has become the predominant cereal for industrial scale malting and brewing of beer, following legislation banning the importation of barley and wheat (Hug et al., 1991). The major disadvantage encountered using sorghum in brewery is its low content or absence of β-amylase (Taylor and Robbins, 1993; Swanston et al. 1993; Verbruggen, 1996). Comparison of the effect of germination on α-amylase and β-amylase activities in sorghum varieties is rare, because most studies focused only on germinated grains (Dufour et al., 1992; Beta et al., 1999). Results about the effect of germination on amylase activities are sometimes contradictory. Contrary to previous results stating that α-amylase and β-amylase activities were not detected in ungerminated sorghum varieties (Ahmed et al., 1996), it is shown that these enzymes are present in all sorghum varieties (Dicko et al., 2006). The results of β-amylase screening in sorghum may be biased because of the used chemical assays, of which some are less specific (ferricaynide, 3,5-dinitro-salicylic acid assays, etc.) for β-amylase than the standard assay described by McCleary BV and Codd (1989). While β-amylase activity did not show an overall increase after germination, α-amylase activity increased up to 20 fold in some varieties (Dicko et al., 2006). The main reason for the difference of the effect of germination between α-amylase and β-amylase may be due to the fact that β-amylase is unlikely *de novo* synthesized during germination (Ziegler, 1999). Using a statistically significant number of samples, it is shown that although α-amylase and β-amylase have a common substrate, e.g. starch, their activities are not correlated in sorghum grain both before and after germination (Beta et al., 1999, Dicko et al., 2006). The clear polymorphism of β-amylase and α-amylase activities in sorghum varieties may give direction for the selection of sorghum varieties containing these enzymes for specific food utilization.

It is interesting to note that amylase activities could be correlated with food processing of sorghum. For instance, low α-amylase activity of tô varieties is beneficial to obtain a relatively stick porridge (Dicko et al., 2006). For “dolo” and industrial beer preparations, high α-amylase and β-amylase activities are desired (Dufour et al., 1992; Taylor and Robbins, 1993). The high amylase activities probably explain the preference for red sorghums for the preparation of “dolo”. In industrial brewing, a specific interest exists in high β-amylase-containing sorghum varieties (Dufour et al., 1992; Taylor and Robbins, 1993; Verbruggen et al., 1993, 1996). Interestingly some malted

sorghum varieties contain β-amylase activities comparable to that of barley malt (Beta et al., 1995, Dicko et al., 2006). These varieties can be suggested for industrial brewing. A constraint in the utilization of sorghum for industrial brewing is the high starch gelatinization temperature (Okafor and Aniche, 1987). For couscous preparation varieties displaying low α-amylase activity are required to avoid starch dextrinization during the process.

In most West African countries bakers do not use composite sorghum/wheat flour. However, acceptable bread can be produced with 30-50% sorghum substitution for wheat (Anglani, 1998; Carson et al., 2000). In analogy with wheat dough, the use of sorghum flour possessing suitable α-amylase activity could increase bread quality (Hilhorst et al., 1999). For bread making, it is important to have sorghum lines with low amylose contents (Lee et al., 2001; Martin et al., 2004). These criteria may give directions for selecting sorghum varieties for bread making.

The (bio)chemical characteristics screened, i.e. starch and starch degrading enzymes are suggested to serve as determinants for sorghum utilization for various foods. The criteria of recommendation of varieties having important (bio)chemical constituents as quality-grade markers for the preparation for foods are shown in Table 3. It is important to stress that the suitability of sorghum varieties for food and beverages is also dependent on the chemical and physical properties of kernels and process conditions. The recommendations made in Table 3 may also depend on technological levels and consumer acceptance for confirmations.

CONCLUSION

Sorghum is a staple food in Africa that has a high environment tolerance and a great (bio) chemical diversity. The content of starch as well as amylase is highly polymorph among sorghum varieties. These findings show that it is possible to use the content of starch and starch degrading enzymes to give directions for selecting the most suitable sorghum varieties for specific food processing.

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